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FINAL PROJECT REPORT

Life Cycle Assessment of Environmental and Human Health Impacts of Flow Battery Energy Storage Production and Use

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PREFACE

The California Energy Commission's (CEC) Energy Research and Development Division supports energy research and development programs to spur innovation in energy efficiency, renewable energy and advanced clean generation, energy-related environmental protection, energy transmission and distribution and transportation.

In 2012, the Electric Program Investment Charge (EPIC) was established by the California Public Utilities Commission to fund public investments in research to create and advance new energy solutions, foster regional innovation and bring ideas from the lab to the marketplace. The CEC and the state's three largest investor-owned utilities—Pacific Gas and Electric Company, San Diego Gas & Electric Company and Southern California Edison Company—were selected to administer the EPIC funds and advance novel technologies, tools, and strategies that provide benefits to their electric ratepayers.

The CEC is committed to ensuring public participation in its research and development programs that promote greater reliability, lower costs, and increase safety for the California electric ratepayer and include:

- Providing societal benefits.
- Reducing greenhouse gas emission in the electricity sector at the lowest possible cost.
- Supporting California's loading order to meet energy needs first with energy efficiency and demand response, next with renewable energy (distributed generation and utility scale), and finally with clean, conventional electricity supply.
- Supporting low-emission vehicles and transportation.
- Providing economic development.
- Using ratepayer funds efficiently.

Life Cycle Assessment of Environmental and Health Impacts of Flow Battery Energy Storage Production and Use is the final report for the A Comparative, Comprehensive Life Cycle Assessment of the Environmental and Human Health Impacts of Emerging Energy Storage Technology Deployment project (Contract Number EPC-16-039) conducted by the University of California, Irvine. The information from this project contributes to the Energy Research and Development Division's EPIC Program.

For more information about the Energy Research and Development Division, please visit the CEC's research website (www.energy.ca.gov/research/) or contact the CEC at ERDD@energy.ca.gov.

ABSTRACT

California adopted SB 100 as a strategic policy to transition California's electricity system to a zero-carbon configuration by the year 2045. Energy storage technology is critical to transition to a zero-carbon electricity system due to its ability to stabilize the supply and demand cycles of renewable energy sources. The life cycle impacts of long-duration energy storage, such as flow batteries is not well characterized compared to more established energy storage systems, such as lead-acid and lithium-ion batteries.

This project conducted a comprehensive life cycle assessment – encompassing the materials extraction, manufacturing, and use of three flow battery technologies, each represented by different chemistries: vanadium-redox, zinc-bromide, and all-iron. The results enabled comparisons with other battery systems from a systematic environmental, health impact, and benefits perspective. Among the three flow battery chemistries, production of the vanadium-redox flow battery exhibited the highest impacts on six of the eight environmental indicators, various potential human health hazards, and per-energy-capacity material costs of $491/kWh across its life cycle. Production of the all-iron flow battery, by contrast, exhibited the lowest impacts according to six environmental indicators, as well as the lowest potential human health hazards, and material costs of $196/kWh. Production of the zinc-bromide flow battery exhibited environmental and human health impacts at a level between the other two battery chemistries, and the lowest costs of $153/kWh on a materials basis.

Since these technologies are not as mature as conventional batteries, there is an opportunity to use the results of this study to improve the design and materials for flow batteries manufacturing. In addition, a use-phase analysis demonstrated that flow batteries deployed in the electric grid, will provide significant net environmental benefits for the first ~200 gigawatt hours (GWh) of capacity installed. However, the environmental impacts from the production of these systems will exceed the benefits after this threshold.

Keywords: flow battery, energy storage, life cycle assessment, environmental impact health impact, economic costs.

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EXECUTIVE SUMMARY

Introduction

California Senate Bill (SB) 100 (De León, Chapter 312, Statutes of 2018) established a statewide goal to eliminate greenhouse gas emissions from the electricity sector by 2045 to reduce climate change impacts on the economy, public health, and environment. Meeting this goal will require a major expansion of renewable energy resources such as wind and solar power. Although wind and solar have complementary generation profiles, their combined capability cannon meet electricity demand. To maintain reliability and cost efficiency of power system operation, energy storage is required to capture generation for use at a later time to meet electric loads. This storage function must also occur across different timescales: hourly, daily, monthly, and seasonally.

Energy storage systems, however, can also result in increased greenhouse gas emissions and other environmental impacts during various life-cycle stages such as materials extraction and system manufacture. When deploying energy systems to the scale needed to support California's renewable energy goals, the greenhouse gas emissions reduction benefits of energy storage must not be superseded by production-related impacts on the environment and human health.

The environmental and health impacts associated with producing battery technologies that can meet short-term storage needs — such as lead-acid and lithium-ion — are well characterized. The same cannot be said for emerging battery technologies that could fulfill long-term storage needs, such as flow batteries, which store energy in an electrolyte liquid. These batteries offer a potential solution for long-term storage needs of 5 hours to 12 hours of discharge at rated power. Additionally, the benefits of deploying flow batteries into the electric grid during the use phase also need to be better understood. Developing the life-cycle understanding of flow battery environmental and health impacts is, therefore, important for ensuring that large-scale energy storage deployment supports SB 100 goals while minimizing or avoiding unintended environmental and health impact consequences. The results of this project fill numerous data gaps in the life-cycle assessment of flow battery production and use and provide opportunities for refining design and manufacturing to maximize net benefits.

Project Purpose

The purpose of this project was to assess the environmental and human health impacts, and cost drivers for three emerging flow battery technologies that could provide long-term storage: vanadium-redox, zinc-bromide, and all-iron. The assessment characterized the environmental and health impacts associated with battery storage production of the most current version of these technologies. Current understanding of life cycle environmental and health impacts has primarily focused on conventional battery systems, while comparable data for flow batteries are lacking or severely outdated in the available literature.

Environmental and human health benefits associated with the use phase (that is, when the flow batteries are incorporated into the electric grid) were also evaluated. The overall effort benefits ratepayers by potentially identifying and avoiding unintended environmental consequences of large-scale deployment of long-duration energy storage.

The goals of this project were to:

1. Develop a complete characterization and advisory understanding of the life-cycle use of resources and environmental and human health impacts of manufacturing, developing, and commercially deploying different types of flow battery energy storage chemistries at scale.
2. Provide information needed by planning agencies and policymakers to promote environmentally benign life-cycle process configurations for flow battery technologies.

Project Approach

The project followed four steps. First, the project team worked with three anonymous flow battery manufacturers to obtain data on materials composition and the manufacturing process and develop a life-cycle inventory for the type of flow battery they have commercialized. Each manufacturer provided data for their commercially available systems (as of late 2017) that was then combined with broader life-cycle inventories for materials extraction and processing from the ecoinvent database. The manufacturer data varied in detail and structure which required the project team to establish a common data structure and system boundary to harmonize the data.

Second, the project team used the life-cycle inventory to model the supply chain of each battery type using SimaPro life cycle assessment software and calculated the material and energy inputs as well as emissions produced in the materials extraction and manufacturing processes. The project team did not address the end-of-life stages of the different flow battery types due to lack of data on the end-of-life pathways for some of the key materials used in these systems. The project team used the Holistic Grid Resource Integration and Deployment (HiGRID) model to predict the emissions benefit associated with the batteries being deployed on a future highly renewable electricity system. The model allowed the project team to characterize the following environmental impact indicators from the production and use-phases emissions for the three flow battery types: global warming potential, particulate matter, ozone depletion potential, acidification potential, freshwater eutrophication (excessive nutrient runoff that affects water quality), ecotoxicity, abiotic (non-living resource) depletion potential, and fossil-fuel cumulative energy demand.

Third, the project team combined the data on life cycle environmental impacts with chemical toxicity data. To assess chemical hazards, the team used GreenScreen® for Safer Chemicals and ReCiPe 2016 to translate the emissions of certain compounds from the manufacturing processes to human health impacts in terms of greenhouse gas emissions and air pollutant effects. For toxicity effects, the project team used the USETox framework to translate chemical properties to cancer and noncancer toxicity impacts. The team also leveraged data from the National Institute for Occupational Safety and Health, the Occupational Safety and Health Administration, and American Conference of Governmental Industrial Hygienists on exposure limits to assess occupational hazards.

Finally, the project team gathered and used cost data for the materials used in each of the flow batteries to assess the cost drivers associated with each flow battery and their sensitivity to fluctuations in material prices. This effort was aimed at informing how materials selection choices could be used to reduce environmental impacts and cost as these technologies mature.

Project Results

Among the three flow battery chemistries, production of the vanadium-redox flow battery exhibited the highest impacts on six of the eight environmental indicators, various potential human health hazards, and per-energy-capacity material costs of $491/kilowatt-hour (kWh) across its life cycle. Production of the all-iron flow battery, by contrast, exhibited the lowest impacts according to the six environmental indicators, as well as the lowest potential human health hazards, and material costs of $196/kWh. Production of the zinc-bromide flow battery exhibited environmental and human health impacts at a level between the other two battery chemistries, and the lowest costs of $153/kWh on a materials basis.

Environmental Impacts

For the materials extraction and manufacturing stages, the research team found that while the three different flow battery chemistries perform differently across the eight environmental impact indicators, certain chemistries performed consistently better or worse across a wider range of indicators.

Out of the three battery chemistries, production of the vanadium-redox flow battery contributed the highest impacts to global warming potential, ozone depletion potential, particulate matter, acidification potential, and cumulative energy demand. This contribution is almost exclusively driven by the emissions associated with the production of vanadium pentoxide used in the battery electrolyte. Selecting more environmentally benign pathways for producing the same electrolyte can significantly decrease the environmental impacts associated with this technology to the point where it could be comparable to or outperform the other flow battery chemistries.

The all-iron flow battery production contributed the lowest environmental impacts to global warming potential, particulate matter, acidification potential, freshwater eutrophication, fossil-fuel cumulative energy demand, and abiotic resource depletion due to its use of relatively benign materials. However, the technology contributed a disproportionately high amount to ecotoxicity.

For the use phase, the project team found that installation of each battery type provided similar environmental benefits, as indicated by increased renewable uptake. However, considering the environmental impacts of production, the net benefit diminished with adding the next unit of battery capacity. The exact capacity values where these occur depend on the environmental indicator and battery type. For example, the vanadium-redox flow battery thresholds ranged from as low as 416 GWh for ozone depletion potential, to as high as 1920 GWh for global warming potential.

Human Health Impacts

For the air emissions in production phase, the vanadium-redox battery exhibits the highest contributions to disability-adjusted life years per kilowatt-hour of battery capacity through global warming, ozone depletion, and particulate matter emissions largely due to the production of the vanadium pentoxide electrolyte, similar to the corresponding trends for environmental impacts. Production of the all-iron flow battery contributed the least to disability-adjusted life years from global warming potential and particulate matter. Zinc-bromide flow battery production showed the lowest contributions from ozone depletion potential.

For human health impacts related to toxicity, production of the zinc-bromide flow battery exhibited the highest contribution towards cancer-related toxicity due to the use of bromine in the electrolyte. All-iron flow battery production showed the highest contribution towards noncancer-related toxicity due to the use of glass fiber reinforced polyester resins.

The production of the zinc-bromide flow battery tended to use chemicals with fewer hazard traits compared to those needed to produce the vanadium-redox and all-iron flow batteries.

Material Cost Drivers

Regarding materials, the vanadium-redox flow battery exhibited the highest material cost per unit of capacity among the three flow batteries. This higher cost was due to the high cost of the vanadium pentoxide electrolyte that accounted for 80 percent of the system material cost. However, vanadium pentoxide prices have historically fluctuated considerably over time which can significantly increase or decrease future vanadium-redox flow battery costs.

The zinc-bromide flow battery exhibited the lowest material cost per unit of capacity on a materials basis driven by the costs of the electrolyte and use of titanium in the system bipolar plate. Price changes in bromine and titanium can also affect zinc-bromide flow battery prices.

The all-iron flow battery showed comparable but slightly higher material costs per unit capacity on a materials basis to the zinc-bromide flow battery due to the use of relatively inexpensive materials, except for the battery membranes that use carbon fiber felt and therefore contribute disproportionately to system costs.

Lessons Learned for Future Research and Development

The project produced the following key principles for improving or expanding on the present research to better inform the design of flow battery energy storage systems to reduce environmental impacts and cost and to support policymakers' ability to evaluate the effectiveness of different energy storage technologies in support of California's energy system goals. First, there can be significant uncertainty in the availability of life cycle inventory data for many of the compounds used in devices as complex as batteries. In this study, there was little available data on the production and end-of-life processes and associated life cycle inventory for materials like vanadium pentoxide that forms the vanadium-redox flow battery electrolyte. For this reason, the project team invested a considerable amount of work in harmonizing the existing industrial and academic literature for a useful and consistent life cycle assessment of the production and use phases. A similar principle applied to human health impacts – many chemicals that are used in the production of these batteries may not be well characterized and therefore researchers must make certain assumptions. Moving forward, these types of assessments can be improved through better-quality life cycle inventories associated with complex compounds used in battery energy storage systems. This potential for improvement applies not only to flow batteries but to conventional batteries as well.

While this study did not assess the end-of-life recycling or disposal options for the three different flow batteries, flow batteries have physically separate electrolyte and electrode assemblies. This potentially enables flow batteries to be easily disassembled, which improves the ability for the materials to be sorted for recycling. Since the three flow battery types use very different chemistries, some may be more amenable to environmentally benign and low-impact end-of-life options than others. Investigating the end-of-life options for flow batteries and comparing them to incumbent energy storage options such as lithium-ion batteries is a subject for future work.

Lastly, the primary contribution of this study was to provide an understanding of the life cycle environmental and human health impacts associated with the production of flow battery energy storage systems so they can be consistently evaluated alongside conventional battery technologies that have more available data and literature. Flow battery energy systems are less mature than other technologies such as lead-acid and lithium-ion batteries, so the materials used, associated manufacturing processes, and performance of flow batteries is continually evolving and can change significantly in a short amount of time. For example, this project used data for commercial flow battery systems as of late 2017. During this three-year project, two of the three companies involved have already released new or revised battery energy storage systems based on the same chemistry, but with improved performance. Therefore, while the results of the current project are the most recent with regards to these technologies, a framework for considering the rapidly evolving design of these systems from a life cycle assessment perspective is needed.

Knowledge Transfer Activities

This project was purely analytical and did not involve demonstration or deployment of battery energy storage systems. There were three intended audiences of the project.

The first audience is state agency staff at the CEC and the California Public Utilities Commission (CPUC) who are involved in policy decisions regarding long-duration energy storage deployment to support California's electricity decarbonization goals. Project briefings were given to state agency staff and the project was also presented at energy storage sustainability workshops hosted by the project team and attended by state agency staff.

The second audience are academic researchers focused on better characterizing the environmental impacts of energy storage supply chains. This audience encompasses researchers focused on material resource sustainability and researchers focused on energy systems planning who can use information on flow battery environmental impacts to consider the effect of their deployment on future electricity system environmental footprints. Specifically, researchers were engaged through a series of peer-reviewed conference presentations and seminars through which project results and implications were conveyed, forming the basis for ongoing collaborations.

The third audience is flow battery manufacturers and the materials engineering industry. The results of this project identify key needs from a materials selection and production standpoint for the three different flow battery chemistries to improve the environmental and health impact profiles as well as reduce costs associated with the different flow battery types. Manufacturers of flow batteries such as those involved in this project can use the results in selecting and sourcing the materials selected for the next product iteration to improve the environmental and human health impact profiles and reduce costs. Additionally, industry and researchers working in materials development can use the project results to identify and develop new materials that enable similar or improved operational functionality in flow batteries while minimizing the impacts of their production. Project results were conveyed to flow battery manufacturers through direct briefings to their management and technical staff at multiple points during the project, as well as through peer-reviewed conference presentations attended by materials suppliers and flow battery manufacturers.

Benefits to California

This research benefits California ratepayers by providing the data necessary to improve the selection of energy storage technologies to support California's renewable energy goals such that the deployment of these technologies (1) does not cause unintended noncarbon environmental impacts, (2) does not cause unintended human health impacts, and (3) minimizes the costs associated with the production of flow battery energy storage for use in providing long-duration energy storage functionality. Specifically, the data provides up-to-date information about the environmental and human health impact profiles of flow battery energy storage, such that these technologies can be assessed alongside more mature lithium-ion battery technologies in planning energy storage deployment for minimum environmental impact. Previously, data on these technologies were either outdated or non-existent, limiting their consideration in energy storage planning. This research also provides the groundwork for future projects by supplying the data necessary to understand and improve the environmental, human health, and cost impact profiles of flow battery energy storage technologies through supply chain reorganization and materials selection or development. Currently, the project team has partnered with flow battery manufacturers to improve their manufacturing techniques and material sourcing, with funding actively being sought via submitted proposals for this work.

CHAPTER 1: Introduction

1.1 Project Context and Motivation

Increasing concerns about environmental issues such as climate change, air pollution, and resource depletion have motivated the introduction of alternative energy resources and the deployment of energy storage technologies that support the adoption of renewable resources. California is pioneering solutions through the reinforcement of policies and laws such as the Renewables Portfolio Standard (RPS) and Senate Bill (SB) 100 (De León, Chapter 312, Statutes of 2018) which require 60 percent of retail electricity sales to be sourced from renewable resources by 2025 and 100 percent of electric demand to be met by zero-carbon electricity resources by 2045. These policies are enacted in parallel to a broader goal of reducing economy-wide greenhouse gas (GHG) emissions to 80 percent below 1990 levels by the year 2050.

Meeting California's long-term energy goals will strongly depend on the use of renewable energy such as wind and solar. However, the drawback of using renewable resources is the mismatch of electricity demand and supply due to time variability in their electricity generation profiles. This mismatch occurs over timescales ranging from hourly to seasonally. Energy storage can be an effective way to compensate for this mismatch, enable a high renewable penetration level on the electric grid, and better enable the use of renewable energy resources. Currently, the leading energy storage technologies are a suite of electrochemical batteries such as lithium-ion, nickel-metal-hydride, and lead-acid for hourly or daily energy shifting, and pumped hydropower for long-term energy shifting. Current conventional battery types, however, may have difficulty in providing scalable long-duration energy shifting capability, and pumped hydropower energy storage has constraints on its scalability due to the need for favorable geographical features. In this context, flow batteries may be able to fill — at least partially — the need for long-duration energy storage. Flow batteries offer the advantages of being able to independently scale their power and energy capacity due to physical separation of their energy and power subsystems, as well as allowing large depths of discharge, minimal degradation, and comparatively long lifespans. Therefore, these systems may fill a key role in the portfolio of energy storage technologies selected to meet California's long-term energy goals.

While energy storage systems are used to provide emissions reductions and associated environmental and health benefits from their use in enabling the use of additional renewable energy resources, it is also important to recognize that these systems contribute emissions and potentially other environmental and health impacts from the materials extraction and manufacturing processes. In planning the large-scale deployment of energy storage systems to meet California's long-term energy goals, it is therefore important that (1) the emissions, environmental, and health benefits from their use are not negated by their effects from their materials and manufacturing processes, and (2) the deployment of these systems does not introduce unforeseen environmental or health impacts. Currently, commercial energy storage technologies such as lithium-ion batteries have been thoroughly studied and characterized from the perspective of the environmental impacts associated with their supply chain due to the use of this technology in consumer electronics and more recently, electric vehicles. However, energy storage technologies that have not matured or proliferated to the same extent but may be a part of the future electricity system have not been similarly studied. Therefore, to make informed decisions about how to plan the portfolio of energy storage technologies for meeting California's long-term energy goals while adhering to the points above, life-cycle assessment of an expanded range of energy storage technologies must be conducted.

This project focuses on building a comprehensive sustainability assessment for the production and use of flow batteries by addressing their environmental impact, human health toxicity, and economic feasibility based on a life cycle perspective. The project team used life-cycle assessment (LCA) as a systematic set of procedures for compiling and examining the inputs and outputs of materials and energy and the associated environmental impact attributable to the production and use of a given product in a specified application. The goal of LCA in this study was to assess the environmental and human health impacts of flow battery production and use when installed at a large scale in future renewable electricity grids.

1.2 Project Overview

This section provides an overview of the project goals, objectives, and approach.

1.2.1 Project Goals, Objectives, and Approach

The primary goals of this project were to:

1. To develop a complete characterization and advisory understanding of the life cycle process configuration resource use, and environmental and human health impacts of developing and commercially deploying different types of flow battery energy storage chemistries to scale.
2. To provide an advisory understanding for planning agencies and policymakers for promoting environmentally benign life cycle process configurations for flow battery technologies.

To achieve these goals, the research conducted under this effort is composed of meeting several objectives, each corresponding to a primary task of the project.

- Develop life cycle inventories associated with the production of three flow battery chemistries, vanadium-redox, zinc-bromide, and all-iron: This task focused on gathering and compiling available data from the three flow battery manufacturers and the industrial and academic literature to develop resource use and waste/emission product inventories for materials extraction, manufacturing, and use processes for each of the flow battery types. Once data were gathered and compiled, additional efforts were needed to ensure that consistent system boundaries and battery composition frameworks were developed such that each flow battery could be assessed on a common basis. This involved reconciling differences in the level of detail provided by each manufacturer as well as differences in data availability for different materials in the three different flow battery types in the academic and industrial literature.
- Translate the life cycle process configuration resource use and waste product emissions to different categories of environmental impacts taking into account their effects on and

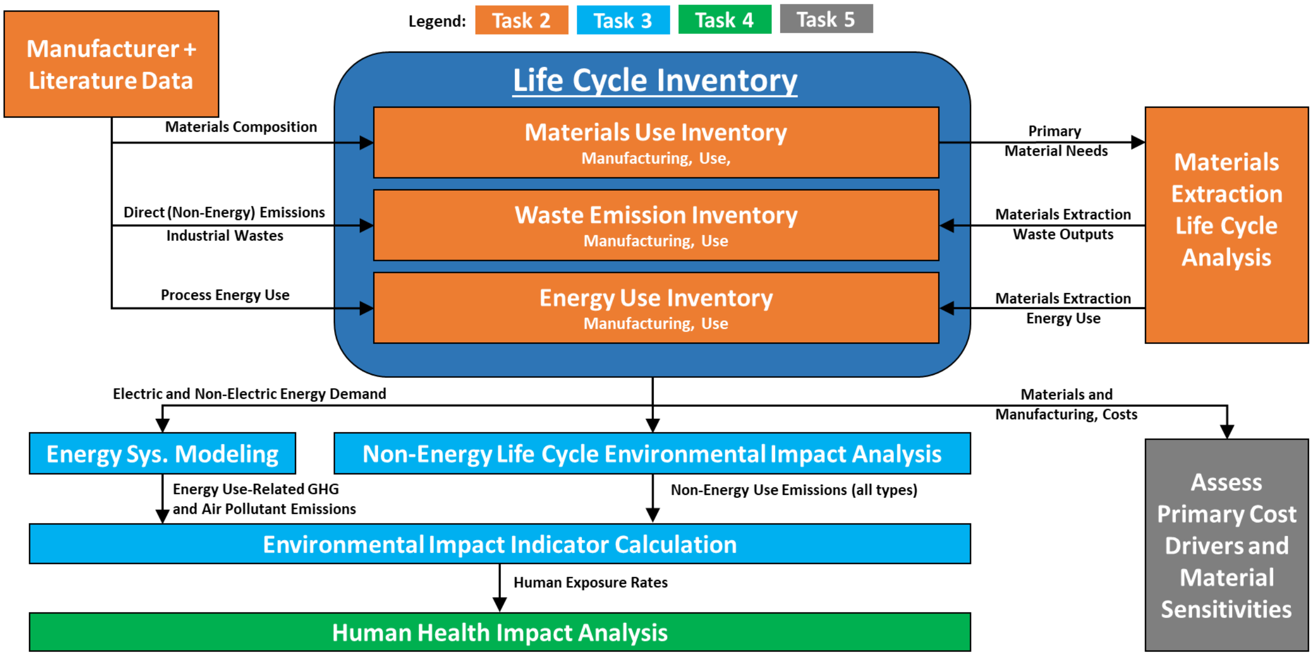
benefits for the energy system: The harmonized life-cycle inventories for each flow battery were used as inputs to the life cycle impact assessment modeling efforts. In this objective, the research team developed life cycle supply chain models for the production of each flow battery type taking into account material composition and manufacturing in the SimaPro life cycle assessment tool. Each flow battery type was evaluated on the contribution of its supply chain to eight environmental impact indicators: global warming potential (GWP), particulate matter (PM), ozone depletion potential (ODP), acidification potential, freshwater eutrophication, ecotoxicity, abiotic depletion potential (ADP), and fossil-fuel cumulative energy demand (CED) using the ReCiPe 2016 framework. In addition to the contributions to environmental impacts from materials extraction and manufacturing, the environmental impact reductions associated with the use of these batteries on a highly renewable future electric grid was assessed using the Holistic Grid Resource Integration and Deployment (HiGRID) model. Therefore, in-use benefits could be compared against the impacts of battery production.

- Translate the contributions of different flow battery types to human health impacts based on air quality, environmental impact, non-cancer toxicity, and cancer-based toxicity: The results for the emissions of different compounds and the use of chemical compounds from the supply chain needed to produce each flow battery type were used as inputs for assessing the contribution of these supply chains to human health impacts. Human health impacts were assessed from multiple perspectives. The first involved characterization of the disability-adjusted life years (DALYs) associated with air pollutant effects, cancer-related toxicity, and non-cancer-related toxicity. The second involved the perspective of chemical hazards using the GreenScreen® for Safer Chemicals hazard assessment framework. The third involved the assessment of occupational exposure limits, assessed using data from the National Institute for Occupational Safety and Health (NIOSH), Occupational Safety and Health Administration (OSHA), and American Conference of Governmental Industrial Hygienists (ACGIH) for exposure limits for different chemicals.
- Assess primary material-based cost drivers for flow battery energy storage systems and sensitivities to materials selection and price fluctuations: The life-cycle inventory provided information on the materials composition for each flow battery type. This information was used to determine the materials that contributed the most towards the overall cost of each flow battery system, the drivers behind any disproportionate contribution, comparison of drivers of cost versus environmental impact, and the sensitivity of flow battery cost to historical price fluctuations for key materials.

Figure 1 presents an overview of the project approach.

This project focused on four primary technical tasks. Task 2 developed material use, energy use, and waste emission inventories for the life-cycle supply chain of each of the three flow battery chemistries (vanadium-redox, zinc-bromide, and all-iron). Task 3 determined the life-cycle environmental impact profiles of the three different flow battery chemistries. Task 4 translated air pollutant, greenhouse gas, and other waste product emissions, as well as process chemicals, into impacts on human health. Task 5 performed a material-based cost assessment to identify primary cost drivers and incentivize the selection of cost-effective, environmentally benign life-cycle supply chain designs for each of the flow battery types.

Figure 1: Schematic Overview of the Project Approach



Source: UC Irvine

CHAPTER 2: Project Approach

2.1 Overview

This chapter covers the approach used to conduct the life-cycle assessment of the vanadium-redox, zinc-bromide, and all-iron flow battery systems from the perspective of environmental impacts, human health impacts, and costs associated with these systems. This chapter only describes the methodology for each task; Chapter 3 describes the results from the application of these methods.

2.2 Life-Cycle Inventory Development

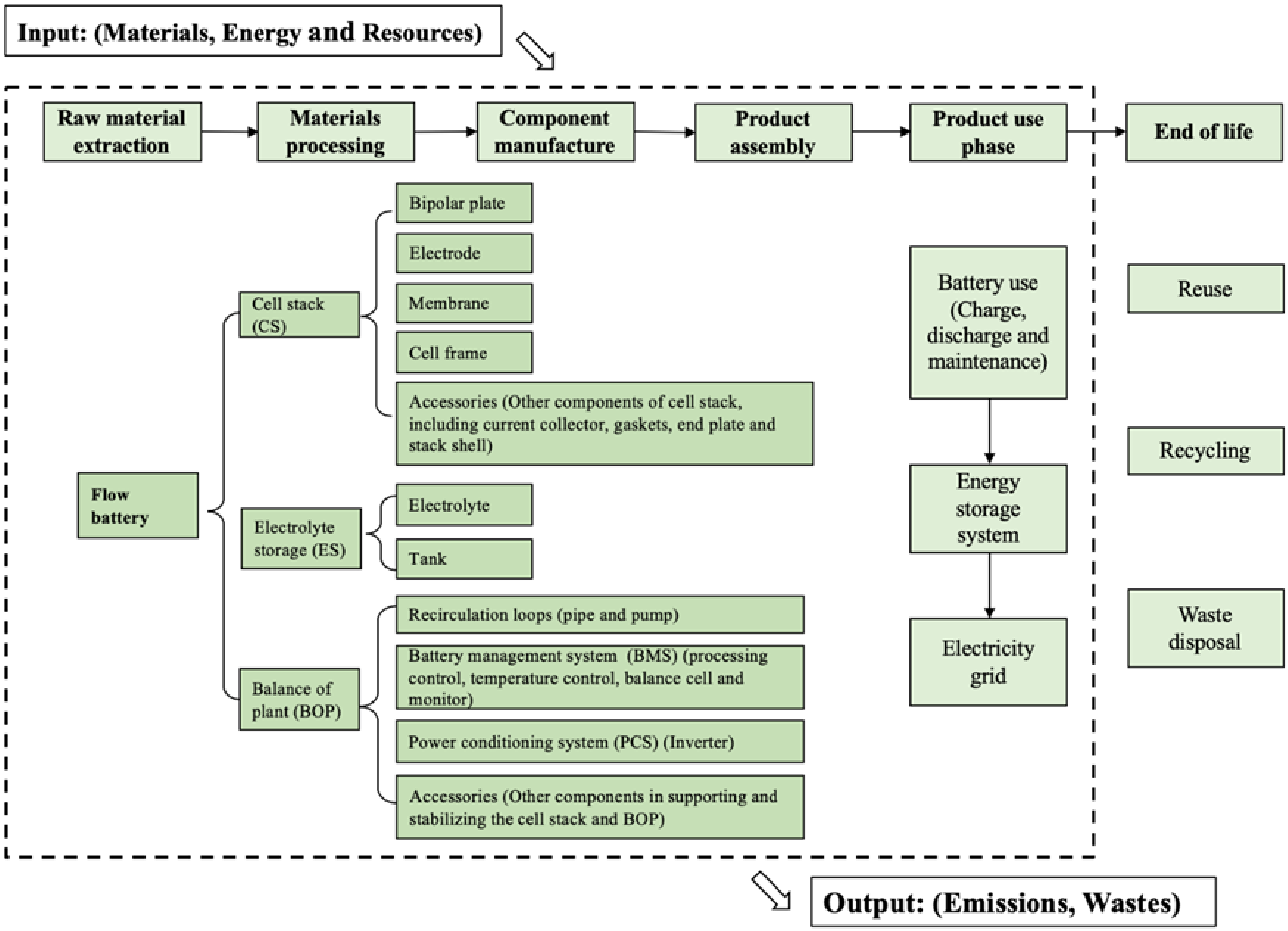
The first step in conducting a life-cycle assessment is to develop the inventory of materials and processes involved in the materials extraction, manufacturing, use, and end-of-life stages of the product in focus. This section describes the approach used to collect data and develop the life-cycle inventory necessary to conduct this analysis.

The project team does not address the end-of-life stages of the different flow battery types due to lack of data on the end-of-life pathways for some of the key materials used in these systems. Since many of these systems are in the early commercial phase, end-of-life management strategies are planned but not well established in practice because these systems have not been in service long enough to be decommissioned on a large scale.

2.2.1 Life Cycle Inventory Overview

A life-cycle inventory (LCI) is a database that is used to estimate the consumption of material, energy, and resources and the quantities of waste flows and emissions caused by or attributable to a product's life cycle [1]. Developing an LCI involves the collection of data that depends on related LCI data sources and the modeling of the product system within a designated system boundary. The two major data sources in this project are (1) data collected from anonymous flow battery manufacturers, and (2) the ecoinvent database, is a widely used and validated life-cycle database for materials and material processing. For materials and processes not available from these two sources, data were obtained from the academic literature. In this study, data are collected from each life-cycle stage of flow batteries including raw material, processing and assembly, use phase, and end-of-life, shown in Figure 2. The LCI modeling established in this study is process-based. For the processing and assembly stages, each of the flow batteries is divided into three components as cell stacks, electrolyte storage, and balance of plant [2]. For further analysis, the cut-off is performed for inventory flows with negligible environmental impacts to highlight the processes with high concern.

Figure 2: Life-Cycle Inventory Boundary for Life-Cycle Assessment of Flow Batteries in Project



Source: UC Irvine

2.2.2 Approach to Data Collection and Organization

The construction of the LCI requires comprehensive data on material, energy, and resource use towards the product life cycle. The major goal is to collect data on raw materials, material processing, and product assembly for flow batteries; the use phase is described in Chapter 3. After abundant literature reviews toward the flow battery fundamentals, tables and data sheets were designed to collect manufacture data from manufacturers. Related LCI data were obtained based on ecoinvent and literature review.

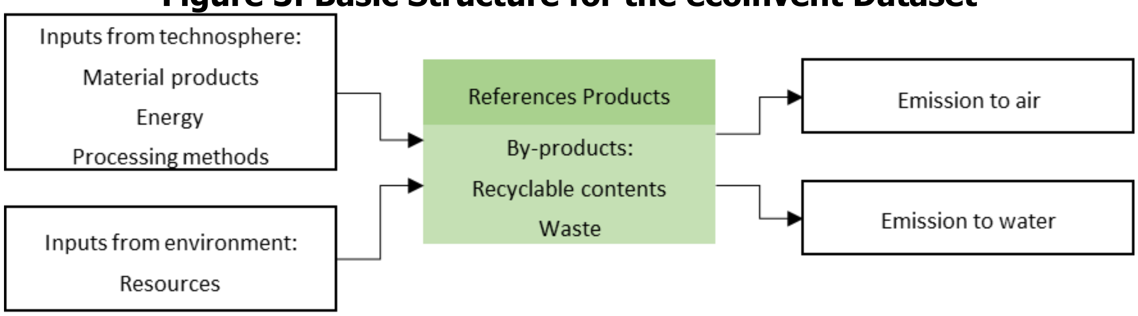
A full review of current research progress on flow batteries was critical for designing the data collection form. To better understand flow battery technologies, several publications were reviewed to identify the principles, mechanisms, and structures of different flow batteries. Recent research developments on flow batteries design and manufacturing and past efforts on sustainability issues for flow batteries were also reviewed to provide insights on what should be highlighted in the data collection process. To capture the design characteristics, the patents drafted by the three manufacturers were researched to acquire the potential material use and structure of the three flow batteries. The data collection form that was sent to the manufacturers is available in Appendix A.

The data collected in this study from flow battery manufacturers include the material use, processing methods, and balance of plant equipment. These data are not included in this report in order to uphold the confidentiality agreement with flow battery manufacturers. To help manufacturers understand the essentials of LCI, the table and datasheet addressed related concepts on LCI and each life-cycle stage was introduced before filling in the data. Considering the characteristics of the flow battery structure, the full flow battery package was divided into three components — cell stacks, electrolyte storage, and balance of plant — and the data collected were organized into these components.

With the data obtained on the raw materials composition and materials processing associated with each flow battery product, the next step was to determine the secondary material inputs and outputs, emissions, and resources used to procure those materials and carry out the specified processing steps. For example, a manufacturer may specify that its product contains a given amount of steel. To complete the LCI, this stage must now determine the materials, energy, and resource inputs and outputs associated with steelmaking. To make this determination, life-cycle data for each of the materials specified by the manufacturers was located and obtained from the ecoinvent database, version 3.4.[1]

In ecoinvent, the dataset for each material type not only provides information on major products produced in a certain activity (called "reference products"), but also the related by-products such as waste and recyclable contents with their weights normalized by the production of one unit of reference products. The related input on material, energy, and resource use and output on emissions to air or water listed are also associated with one unit of reference product production. Figure 3 provides the basic structure for the ecoinvent dataset

Figure 3: Basic Structure for the ecoinvent Dataset



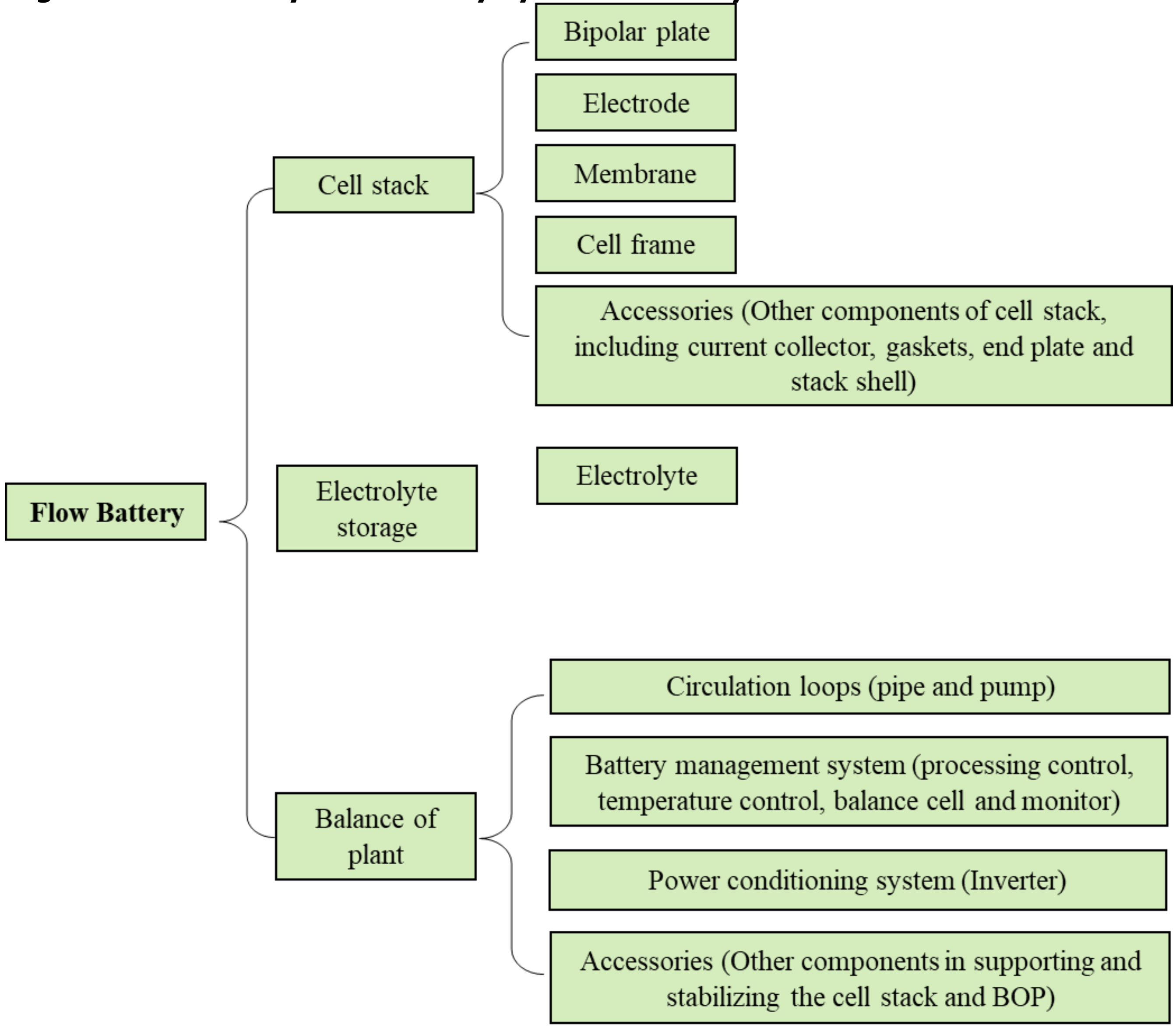
Source: UC Irvine

There are three system model databases in ecoinvent: (1) cut-off system model, (2) allocation at the point of substitution (APOS) system model, and (3) consequential system model. Additional detail on the three are available in the online documentation of ecoinvent [4]. The project team chose the cut-off model because it does not have built-in assumptions for the impacts of byproducts from expanded activities, allowing the data to focus more on the targeted products themselves. For the cut-off model, the system boundary of each activity is set to closely encompass the major processes to manufacture the reference products and

[1] ecoinvent (correct case) was originally developed by the Paul Scherrer Institute in Switzerland to serve as a centralized compilation of life cycle data on various materials and processes used in multiple types of products. It covers world-wide LCI data which are up-to-date, transparent, and understandable with assured data quality [3].

allocable by-products. The consequential system model is designed for consequential LCA, which is not suitable for this work. Figure 4 presents the LCI breakdown for flow battery production used in this study.

Figure 4: The Life-Cycle Inventory System Boundary for Flow Batteries Production



Source: UC Irvine

If data on a required material type was not found in ecoinvent, the LCI data were extracted from most relevant and time-efficient life cycle assessment studies in the academic and industrial literature and integrated as appropriate into the study. In case the system boundary of the LCI data described in the literature does not exactly match with the desired activities, some cut-offs were performed to exclude nonrelated activities and make sure the final data were comparable with the datasets in ecoinvent. In this case, the LCI data on vanadium pentoxide and carbon fiber were extracted from the literature.

2.3. Conducting the Life Cycle Impact Assessment

2.3.1 Introduction to Life Cycle Impact Assessment

Life-cycle impact assessment (LCIA) refers to the evaluation, characterization, and calculation of the potential impacts associated with the constructed life-cycle inventories within the range of the selected system boundary, which may include the raw materials extraction, transportation, production manufacturing, and assembly, use-phase, and end of life. According to ISO 14042 [5], there are three mandatory elements required to perform an LCIA:

1. Selection of impact categories, categories indicators, and characterization models.
2. Assignment of the inventory data to the chosen impact categories.
3. Calculation of impact category indicators using a characterization factor.

Other important elements specified but not designated as mandatory include normalization, grouping, and weighting [6]. For this study, the research team quantified impacts using the following environmental midpoint indicators: global warming potential (GWP), particulate matter (PM), ozone depletion potential (ODP), acidification potential (AP), eutrophication (EP), ecotoxicity (E), abiotic depletion potential (ADP), and cumulative energy demand (CED). To fully investigate the cause-effect chain of the life-cycle inventory to certain impact categories usually requires extensive research on the impact pathways, affected area of protection, and spatial and temporal variability. Those complex models are not the major consideration of LCIA as the result is usually represented as an aggregated score based on the characterization factor (CF), which is an integrated model output. The calculation of CF usually will relate or translate the elementary flow into its impact on the chosen indicator for the impact category [5]. A generic framework can be expressed as [7]:

$$CF = FF \cdot XF \cdot EF \quad (1)$$

where the characterization factor (CF) is the product of a fate factor (FF), an exposure factor (XF), and an effect factor (EF). The application of the characterization factor to the impact score (IS) is straightforward [7]:

$$IS = Q \cdot CF \quad (2)$$

where Q is the quantity of the elementary flow and the total impact score is the aggregation of the impact score of each elementary flow.

The life cycle assessment determined the environmental impacts for the production of three different types of flow batteries on the basis of per kWh battery energy capacity and the impacts in the use-phase when these systems perform the common function of shifting excess renewable generation on the electric grid over a lifetime of 20 years. Based on the evaluation, the project team selected the GWP, PM, ODP, AP, EP, E, ADP, and CED for evaluation. The following section illustrates the models and methods used for each impact category. The LCIA results on the manufacturing of the three flow batteries are presented on a per-kWh of energy capacity basis. The assessment of each indicator is briefly described below.

Global Warming Potential

Global warming impacts are characterized by GWP, which is very consistent in each LCIA method and the characterization factors were all adopted from the Intergovernmental Panel on Climate Change (IPCC). The annual report from the IPCC provides up-to-date information on the CFs for the greenhouse gases and the results were converted to the units of carbon dioxide equivalency (CO_2eq). In this case, the project team applied the ReCiPe 2016 midpoints [8] with a GWP time horizon of 100 years, using a hierarchist perspective (H) as the valuation method that is often encountered in LCA studies and considered as a default approach.

Ozone Depletion Potential

ODP is defined as a relative measure of the ozone depletion capacity of substances such as chlorofluorocarbons (CFC) and other halocarbons, and the reference substance used in ODP is trichlorofluoromethane (CFC-11) [6,8]. In this study, the ODP results were calculated using the ReCiPe 2016 midpoints.

Particulate Matter

PM impacts were defined as PM 2.5 equivalent using the ReCiPe 2016 midpoint. PM 2.5 refers to particles with a diameter of less than 2.5 micrometers (μm) and usually consists of a complex mixture of organic and inorganic substances. The secondary PM 2.5 aerosols formed due to the emissions of sulfur dioxide (SO_2), ammonia (NH_3), and nitrogen oxides (NO_x) also contribute to human health problems [9].

Acidification Potential

This study assesses only terrestrial acidification (as opposed to ocean acidification). Terrestrial acidification is largely caused by inputs of nitrogen and sulfur and has been investigated by several LCIA methods with different modeling tools. In this study, AP is assessed using the ReCiPe 2016 midpoints expressed in SO_2-equivalents.

Eutrophication

Eutrophication is defined as nutrient enrichment of the aquatic environment. Eutrophication is characterized by phosphor emissions to freshwater equivalents, as per the ReCiPe 2016 midpoints. In the ReCiPe 2016 midpoint indicators, this metric only considers the freshwater eutrophication due to the discharge of nutrients into the soil or into freshwater bodies [8].

Ecotoxicity

Ecotoxicity is a measure of the potential for hazardous degradation of ecological systems. In this analysis, the ecotoxicity model the project team considered is the USEtox 2.0 midpoint [10], where the indicator for the freshwater ecotoxicity is expressed as the potentially affected fraction of species due to the change in substance concentration in freshwater, integrated over time and volume per substance mass emitted to freshwater ($PAF \cdot m^3 \cdot day$).

Cumulative Energy Demand

CED is used to investigate the energy use throughout the life cycle on a good or service. In this case, the CED results were calculated using the ecoinvent embedded method which considers both direct (from materials treatment) and indirect energy use (from materials extraction). CED can also be separated into total CED, which assesses the total amount of energy used, and nonrenewable CED, which characterizes only the energy use from nonrenewable primary energy sources.

Abiotic Resource Depletion

The definition of abiotic resources is natural resources that are regarded as non-living. ADP is one widely addressed impact category in LCIA with various methodologies developed. Therefore, the results for this metric based on different methods and boundary conditions can be very different. Currently, there are remaining controversies toward depletion-related impact categories, but the most widely adopted method was created by Guinée [11] under the CML LCIA methodology [8] and the reference unit used is a unit-mass of antimony, which is used in this study.

2.3.2 Structural Path Analysis

To capture the major environmental impacts of the materials use and processing methods behind each component, the project team also performed a structural path analysis [8] in which all the unit processes reflecting the first-tier level of the production activities that exhibit higher contributions to the total impacts were summarized and analyzed. For each flow battery type, the use of critical materials and major processing techniques can be the dominant contributor towards the environmental impacts associated with the whole life cycle stage of the flow batteries. First, the results can highlight the material intensities inside the production chains of the flow battery technologies which will help to improve the materials selection processes into using more environmentally benign and less scarce materials. Second, the analysis of high impact processing techniques is intended to bridge the gap between research work and real industrial applications to promote cleaner and less energy-intensive manufacturing processes. The results of the structural path analysis (SPA) are summarized in Appendix D. The project team set the cut-off value as a 1 percent contribution to the total impact score to avoid mapping an excessive amount of unit processes. The team also included the percentage contribution of the top three components for each unit process if their relative contribution was higher than 5 percent.

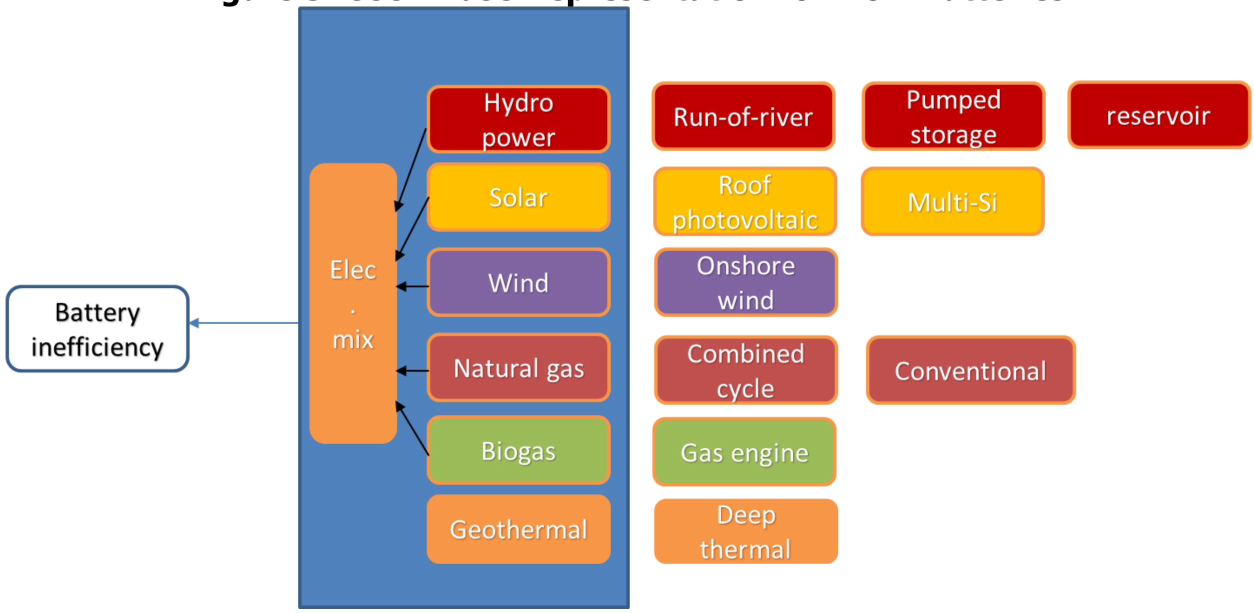
2.3.3 Use-Phase Analysis

In this analysis, the flow batteries were dispatched to store otherwise curtailed renewable electricity generation when the electricity supply exceeds the electric demand and releases the energy to meet the demand when it exceeds renewable generation in later hours. The environmental impact of the battery application is coming from the electricity that is wasted due to the inefficiency of the battery system. The deployment of flow batteries is simulated using the Holistic Grid Resource Integration and Deployment (HiGRID) model. HiGRID determines the hourly dispatch of electricity generation and complementary technologies on the electric grid subject to the constraints of balancing supply with demand, providing sufficient reliability services, and transmission and distribution losses. As outputs from these processes, HiGRID produces metrics for the environmental impact such as annual greenhouse gas emissions, criteria pollutant emissions, fuel usage, and the annual delivered energy by resource type. For this study, the different electric grid configurations were simulated with different sizes of flow battery energy and power capacity.

Two scenarios were considered based on the PATHWAYS study conducted by Energy Environmental Economics (E3). The PATHWAYS study determined different technology portfolios for reaching an 80 percent reduction in economy-wide GHG reductions from 1990 levels in California by 2050. This study considered 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 these loads and the 2050 GHG reduction goal were determined based on resource availability and cost. Parameters used from this study include the installed capacities of electricity generation technologies, the penetration level of complementary technologies such as electric vehicles and demand response, and the profiles of electric loads from industrial, commercial, residential, and transportation sectors. Two scenarios from the PATHWAYS study were simulated here: a 2030 scenario corresponding to a 50 percent renewable penetration, and a 2050 scenario corresponding to a 90 percent renewable penetration.

The environmental impact of the batteries during the use-phase was based on the inefficiency of the battery during its charging and discharging processes. As a result, environmental impacts can be traced back to the corresponding electricity generation resources that drive these processes. Therefore, the mix of electricity delivered in an electric grid whose operation considers the effect of batteries on electricity resource operation is very important to capture. The life cycle impacts associated with electricity generation sources were also accounted for since the deployment of flow batteries in renewable shifting applications alters the mix of delivered electricity to meet demand, and subsequently the environmental impacts associated with the use of different electricity sources. The sources of electricity generation included natural gas, biogas, geothermal, wind, solar photovoltaic (PV), and hydropower. Biogas is used to offset the natural gas that is consumed by the gas turbine of combined-cycle power plants and is the only bioenergy technology considered in this analysis. The biogas used in this case was a mix of different resources such as biowaste and sewage sludge [2], as specified in the ecoinvent database. Wind, solar, geothermal, and small hydropower combined with biogas were counted as renewable resources. The electricity generated from wind was decomposed into wind turbines of different sizes. The percentage of turbines smaller than 1 megawatt (MW), from 1-3 MW and larger than 3 MW was determined by the dataset in ecoinvent. Solar power was divided into open-ground and rooftop slanted installation PV panels. The rooftop solar panel was assumed to only be fixed since no axis rooftop data are provided by the ecoinvent database. Hydropower was composed of run-of-river and large reservoir facilities. Figure 5 illustrates how the use-phase system was formed. The efficiency of flow batteries was assumed to be 70 percent in this case.

Figure 5: Use-Phase Representation for Flow Batteries



Source: UC Irvine

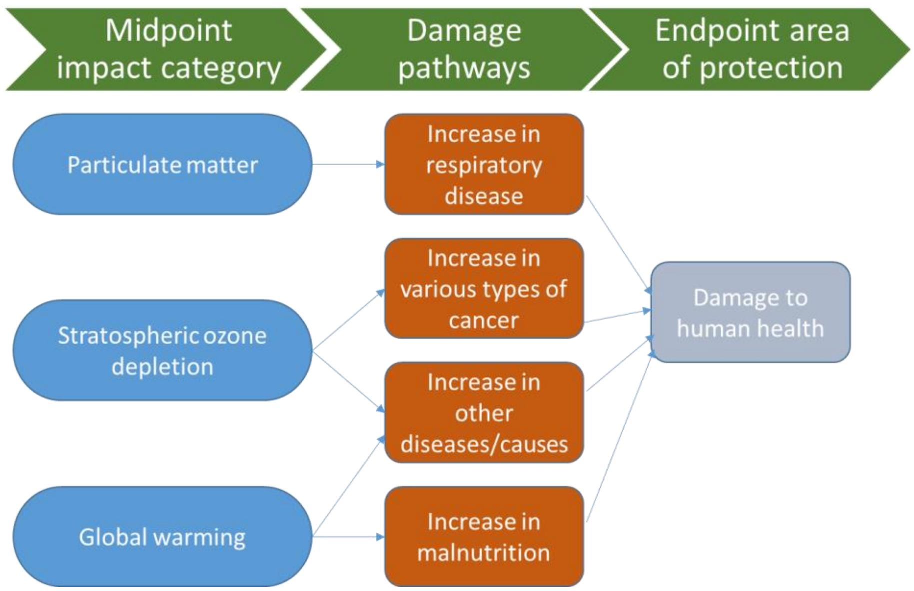
The main characteristic of flow batteries is that their power and energy capacity can be decoupled. This characteristic makes it possible to use different ratios of power versus energy capacity to serve the energy demand. It also provides an opportunity to create a map to show the environmental impact of different scales of battery deployment and the benefit to the grid by installing batteries. The environmental impact of battery energy storage was calculated by using Simapro, taking into account the use-phase and manufacturing impacts. However, the transportation of raw materials to the manufacturing plant was not taken into account. The end-of-life phase is not included in this report. The GHG emission reduction achieved by using batteries was studied by the grid analysis tool HiGRID using the energy resource mix predicted by E3 PATHWAYS study for 2050 in California. The annual GWP emission of the electric grid with batteries of different scales of energy and power capacity was obtained by comparing the original emissions in the case with zero battery usage in the grid with the emissions of the case grid with battery installed to different capacities. To obtain a broad view of the GWP benefit as a function of different energy and power capacity values, an inventory of flow batteries with various energy capacity to power capacity ratios was constructed. The whole battery inventory was divided into components that scale with energy capacity and those that scale with power capacity. The energy segment included the tanks and electrolyte. The cell stack, including membrane, electrode, and bipolar plate composed the parts that scale with power capacity. The balance of plant component sizes mainly scaled with energy capacity. The balance of plant can satisfy a range of 1-5 times that of the original energy to power ratio. For the use-phase analysis, the vanadium flow battery was used as representative.

2.4 Conducting the Human Health Impact and Chemical Hazard Assessment

2.4.1 Overview of Human Health Impact and Chemical Hazard Assessment

LCIA and chemical hazard assessment (CHA) tools were used to investigate the human health impacts from two different perspectives. The LCIA aims to estimate the potential impacts associated with the product life cycle inventories. By using characterization factors, LCIA converts emissions to environmental impacts scores. Characterization factors indicate the environmental impact per unit of the product or system researched. There are two ways of calculating characterization factors: midpoint and endpoint. Midpoint characterization factors are usually located somewhere along the impact pathway, usually at the point after which the process reaches a certain stage for all the chemicals or flows in the impact category. Endpoint indicators provide more information on the impact on valued outcomes such as human health, tangible ecosystem qualities, and resource scarcity. In this report, we focus on human health outcomes [8]. LCIA was used to assess the DALY outcomes during the manufacturing production and functional use of flow batteries by considering the environmental impacts caused by the GWP, ODP, and PM2.5 and the human health impacts (human toxicity potential - HTP) according to cancer and noncancer health effects. The pathways of translating midpoints to endpoint indicators are illustrated in Figure 6.

Figure 6: Translation of Midpoints to Human Health Impacts

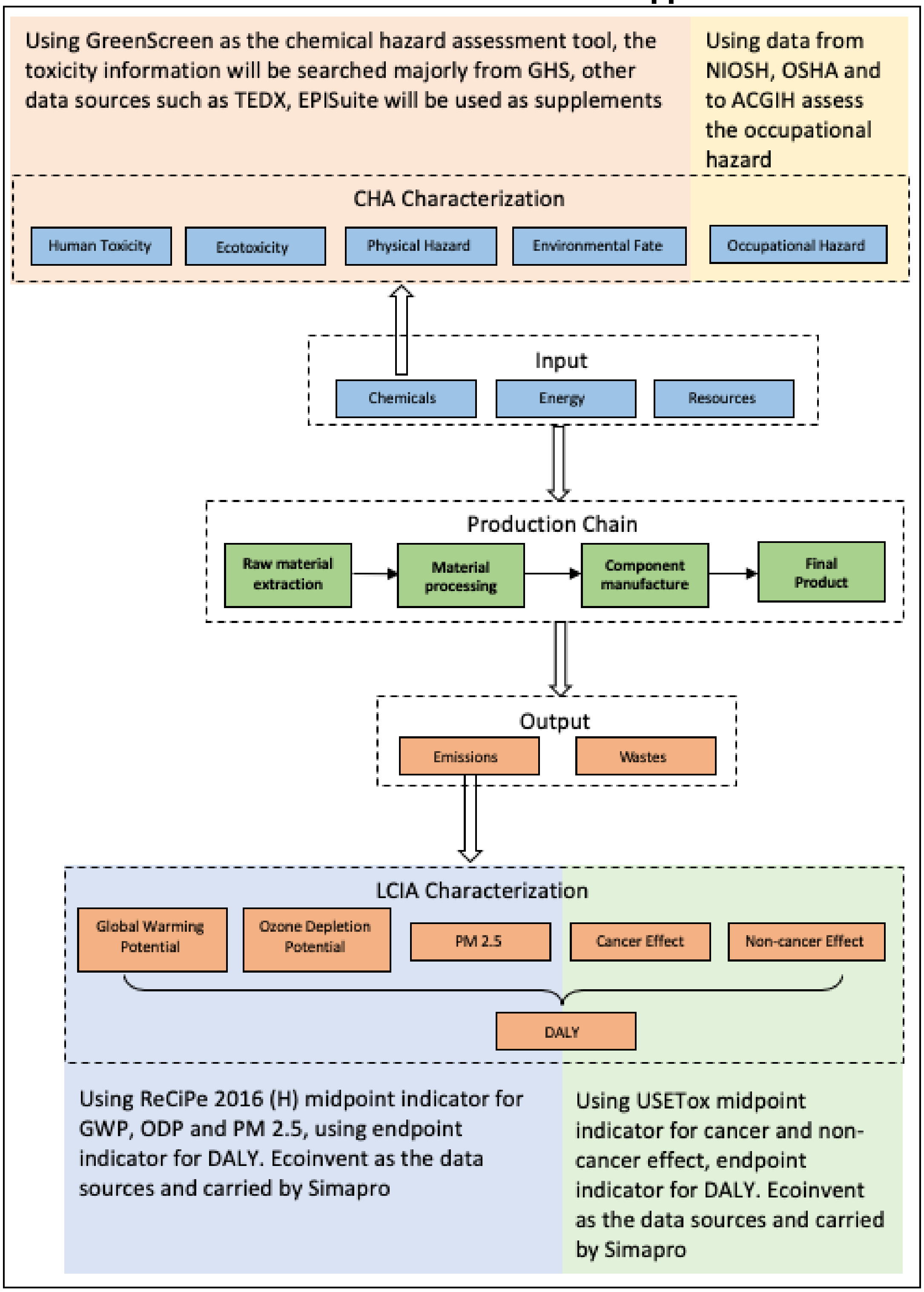


Source: UC Irvine

The CHA, designed to investigate the inherent hazard potentials of chemicals used in commercial products, was used to assess the human toxicity, ecotoxicity and environmental fate, physical hazard, and occupational health characteristics of the chemicals used in the flow battery systems. A schematic illustration of the process flow for the human health impact assessment is provided in Figure 7.

Based on the LCI developed in Chapters 2 and 3, emissions from the production chain as classified and characterized by midpoint indicators were interpreted to human health endpoints as DALYs. The conversion factors of GWP, ODP, and PM2.5 were adopted from the ReCiPe 2016 endpoints assessment embedded in Simapro [8]. The conversion factors on cancer and noncancer effects were calculated by using the USETox modeling approach [10] embedded in Simapro. The CHA framework used in this study was GreenScreen® for Safer Chemicals (GreenScreen®) [12] and the occupational health characteristics were evaluated based on the recommended exposure limit (REL) established by the NIOSH, the permissible exposure limit (PEL) established by OSHA [13], and the threshold limit value (TLV) from ACGIH [14].

Figure 7: Overview of Human Health Impact and Chemical Hazard Assessment Approach



Source: UC Irvine

2.4.2 Human Health Impact Endpoint Assessment

The endpoint characterization factors (CFe) in the LCIA were derived directly from the midpoints characterization factors (CFm):

$$CF_e = CF_m \times F_{M \to E}$$

whereby $F_{M \to E}$ is the midpoint to endpoint conversion factor.

The conversion factors used to translate the midpoint indicators for the five impact categories — GWP, ODP, PM 2.5, HTP cancer and noncancer — to DALY are summarized in Table 1.

Table 1: Midpoint to Endpoint Characterization Factors

Impact category	Unit	Conversion factor	Methodology
GWP	DALY/ kg CO_2 to air	9.28E-7	ReCiPe 2016
ODP	DALY/ kg CFC11 to air	5.31E-4	ReCiPe 2016
PM 2.5	DALY/ kg PM 2.5 to air	6.29E-4	ReCiPe 2016
HTP cancer	DALY/ cases	11.5	USETox 2.0
HTP non-cancer	DALY/ cases	2.7	USETox 2.0

Source: UC Irvine

2.4.3 Chemical Hazard Assessment

2.4.3.1 GreenScreen® For Safer Chemicals

One of the most widely used CHA frameworks is GreenScreen®, which was created by Clean Production Action, to serve as a decision framework developed to screen chemicals based on their hazard endpoints using transparent and systematic benchmarking criteria [12]. GreenScreen® has become widely accepted and used in industry, nongovernmental organizations, and government agencies. GreenScreen® includes information on 20 hazard endpoints (listed in Table 2) including those related to human health, environmental toxicity and fate, and physical hazards. The selection and evaluation of these 20 hazard endpoints were aligned with several national and international protocols such as the Globally Harmonized System of Classification and Labeling of Chemicals (GHS), the European Union’s Registration, Evaluation, Authorization, and Restriction of Chemicals (REACH), and the U.S. Environmental Protection Agency’s Design for Environment Program [15–17].

2.4.3.2 Identification of Chemicals of Concern

The identified materials used in the flow batteries for CHA in this chapter are categorized as primary materials and processing chemicals. The information on primary materials was provided by the manufacturers while information for the processing materials was collected using a combination of ecoinvent and literature data. In Chapter 2, the project team obtained from flow battery manufacturers detailed information on the primary materials used in the different battery systems. The team had proprietary data on all the primary materials used in the three batteries, including their weight ratio compared to the total system weight. To protect the confidentiality agreement with flow battery manufacturers, that information is not included in this report. Many of the materials in the flow batteries are polymers or complex materials that cannot be assessed directly using CHA methods since CHA is designed to evaluate only pure substances. Thus, to assess these complex materials that require multiple chemicals used during their manufacturing, as well as to incorporate life cycle thinking, some of the primary materials were expanded into compositional materials and process materials, which were then assessed.

Table 2: Hazard Endpoint Information Included in GreenScreen®

Hazard Groups	Hazard Endpoints
Human Health Group I	Carcinogenicity (C), Mutagenicity & Genotoxicity (M), Reproductive Toxicity (R), Developmental Toxicity (D), Endocrine Activity (E)
Human Health Group II	Acute Mammalian Toxicity (AT), Systematic Toxicity & Organ Effects (ST-single), Neurotoxicity (N-single), Skin Irritation (IrS), Eye Irritation (IrE)
Human Health Group II*	Systematic Toxicity & Organ Effects* Repeated Exposure sub-endpoint (ST-repeated), Neurotoxicity * Repeated Exposure sub-endpoint (N-repeated), Skin Sensitization (SnS), Respiratory Sensitization (SnR)
Environmental Toxicity & Fate	Acute Aquatic Toxicity (AA), Chronic Aquatic Toxicity (CA), Persistence (P), Bioaccumulation (B)
Physical Hazards	Reactivity (Rx), Flammability (F)

Source: UC Irvine

To conduct a GreenScreen® assessment, the general processes are:

1) Identify chemicals of concern
2) Search for toxicity data
3) Classify hazard level
4) Assign GreenScreen® Benchmark™ (BM) score

2.4.3.3 Toxicity Data Sources

Various data sources were considered in completing a GreenScreen® assessment. For this study, the project team used the following sources: the GHS-Japan [18], GESTIS [19], European Chemicals Agency Registered Substances (ECHA CHEM) [20], Hazardous Substances Data Bank (HSDB) [21], EPI SUITE™ [22], EU SVHC List [23] and The Endocrine Disruption Exchange (TEDX) [24]. The use of various data sources is required by the GreenScreen® framework because it is impossible to acquire the toxicity information for all the 20 hazard endpoints from a single data source [12]. In the GreenScreen® guidance, the recommended sequence in using data sources are:

1. Using experimentally valid data from authoritative sources such as data sources published by governmental organizations — the GHS-Japan, GESTIS, ECHA CHEM, and EU SVHC data sources fall into this category.

2. Using experimentally valid data from screening sources such as data sources published by research institutes and non-governmental organizations, which is the case for TEDX.
3. Using predictive or modeling data to fill the data gaps if not enough information can be acquired from the previous two approaches — EPI SUITE™ is the predictive modeling software applied in this case.

GHS, an internationally agreed-upon system created by the United Nations, was designed to replace the various hazard classification systems in different countries by using a consistent set of criteria. GHS-Japan, a GHS-based database containing information on approximately 3000 chemicals, was used in this study. The GESTIS substances database, also GHS-based data sources used in this study, is maintained by the Institute for Occupational Safety and Health of the German Social Accident Insurance (IFA) and provides GHS classifications that may not have been found in GHS-Japan. The GHS-Japan and GESITS are both GHS-based data sources, which include information on multiple hazard endpoints such as carcinogenicity, mutagenicity, reproductive toxicity, developmental toxicity, acute mammalian toxicity, systematic toxicity and organ effects, neurotoxicity, skin irritation, eye irritation, skin sensitization, respiratory sensitization, acute aquatic toxicity, chronic aquatic toxicity, reactivity, and flammability. These sources did not include information on endocrine toxicity, persistence, and bioaccumulation, which are also important endpoints.

With regard to environmental fate, the persistence in GreenScreen® is defined as "the length of time the chemical can exist in the environment (air, water, soil or sediment) before being destroyed" for which the standard test is based on the substance's half-life. Bioaccumulation in GreenScreen® is defined as "a process in which a chemical substance is absorbed in an organism by all routes of exposure as occurs in the natural environment" which the bioaccumulation factor (BAF) or the logarithmic value of the n-octanol/water partition coefficient (log K_{ow}) are usually used as indicators for evaluation. Acquiring the data for persistence and bioaccumulation assessment is difficult as the experiments require much time and the results vary depending on the research objective and the experimental conditions. To ensure there is sufficient data for persistence and bioaccumulation, three data sources are investigated: ECHA CHEM, HSDB, and EPI SUITE™..

ECHA CHEM, which is managed by the European Chemicals Agency corresponding to the REACH law, has dossiers on over 20,000 chemicals used in Europe based on the data registered by the manufacturer or summarized by the governmental organizations. Compared to GHS-Japan and GESITS, the data documented in ECHA CHEM not only include GHS-based toxicity information, but also extensive information on the environmental fate.

HSDB is a toxicology data file maintained by the National Library of Medicine in which the related information on persistence and bioaccumulation can be found in the environmental fate and exposure section. EPI SUITE™ is an estimation program developed by the USEPA and Syracuse Research Corporation. Instead of direct reference to experimental toxicological test results, EPI SUITE™ uses structure-activity relationships to estimate the toxicity of the chemical of interest. The estimation process starts from a molecular structure represented using Simplified Molecular-Input Line-Entry System (SMILES) notation and uses various modeling approaches such as group contribution or linear free energy relationships to predict hazard endpoints. It can provide information on environmental fate such as log K_{ow}, BAF, biodegradability, and atmospheric half-lives.

The last hazard endpoint that cannot be assessed via previously mentioned data sources is the endocrine toxicity, which is generally defined as a chemical with the inherent ability to interact or interfere with one or more components of the endocrine system resulting in a physiological effect. Two additional data sources, EU SVHC list and TEDX, were consulted for assessing endocrine toxicity. The EU SVHC list is an authoritative data list that collects existing endocrine disruptors in the ECHA. Another source, TEDX, known as the endocrine disruption exchange, assesses and compiles evidence for substances that interfere with development and reproductive function, and provides a limited, but complementary, data set for substances that are suspected or known to be endocrine disruptors. Hence, if a chemical has a record in the EU SVHC List, it is classified as possessing a high endocrine toxicity potential, but if only recorded in TEDX, it is classified as possessing a medium endocrine toxicity potential. In summary, the capability of each data source on determining the hazard endpoints is presented in Table 3.

Table 3: Hazard Endpoints Included in Each Data Source

Data Source	Hazard Endpoint
GHS-Japan	C, M, R, D, AT, ST, N, IrE, IrS, SnS, SnR, AA, CA, Rx, F
GESTIS	C, M, R, D, AT, ST, IrE, IrS, SnS, SnR, AA, CA, Rx, F
ECHA CHEM	C, M, R, D, AT, ST, IrE, IrS, SnS, SnR, AA, CA, P, B, Rx, F
HSDB	P, B
EPI SUITE™	P, B
EU SVHC List	E
TEDX	E

C=carcinogenity; M=mutagenicity; R=reproductive toxicity; D=developmental toxicity; AT=acute mammalian toxicity; ST=systematic toxicity and organ effects; N=neurotoxicity; IrS=skin irritation; IrE=eye irritation; SnS=skin sensitization; SnR=respiratory sensitization; AA= acute aquatic toxicity; CA= chronic aquatic toxicity; Rx= reactivity: F=flammability; P=persistence; B=bioaccumulation; E=endocrine toxicity.

Source: UC Irvine

2.4.3.4 Hazard Classification and Benchmark Decision Logic

After compiling compile the appropriate toxicity information for a given chemical, a classification level (Very Low (vL), Low (L), Moderate (M), High (H), or Very High (vH)) can be applied for each hazard endpoint. An example of the classification approach is provided in Figure 8 for carcinogenicity.

Figure 8: Hazard Criteria for Classification of Carcinogenic Substances

	Information Type	Information Source	List Type	High (H)	Moderate (M)	Low (L)
Carcinogenicity (C)	Data	GHS Criteria & Guidance		GHS Category 1A (Known) or 1B (Presumed) for any route of exposure	GHS Category 2 (Suspected) for any route of exposure or limited or marginal evidence of carcinogenicity in animals	· Adequate data available and negative studies; and · GHS not classified
	A Lists	US EPA – IRIS Carcinogens (1986)	Authoritative	Group A or B1 or B2	Group C	Group E
		US EPA – IRIS Carcinogens (1996, 1999, 2005)	Authoritative	Known or Likely		Not Likely
		EU – REACH Annex XVII CMRs	Authoritative	Category 1 or 2	Category 3	
		EU – Annex VI CMRs	Authoritative	Carc 1A or 1B	Carc 2	
		EU – GHS (H-Statements)	Authoritative	H350 or H350i	H351	
		EU – R-Phrases[1]	Authoritative	R45 or R49	R40	
		EU – SVHC Candidate List	Authoritative	Carcinogenic – Candidate list		
		EU – SVHC Prioritisation List	Authoritative	Carcinogenic – Prioritized for listing		
		EU – SVHC Authorisation List	Authoritative	Carcinogenic – Banned unless Authorised		
		GHS – [COUNTRY] Lists (Australia, Indonesia, Japan, Korea, Malaysia, Taiwan and Thailand)	Screening	Category 1A or 1B or H350 or H350i	Category 2 or H351	Not Classified
		GHS – [NEW ZEALAND]	Screening	6.7A	6.7B	Not Classified
		IARC	Authoritative	Group 1 or 2a	Group 2b	Group 4
		MAK	Authoritative	Carcinogen Group 1 or 2	Carcinogen Group 3A or 3B or 4 or 5	
		US CDC – Occupational Carcinogens	Authoritative	Occupational Carcinogen		
		US NIH – Report on Carcinogens	Authoritative	Known or Reasonably Anticipated		
		CA EPA – Prop 65	Authoritative	Carcinogen		
	B Lists	US EPA – IRIS Carcinogens (1986)	Authoritative	Group D		
		US EPA – IRIS Carcinogens (1999)	Authoritative	Suggestive Evidence, but not sufficient to assess human carcinogenic potential		
		US EPA – IRIS Carcinogens (2005)	Authoritative	Suggestive evidence of carcinogenic potential		
		IARC	Authoritative	Group 3		
		CA EPA – Prop 65 (with qualifications)[2]	Authoritative	Carcinogen – specific to chemical form or exposure route		

Source: GreenScreen® for Safer Chemicals [12]

After each endpoint classification is completed, the GreenScreen® decision logic (described below) is applied to assign a benchmark (BM) score to each chemical. There are five possible BM scores: chemical of high concern (BM-1), use but search for safer alternatives (BM-2), use but still opportunity for improvement (BM-3), safer chemical (BM-4), and unspecified due to insufficient data (BM-U). In the current study, a BM-U score is assigned when no information can be found for the given chemical. An official GreenScreen® assessment requires a third-party validation, which was not done here, therefore, these benchmark scores are currently designated as 'GreenScreen® -based'.

This report includes the details of this decision logic here so that the results presented below are easier to understand.

A chemical is assigned a BM-1 score if any of the following are true:

a) High P *and* High B, *and* {[Very High T, where T is Ecotoxicity (i.e., AA or CA) *or* any Group II Human (AT, ST-single, N-single, IrS or IrE)] *or* [High T, where T is Group I *or* II* Human]}
b) Very High P *and* Very High B
c) Very High P *and* {[Very High T (Ecotoxicity *or* Group II Human)] *or* [High T (Group I *or* II* Human)]}
d) Very High B *and* {[Very High T (Ecotoxicity *or* Group II Human)] *or* [High T (Group I *or* II* Human)]}
e) High T (Group I Human)

If any of the BM-1 criteria are true, the CHA is complete for this chemical. If not, the process moves on to assess the BM-2 criteria, which are:

a) Moderate P *and* Moderate B *and* Moderate T (Ecotoxicity or Group I, II *or* II* Human)
b) High P *and* High B
c) High P *and* Moderate T (Ecotoxicity or Group I, II *or* II* Human)
d) High B *and* Moderate T (Ecotoxicity or Group I, II *or* II* Human)
e) Moderate T (Group I Human)
f) Very High T (Ecotoxicity *or* Group II Human) *or* High T (Group II* Human)
g) High Flammability *or* High Reactivity

If any of the BM-2 criteria are true, the CHA is complete for this chemical. If not, the process moves on to assess the BM-3 criteria, which are:

a) Moderate P *or* Moderate B
b) Moderate Ecotoxicity
c) Moderate T (Group II *or* II* Human)
d) Moderate Flammability, *or* Moderate Reactivity

If any of the BM-3 criteria are true, the CHA is complete for this chemical. If not, the process moves on to assess the BM-4 criteria, which are:

a) Low P and Low B and Low T (Ecotoxicity, Group I, Group II, and Group II* Human) and Low Physical Hazards (Flammability and Reactivity)

2.4.4 Occupational Health Impact Potential

Three data sources addressing occupational hazards were considered in this assessment: recommended exposure limit (REL) established by the National Institute for Occupational Safety and Health (NIOSH) [25], the permissible exposure limit (PEL) established by the Occupational Safety and Health Administration (OSHA) [13], and the threshold limit value (TLV) from the American Conference of Governmental Industrial Hygienists (ACGIH) [14]. The PEL considered in this study includes data not only on a national scale but also one derived based on the California local scale, which is abbreviated as Cal PEL for clarification. Generally, the time-weighted average (TWA) concentration values were used. A 10-hour TWA was used for REL, and an 8-hour TWA was used for TLV and Cal PEL. The data provided for the PEL are usually given as a TWA, but in some cases only short-term exposure or ceiling limits were available.

2.5. Conducting the Materials-Based Cost Analysis

2.5.1. Literature Review

From 2010 to 2019, 21 studies were published on assessing the costs of redox flow batteries. Of these 21 studies, 18 studies addressed the cost analysis of vanadium redox flow battery (VRFB) [26–31] and 5 studies are related to zinc bromide flow battery (ZBFB) [32,33]. Only 1 study about the all-iron flow battery (IFB) cost analysis was conducted [34]. This section provides an overview of these studies with respect to the major methodologies used for cost analysis and key components that were identified to account for the bulk of the overall cost.

Techno-economic analysis (TEA) has generally been the method used to assess the costs of flow batteries, where the costs assessed are associated with the technical composition of the battery systems. Techno-economic models offer an effective way to reflect the cost reduction potential with technical improvements [12].

Within TEA, three different approaches have been used to account for the technical configuration of flow battery systems. The first involves utilizing data for a prototype to estimate the configuration of a full-scale system [34]. The second involves building the configuration of the system by gathering general information on the number of cells in the cell stack [35,36]. The third and most common method usually starts from electrochemical models. After calculating the voltage and current density needed for the system, the required area and number of cells were determined, followed by defining the necessary supporting stack components [26,37]. With the power system components determined, other components associated with energy storage and balance of plant can be added, such as the depth of discharge (DOD); flow rates were related to the amount of electrolytes, pumps, and tanks required [26]. A major advantage of the third method is that it provides a parametric model that can assess the costs of a range of different flow battery capacities.

Another cost estimating approach described in the literature [27] is to calculate the battery cost as a sum of the costs of the flow battery subsystems, as shown in equation (1), below; the system cost is comprised of the power system cost, energy system cost, and the balance of plant (BOP) cost [27]:

$$C_{sys} = P * c_P + E * c_E + C_{BOP} \qquad (3)$$

where c_P is the power system cost ($\$kW^{-1}$) and c_E is the energy system cost ($\$kWh^{-1}$).

Cost analysis aims to identify the key components or materials that contribute the most to the overall cost. The cost results are sensitive to all components in the cell system and improvements in key parameters can alter the results significantly. Energy-to-power ratio (E/P) is generally a determining factor in the resulting distribution of costs by component. Additionally, the limits for state of charge (SOC), current density [28,36], active species concentration [28], cell voltage, and the cost of the vanadium electrolyte [29], separator, bipolar plate, and felt were considered important to the cost. Other than the technical composition of the battery systems, the annual production rate also influences the cost. Ha and Gallagher [35] showed that the VRFB would have lower costs at high production volumes due to their simple design and manufacturing process.

As stated previously, the VRFB has received more attention in cost analyses present in the literature. Since there is not a standardized way to build the TEA framework, the level of detail and cost distribution by component varies significantly in the literature. However, some trends can be observed. For instance, the electrolyte and power stacks were generally the most critical components in the system cost structure. Additionally, the cost of assembly and the control system could contribute 10 percent to 40 percent to the system depending on the system boundaries.

The electrolyte cost, especially vanadium and electrolyte preparation, shows the largest impact on the overall cost [26,38] Inside the power stack, membrane, gasket [28], felt electrodes and the bipolar plates were substantial to the cost. The membrane and bipolar plates show promising opportunities for stack cost reduction [26]. One study reveals that a 25 percent potential cost could be achieved by using large bipolar plates [26]. Bipolar plates account for the cost difference between small and large cells [30]. Detailed cost analysis of bipolar plates including cost structure and material usage could be found in [39]. Additionally, enabling nanoporous separators so that active species are too large to pass through the separate pores or H+ ion-exchange membrane could lower costs [40]. Zheng et al. [36] investigated the cost reduction potential of various component improvements.

This study found that the current density is a leading factor contributing to the cost reduction, followed by membranes and bipolar plates. High current density could lead to more than 50 percent cost reduction. Therefore, efforts should be made for developing high conductivity, surface activity, and low flow resistance electrode. Previous studies showed that in the ZBFB, the cell cost can account for up to 87 percent of the total cost of a 2 hour system [36]. The power control system including converter or other power interconnections is another cost driver for ZBFB, which accounts for 32 percent of the total cost [41].

Based on the literature survey, we concluded that most techno-economic models have been built on the calculated cell parameters. No previous study has focused on a cost analysis based on commercialized battery designs, nor have all three flow battery technologies been studied in detail together. Thus, in this report, TEA methods are used to explore the material cost structure and uncertainty, for all three flow battery technologies, VRFB, ZBFB, and IFB.

2.5.2 Technoeconomic Analysis Model for Flow Batteries

To perform the analysis of cost sensitivities and their behavior relative to changes in environmental impact, the methods of technoeconomic analysis (TEA) were employed [42–45]. The major goal is to investigate and understand the major cost contributors for flow battery systems since these technologies are relatively early in their commercial deployment compared to alternatives such as lithium-ion batteries. Therefore, this section focuses on materials cost since these costs were fundamental to each flow battery type, while the other costs (e.g., utilities, labor, and fixed costs) will vary from manufacturer to manufacturer and business strategy and were not able to be assessed with current data availability. Thus, for this project, the TEA is focused on material costs and is based on the product specifications (see Table 4) and the materials inventory data provided by the flow battery manufacturers (see Table 5). The material cost assessment is performed for the three flow batteries based on this materials inventory and the unit materials cost searched from various sources. The cost distribution by battery component is determined to highlight the major cost drivers in the battery system. For comparison, the normalized dollar value per kWh battery capacity for the three flow batteries was also evaluated.

Table 4: Product Specifications for Three Flow Batteries

Specification	VRFB	ZBFB	IFB
Product Weight (kg)	32,287	3,844	26,232
Energy Capacity (kWh)	500	125	400
Rated power (kW)	125	25	100
Discharge Time (hour)	4	5	4
Energy Density (Wh/kg)	15.49	32.52	15.25

Source: UC Irvine

Table 5: Component Breakdown and Materials Used in Three Flow Batteries

Component	Vanadium-Redox flow battery	Zinc-Bromide flow battery	All-Iron flow battery
Cell stack			
Bipolar plate	Graphite Polyethylene	Titanium Polyethylene	Graphite Vinyl ester
Electrode	Carbon fiber felt	/	Carbon fiber felt
Membrane	Nafion®	/	Polyethylene
Cell frame	Glass fiber Polypropylene	Polyethylene	Glass fiber reinforced polymer
Accessories			
Current collector	Copper	Titanium	Aluminum
Gasket		Polyethylene	Ethylene propylene diene
Supporting shell and frame	Steel Chlorinated polyvinyl chloride	Steel Polyethylene	Steel
Electrolyte storage			
Electrolyte	Hydrochloric acid Sulfuric acid Vanadium pentoxide Water	Zinc bromide Bromide Water	Ferrous chloride Potassium chloride Manganese chloride Water
Tank	Polyethylene	Polyethylene Steel	Isophthalic polyester
Balance of plant			

Component	Vanadium-Redox flow battery	Zinc-Bromide flow battery	All-Iron flow battery
Pump	Unit part	Unit part	Unit part
Pipe	Polyethylene	Polyethylene	Polyvinyl chloride
Battery management system			
Inverter	Unit part	Unit part	Unit part
Balance of plant accessories	Titanium Polyvinylidene fluoride	Polyethylene Steel Titanium Aluminum	/

An entry of "/" means that a material is not applicable for that component.

Source: UC Irvine

2.2. Materials Cost Data and Uncertainty

For the TEA model, data on the prices of key materials used in the flow battery systems were required. Gathering material cost information that complies with data quality and reliability standards, however, can be difficult. The cost of materials is subject to the dynamics of global markets and trade, causing these values to vary over time. Additionally, materials such as the Nafion® membrane and glass fiber reinforced polymer cell frame are complex synthetic materials that are protected by patents as private products, therefore prices for these must be estimated. The sources for price information in our case can be classified into four types: (1) international market prices, (2) United States import prices, (3) literature prices, and (4) retail prices.

The international market price is suitable for materials traded as bulk commodities, where prices are continuously monitored and updated in international trade, such as copper and aluminum. The international market price, however, may not represent the prices paid in a specific geographical area because different countries have different exchange rates and policies as well as local tariffs.

The U.S. import price is collected based on the price of goods imported to the U.S. These are well documented by several U.S. governmental institutes and databases such as the United States Geological Survey (USGS) and Statista. The import price is converted into a dollar value for the U.S. case, which is equal to the world price plus any transport, tariff, and other costs that customers would bear for importing the material to the U.S. [46]. The import price may also not be an accurate prediction as the manufacturers' purchase source is not disclosed.

The literature price is based on price values found in the published literature for the materials cost of flow battery production. The advantage of using literature data is that the cost information is complete even for materials that are difficult to track to a market, and this data is peer-reviewed. Due to the lack of original studies and primary data in these studies, however, much of the cost information in literature studies are predicted values, while some are cited from previous publications. These values, therefore, may not capture the dynamic price variations to reflect the current situation.

The retail price is the material price collected from the vendors who purchase those materials from upstream supply chains and sell them directly to the commercial end-users. These prices, however, may not apply to this study as flow battery manufacturers do not necessarily buy their materials from second-hand vendors.

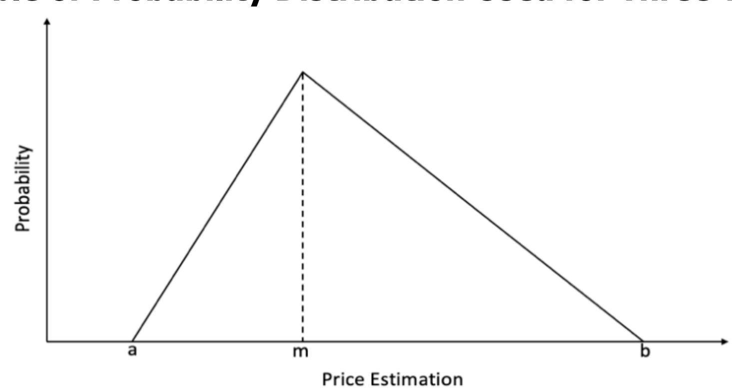
Due to the dynamic nature of market price and the uncertainty associated with different sources, the project team noted the price sources collected for each material considering the requirement of transparency. Furthermore, due to the variations in the market prices for materials, a sensitivity analysis was conducted to explore the uncertainty in market price variability for selected materials, specifically: vanadium pentoxide, titanium, bromine and carbon fiber felt. The vanadium pentoxide was used as the electrolyte in the VRFB, the titanium and bromine were used in the bipolar plate and electrolyte, respectively, for ZBFB, and carbon fiber felt was the electrode used for VRFB and IFB but was also used in the IFB balance of plant as a rebalancing cell which is unique among the three batteries.

For these four materials, a three-point estimation was applied for estimation based on a pessimistic price (worst case), most likely price (current value), and optimistic price (best case). The three-point estimation created an approximate probability distribution to predict the outcomes of future events, for example, materials price, when only limited information is available. Usually, a beta or triangular distribution is assumed and, in this study, a double-triangular distribution was used, as shown in Figure 9. The notation "a" is the optimistic price which represents the best case, "b" is the pessimistic price indicating the worst case, and "m" is the most likely price, which indicates the current price [47]. With the three value points determined, a weighted average (*E*) as expected price and a standard deviation (SD) was calculated as follows:

$$\mathrm{E} = (\mathrm{a} + 4\mathrm{m} + \mathrm{b}) / 6 \quad (4)$$

$$\mathrm{SD} = (\mathrm{b} - \mathrm{a}) / 6 \quad (5)$$

Figure 9: Example of Probability Distribution Used for Three-Point Estimation



Source: Project Management Institute [47]

2.5.3 Trade-Offs between Costs and Environmental Impact

In addition to assessing the material cost and component-based cost drivers for the three flow battery systems, this study also assessed how changes in material cost between the three flow battery systems compare against their environmental impacts. To accomplish this, the research team referred to the results presented on the environmental impact of the three flow battery systems on different impact indicators. The team then compared the performance of the three flow batteries based on material cost versus different environmental impacts. For this comparison, only the cell stack and electrolyte storage were considered since these are core components of each battery system. The balance of plant components were excluded since these are often selected due to the design choices of a specific manufacturer and are therefore subject to significant variation. For this comparison, the project team regarded the material cost and environmental impact values of the VRFB as the reference values against which the ZBFB and IFB were compared. This was done because the VRFB is currently the most mature of the flow battery technologies.

CHAPTER 3: Project Results

3.1 Materials Life Cycle Inventory for Flow Batteries

This chapter presents the current LCI data collection results on flow battery production. For each flow battery, a process flow chart is provided to illustrate the production process. The following data tables include information on material use, processing methods, and accessory equipment for each flow battery and the data sources used for finding the LCI data.

3.1.1 Vanadium-Redox Flow Battery

A flowchart of the material inputs for production of the VRFB is presented in Figure 10. The data for VRFB materials composition was provided by a manufacturer of this technology. The raw materials and their weight are listed on the left, the processing methods for these materials as necessary are provided in the center, with the arrows leading to the final components in the whole flow battery package consisting of those processed materials.

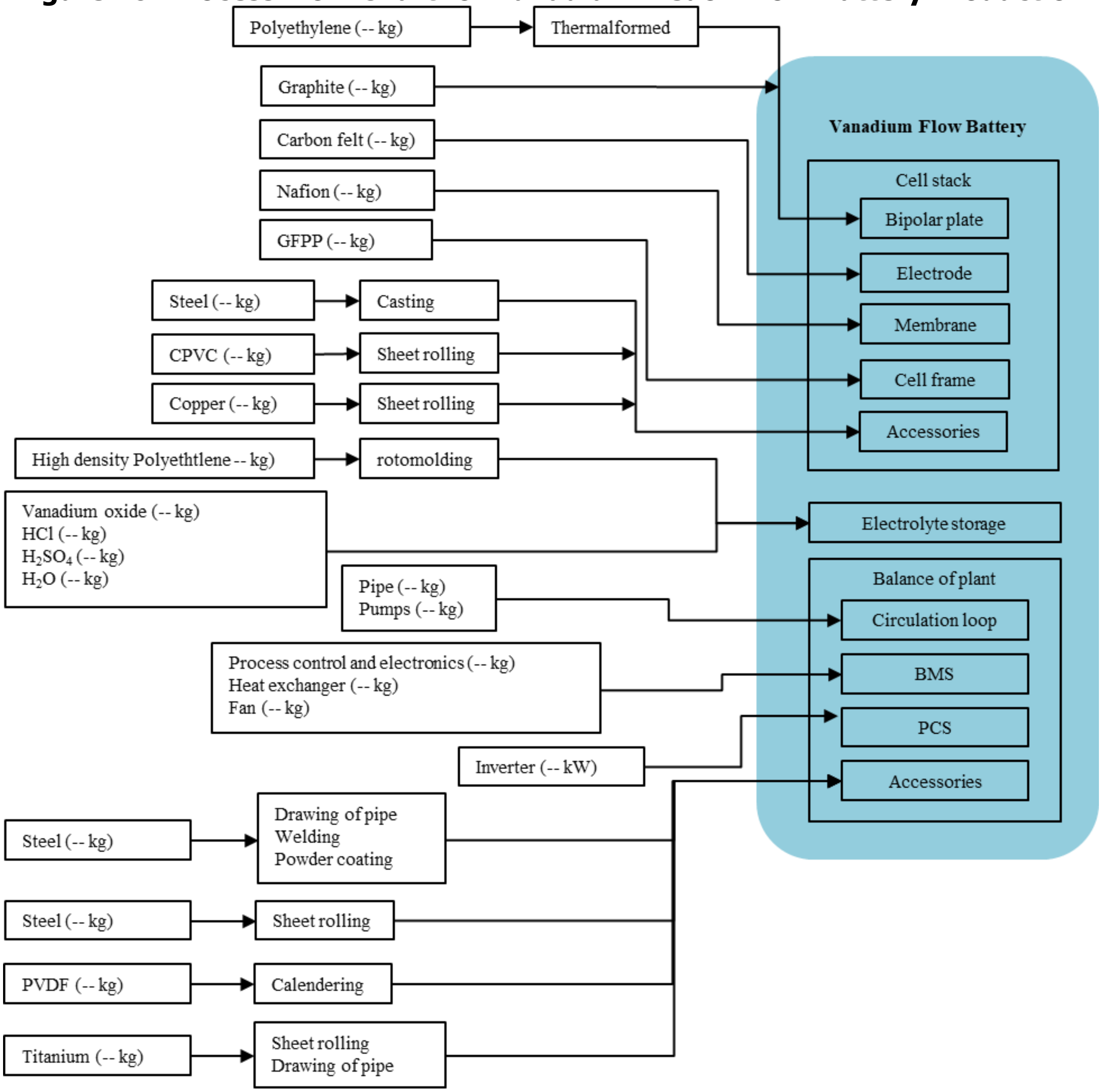
The raw materials used for a single VRFB unit are listed in **Error! Reference source not found.**. Most of the data for other materials, energy, and emissions inputs/outputs associated with raw material production can be found in ecoinvent except for one material (polyvinylidene fluoride), which was replaced by a functionally equivalent material that had available life cycle data.

Table 6: Materials Used in Vanadium-Redox Flow Battery

Materials name	Unit	Sources	Notes
Steel (unalloyed)	-- kg	ecoinvent	
Polyethylene	-- kg	ecoinvent	
Polyvinyl chloride	-- kg	ecoinvent	
Polyvinylidene fluoride	-- kg	ecoinvent	Replaced by polyvinyl fluoride (PVF)
Copper	-- kg	ecoinvent	
Aluminum	-- kg	ecoinvent	
Titanium	-- kg	ecoinvent	
Vanadium pentoxide	-- kg	Literature	
HCl	-- kg	ecoinvent	
H_2SO_4	-- kg	ecoinvent	
H_2O	-- kg	ecoinvent	
Graphite	-- kg	ecoinvent	

Source: UC Irvine

Figure 10: Process Flow Chart for Vanadium-Redox Flow Battery Production



Source: UC Irvine

The major materials used for VRFB manufacturing are vanadium pentoxide, steel, hydrochloric acid, and polyethylene. Due to a lack of information in ecoinvent, the LCI data for vanadium pentoxide production was acquired through a literature review. Vanadium pentoxide is a by-product during the steel production process, and literature is available that contains the data for the extraction of vanadium pentoxide through the crude steel production process using vanadium titano-magnetite [48]. The details on LCI data generation for vanadium pentoxide are provided in Appendix B.

The processing methods for VRFB are listed in Table 7, divided into steel treatment, plastic treatment, and nonferrous treatment. Data for other materials, energy, and emissions inputs/outputs associated with each of these processes can be found in ecoinvent. However, notice that the units for welding and powder coating were not based on weight but rather length and area, respectively.

Table 7: The Processing Methods for Vanadium Redox Flow Battery

Process name	Unit	Sources
Steel treatment		
Welding	m	ecoinvent
Powder coating	m^2	ecoinvent
Sheet rolling	kg	ecoinvent
Drawing of pipe	kg	ecoinvent
Casting	kg	ecoinvent
Plastic treatment		
Calendering	kg	ecoinvent
Extrusion	kg	ecoinvent
Thermal forming	kg	ecoinvent
Nonferrous treatment		
Extrusion	kg	ecoinvent
Cutting	kg	ecoinvent
Drilling	kg	ecoinvent
Machining	kg	ecoinvent
Powder coating	m^2	ecoinvent

Source: UC Irvine

Error! Not a valid bookmark self-reference. presents the balance of plant equipment used in VRFB. For these types of materials and products, the LCI data were collected based on information provided by manufacturers and then incorporated with other data found in ecoinvent for each life cycle stage.

Table 8: Balance of Plant for Vanadium Redox Flow Battery

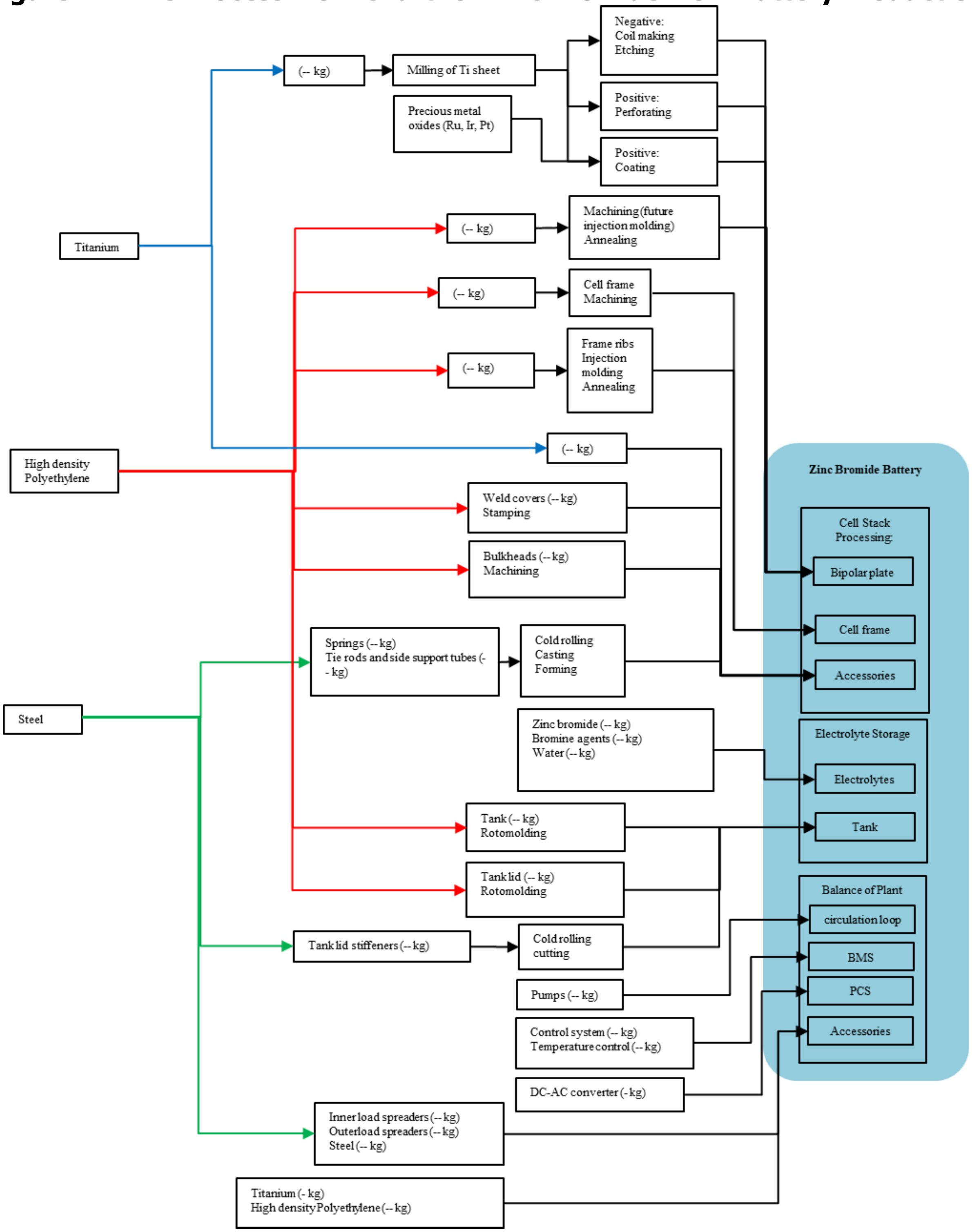
Equipment name	Sources
Fans	Manufacturer
Pumps	ecoinvent
Transformers	Manufacturer
Inverter	ecoinvent
Other	Manufacturer

Source: UC Irvine

3.1.2 Zinc Bromide Flow Battery

A flowchart for the ZBFB production is presented in Figure 11. The data on ZBFB material composition was provided by a manufacturer of this technology.

Figure 11: The Process Flow Chart for Zinc Bromide Flow Battery Production



Source: UC Irvine

Of the three manufacturer datasets obtained, the ZBFB dataset was the most detailed. The major materials used for ZBFB cell stacks are titanium, high-density polyethylene (HDPE), and steel. The electrolyte in the ZBFB is primarily composed of zinc bromide and bromine agents, while the balance of plant primarily consists of pumps, temperature control systems, inverter, and other components. The details on the raw material use for the ZBFB are shown in Table 9. The LCI datasets for the raw material production were obtained from ecoinvent, except for zinc bromide.

Table 9: Materials Used for Zinc-Bromide Flow Battery

Materials name	Unit	Sources	Notes
Steel (unalloyed)	-- kg	ecoinvent	
Titanium	-- kg	ecoinvent	
High-density polyethylene	-- kg	ecoinvent	
Zinc Bromide (Zinc Oxide and Bromine)	-- kg	ecoinvent	Zinc Bromide replaced separately by ZnO and Br_2, provided by the manufacturer, considering HBr is made from Br_2.
Bromine	-- kg	ecoinvent	
Water	-- kg	ecoinvent	
Copper	-- kg	ecoinvent	
Aluminum	-- kg	ecoinvent	

Source: UC Irvine

The data on processing methods for the ZBFB were divided into titanium treatment, HDPE treatment, and steel treatment, presented in Table 10. The data on processing methods provided by the manufacturer were detailed, therefore not all the processing methods were found in ecoinvent. For example, limited data existed on titanium and plastic manufacturing. For titanium, the milling, perforating, and coating were all generated based on the datasets of other metals treatment in ecoinvent and data were unavailable for titanium coil making and surface etching. For HDPE, LCI data were unavailable on machining and annealing processes as that type of LCI data can be largely dependent on material types, machines used, locations, and processing times. They were all replaced by injection molding as the manufacturer indicated that they will use injection molding to replace these in the short term from the perspective of saving more materials. The rotational molding used for manufacturing the electrolyte storage tank was replaced by blow molding due to a lack of available LCI data.

Table 10: Processing Methods for Zinc-Bromide Flow Battery

Process name	Unit	Sources	Notes
Titanium treatment			
Ti milling	kg	ecoinvent	Generated based on Al milling
Coil making	kg		Not found
Etching	kg	ecoinvent	Need more information
Perforating	kg	ecoinvent	Generated based on Al drilling
Coating	m^2	ecoinvent	Generated based on Steel coating
High-Density Polyethylene treatment			
Machining	kg		Not found
Annealing	kg		Not found
Injection molding	kg	ecoinvent	Replacement for machining and annealing in all HDPE processing
Stamping			Not found
Rotational molding	kg	ecoinvent	Replaced by blow molding
Steel treatment			
Cold rolling	kg	ecoinvent	
Casting	kg	ecoinvent	
Cutting	kg	ecoinvent	

Source: UC Irvine

The details on the balance of plant equipment for the ZBFB are shown in Table 11. The input for LCI regarding this equipment was generated based on the information provided by the manufacturer as stated before for VRFB. The material used for each equipment type in the ZBFB is provided. As the data provided for the ZBFB were more detailed than for the other two flow batteries, it was important for the project team to ensure that all the data were at the same level of detail when comparing the environmental and human health impacts for the three flow batteries.

Table 11: Balance of Plant for Zinc-Bromide Flow Battery

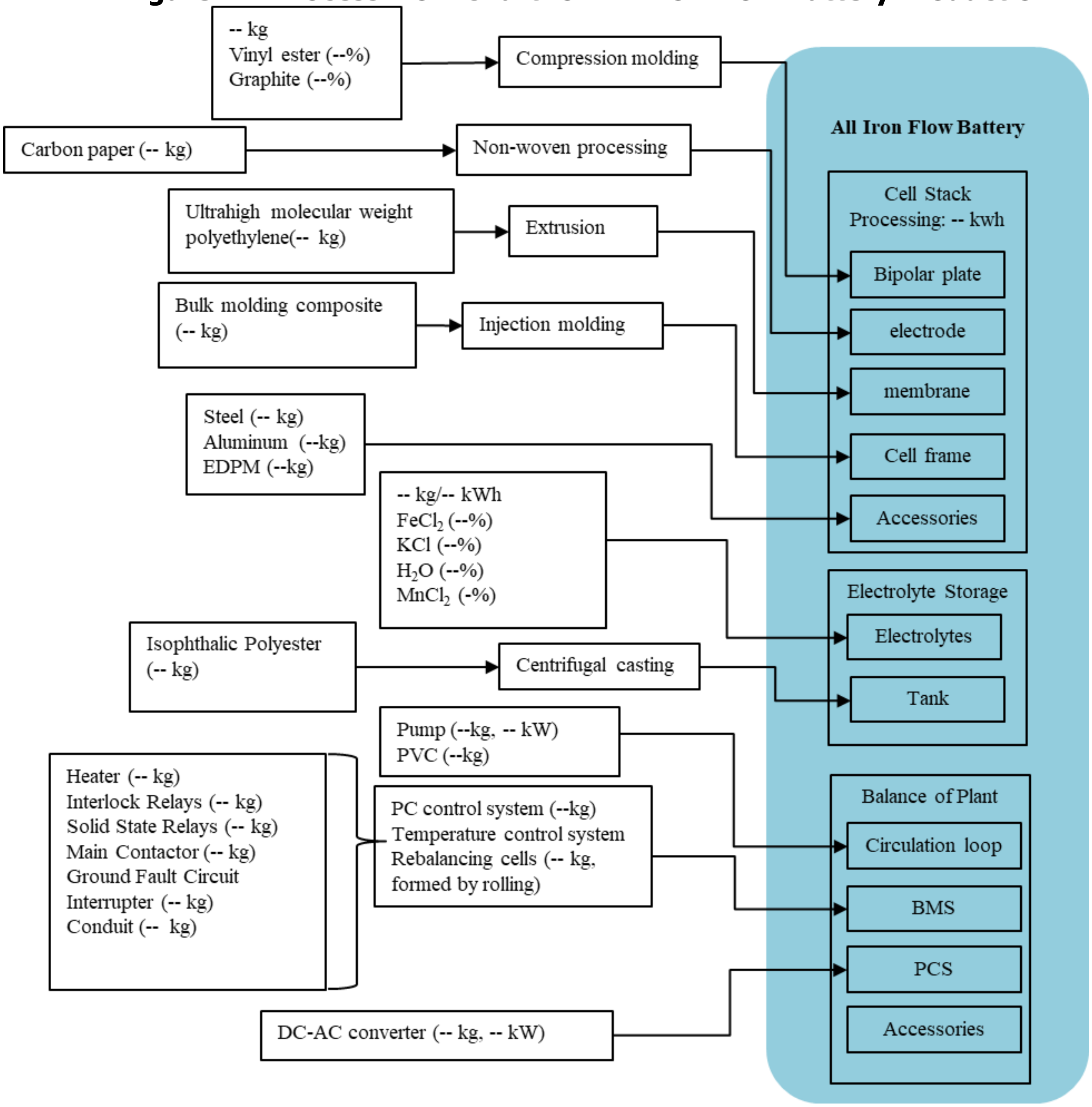
Equipment name	Parameters	Sources
Pumps	• Main pump: -- kg, steel • QBr control valve: -- kg, steel • Glycol pump: -- kg, steel Pump subframe: --kg, steel	Manufacturer
Temperature control	Radiator/fan: --kg, Al (steel copper)	Manufacturer
Inverter	-- kg, Cu, Al	Manufacturer
Other	• Return flow diffusers: --kg, HDPE. • HEX Coil bolts: --kg, Ti. • Stack support: -- kg, steel. • Misc. hardware/structure: --kg, steel. • Misc. HDPE (Piping, fittings, etc.): --kg, HDPE. • Misc aluminum, -- kg. • Skid assembly (columns, supports): -- kg, steel	Manufacturer

Source: UC Irvine

3.1.3 All Iron Flow Battery

The process flow chart for the IFB is shown in Figure 12. Data on the IFB were provided by a manufacturer of this technology and were also organized based on the three components we proposed for each flow battery. The major materials used for the IFB cell stacks were vinyl ester, graphite, and steel. For electrolyte storage, the materials primarily consisted of iron chloride and potassium chloride, and isophthalic polyester is used for manufacturing the storage tank. The major difference in the balance of plant equipment for IFB compared with the other two flow batteries is the presence of a rebalancing cell, which is unique in IFB. It should be noted that the IFB product is undergoing revision as the product matures, which affects the details for available data.

Figure 12: Process Flow Chart for All-Iron Flow Battery Production



Source: UC Irvine

Table 12 shows the details of raw materials comprising IFB. Most of the LCI data could be obtained from ecoinvent except for ultrahigh molecular weight polyethylene, and HDPE was used as a substitute. For carbon paper (which is one type of carbon fiber), the LCI data were found through a publication in which most of the data were generated based on modeling calculations [49].

Table 12: The Materials Used for All Iron Flow Battery

Materials name	Unit	Sources	Notes
Steel (unalloyed)	-- kg	ecoinvent	
Vinyl ester	-- kg	ecoinvent	
Graphite	-- kg	ecoinvent	
Carbon paper	-- kg	Literature review	
Ultrahigh molecular weight polyethylene	-- kg	ecoinvent	Replaced by high-density polyethylene
$FeCl_2$	-- kg	ecoinvent	
KCl	-- kg	ecoinvent	
H_2O	-- kg	ecoinvent	
Isophthalic polyester	-- kg	ecoinvent	

Source: UC Irvine

The processing methods for each material in the IFB are provided in Table 13. The extrusion and injection molding were the only two processes available in ecoinvent. The LCI data on compression molding used for the redox electrode in cell stacks were replaced by thermoforming with calendaring due to the similarity of the two plastic forming processes. The non-woven processing and centrifugal casting consisted of several steps with different processing technologies, and LCI data on these processes were unavailable. The balance of plant equipment for the IFB is shown in Table 14, and the strategy for LCI modeling on this part was the same as used with the other two flow battery types.

Table 13: Processing Methods for All-Iron Flow Battery

Process name	Unit	Sources	Notes
Compression molding	kg	ecoinvent	Replaced by thermoforming, with calendering
Non-woven processing	kg		Not found
Extrusion	kg	ecoinvent	
Injection molding	kg	ecoinvent	
Centrifugal casting	kg		Not found

Source: UC Irvine

Table 14: Balance of Plant for All-Iron Flow Battery

Equipment name	Parameters	Sources
Pumps	-- kg, -- kw,	Manufacturer
Temperature control	Heater = -- kg/system Interlock Relays = -- kg/system Solid State Relays = -- kg/system Main Contactor = -- kg/system Ground Fault Circuit Interrupter = -- kg/system Conduit = -- kg/system	Manufacturer
Inverter	--kg, -- kw, Steel case, Al heat sink. Semiconductors	Manufacturer
Other	Control system:--kg, PC, Rebalancing cells: -- kg, coated carbon cloth, roll to roll assembly fixture Outshell: -- kg steel	Manufacturer

Source: UC Irvine

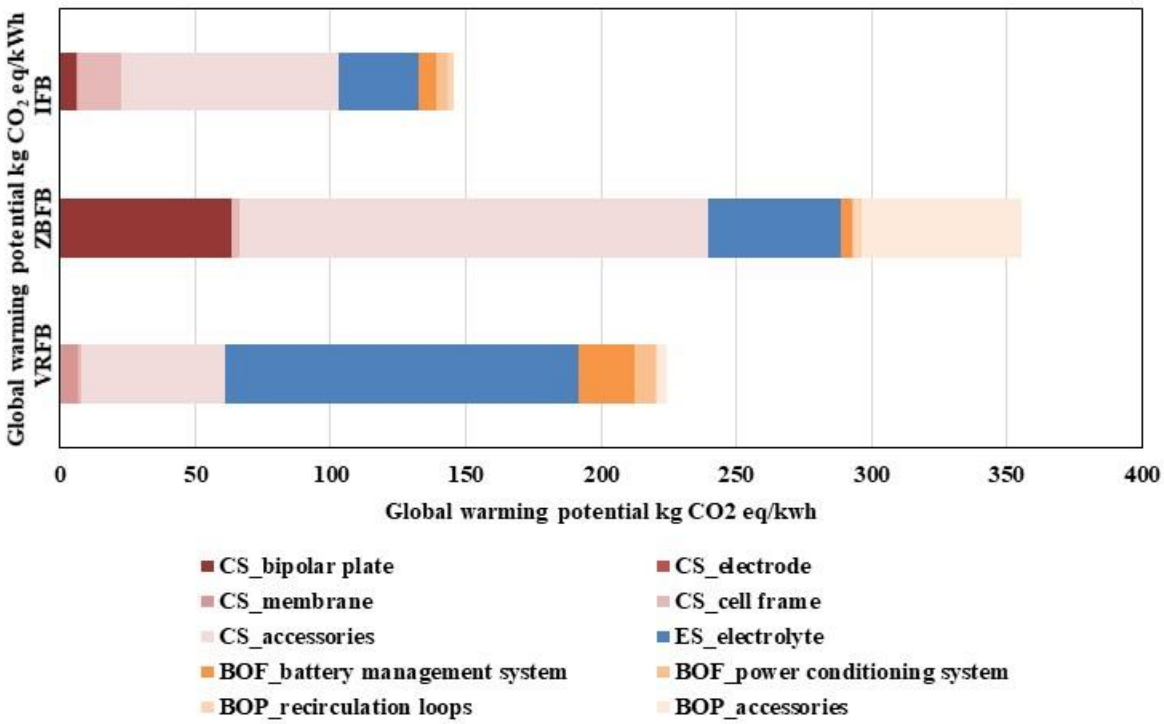
3.2 Environmental Life-Cycle Impact Assessment Results

3.2.1 Materials Extraction and Manufacturing of Flow Batteries

3.2.1.1 Global Warming Potential

The calculated GWP results are shown in Figure 13. Considering all the components including the accessories used, clearly the ZBFB exhibited the highest impact on GWP while the IFB exhibited the lowest impact. The high total impact of the ZBFB was due to the cell stack accessories, bipolar plate, and balance of plant accessories. For the VRFB, the electrolyte was the highest contributor for its GWP, followed by the cell stack accessories; for the IFB, the impact was also largely due to the cell stack accessories. Because the energy capacity of one unit of ZBFB is lower than the VRFB and IFB, the GWP associated with the accessories for ZBFB was slightly increased when normalized by per kWh as the functional unit. As shown in the previous flow charts, the major material and energy inputs for those accessory components were steel production and related processing methods, indicating the use of metals and alloys that will contribute to a higher GWP compared to using other materials such as polymers, salts, and carbon-based materials. This was also shown by the high impact of the electrolyte used in VRFB since the vanadium pentoxide is a typical byproduct of the steel manufacturing process, which will partly exhibit the impact of steel production. The bipolar plate for ZBFB majorly consisting of titanium also has high GWP.

Figure 13: Global Warming Potential Results of Each Component in Three Flow Batteries



Source: UC Irvine

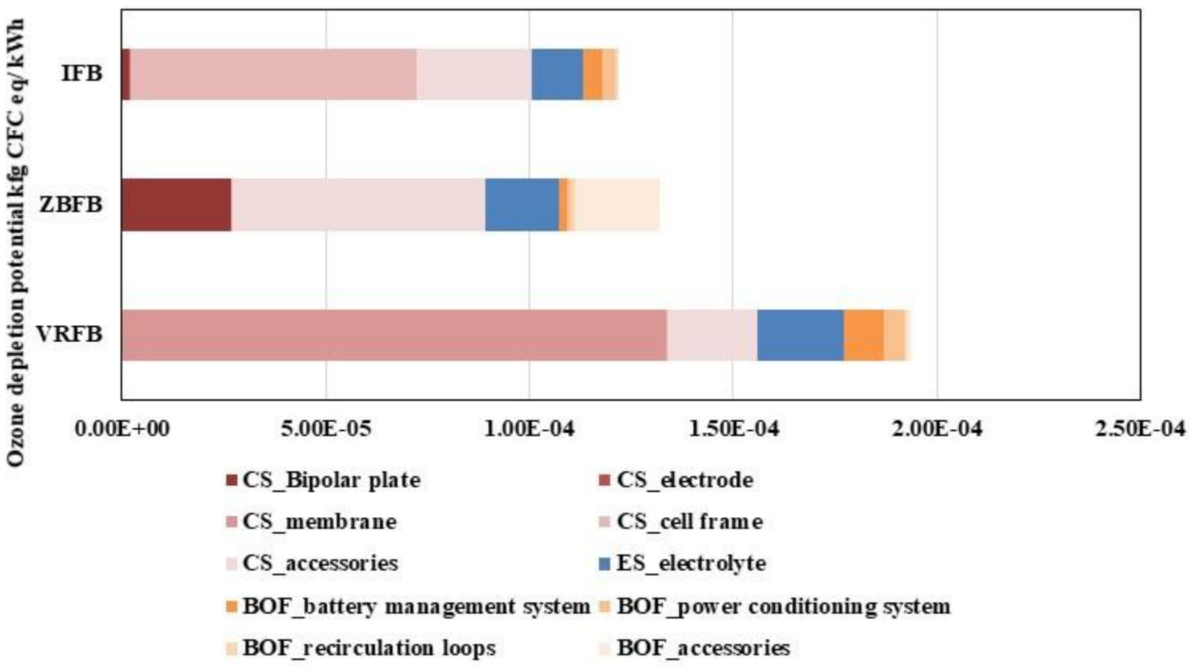
The SPA results in Appendix C summarize the unit processes that contributed to a high GWP for the three flow batteries. For the VRFB, most of the unit processes were associated with vanadium pentoxide production, which was used in the electrolyte. For the ZBFB and IFB, the high impacts were mostly contributed by the use of energy sources such as hard coal, heat, and electricity during the steel production and processing used in the cell stack accessories. Since the raw materials used in those flow batteries were produced in different areas of the world, the factories in the United States are responsible for the assembly of the battery package. The inventories used in the study were mostly based on the rest-of-world data and global data in which the energy sources were a mix from different countries and districts. The GWP of different energy resource mixes is different and the energy sources with high impacts are usually from developing countries such as China (CN) which has a high production volume of steel products. Note that since the analysis used globally averaged data, the project team took the geographic distribution of resource use for manufacturing as specified in the ecoinvent database. This distribution is included in the SPA, but the team did not independently compile this distribution. Using a different mix of geographical sources (that is, for materials processing or other steps) may produce different results.

It is important to note that for the ZBFB, the high impact due to system accessories was a function of the design of the specific ZBFB units from Primus Power which were used to represent this technology in this analysis. This impact is not representative of ZBFB technology as a whole and, in discussions with Primus Power, a new unit design was already being deployed that may have a leaner accessory material profile. As a more general note, improvements in the design of the representative flow battery units assessed here can improve life cycle environmental impact profiles.

3.2.1.2 Ozone Depletion Potential

The ODP results are shown in Figure 14.

Figure 14: Ozone Depletion Potential Results of Each Component in Three Flow Batteries



Source: UC Irvine

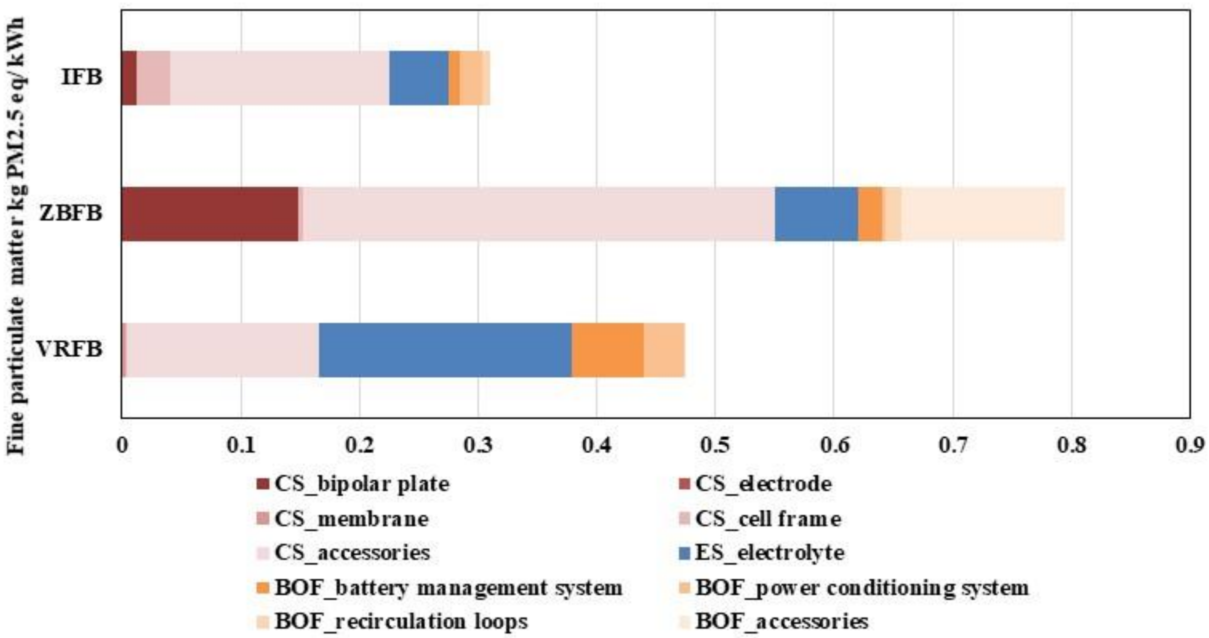
These results show that the ODPs of the three flow batterieswere very similar and the impact of the VRFB is higher than the ZBFB and IFB. The components that trigger high ODP were very different in different flow batteries. For the VRFB, the major trigger was the membrane which uses Nafion, a polymer compound. In the ZBFB, the impact was triggered by the cell stack accessories that were related to steel production and processing. For the IFB, the cell frame was the major component that contributed to the ODP and the materials used were the glass fiber reinforced polyester resin that is used as the bulk molding compound for injection molding.

The SPA analysis in Appendix C presents the major unit processes behind those materials use inside those high ODP components. For example, the raw materials used to produce the Nafion membrane in the VRFB are tetrafluoroethylene, trichloromethane, and chlorodifluoromethane which contain typical ozone-depleting materials. The adipic acid used in the IFB cell frame is one major processing material used to produce the polyester resin that has high ODP. Due to the unique design of the integrated titanium bipolar plate of ZBFB which eliminates the use of membrane and cell frame, the project team found the ODP impacts were primarily triggered by the titanium production and electricity use for steel manufacturing whose contribution on ODP is about one magnitude lower.

3.2.1.3 Particulate Matter

The PM 2.5 results for the three flow batteries are shown in Figure 15. The results indicate that the ZBFB had the highest impact due to the cell stack accessories and bipolar plate which were also closely related to the metal and alloys production and processing. The VRFB had the next higher impact, caused by the electrolyte and cell stack accessories and a similar contribution is also shown for the IFB. The drivers of these results were very similar to those for the GWP results: the use of a large amount of metals and alloys as accessories. From the SPA analysis shown in Appendix C, production of vanadium pentoxide, copper, titanium, and steel were the unit processes that triggered high PM 2.5 results. This was largely associated with the higher energy demand for their production and processing, which consumed different mixes of energy sources in different countries and districts that have high emission potentials of the sulfur dioxide (SO_2), ammonia (NH_3), and nitrogen oxides (NOx). These will induce the formation of PM 2.5 aerosols.

Figure 15: PM 2.5 Results of Each Component in Three Flow Batteries

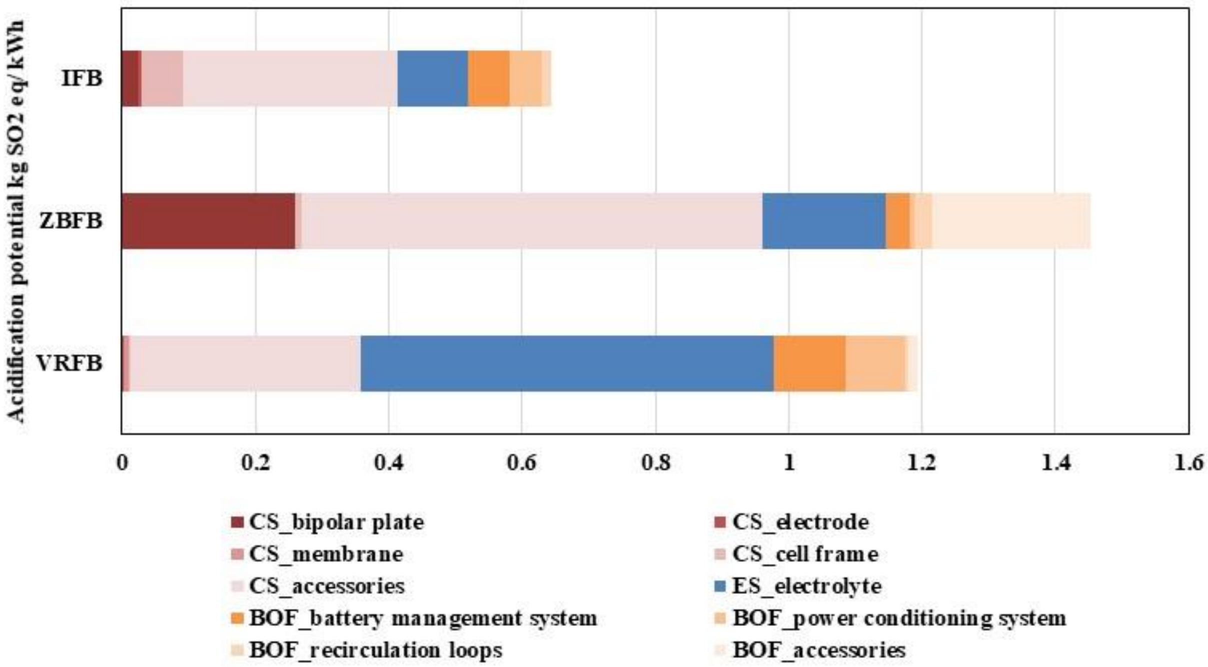


Source: UC Irvine

3.2.1.4 Acidification Potential

The results for the three flow batteries in Figure 16 indicated the same trend with the PM 2.5 and GWP results and the SPA results shown in Appendix C were also similar to the PM 2.5 results because the unit processes have a high potential of acidification were related to the metals and alloys production and processing.

Figure 16: Acidification Potential Results of Each Component in Three Flow Batteries

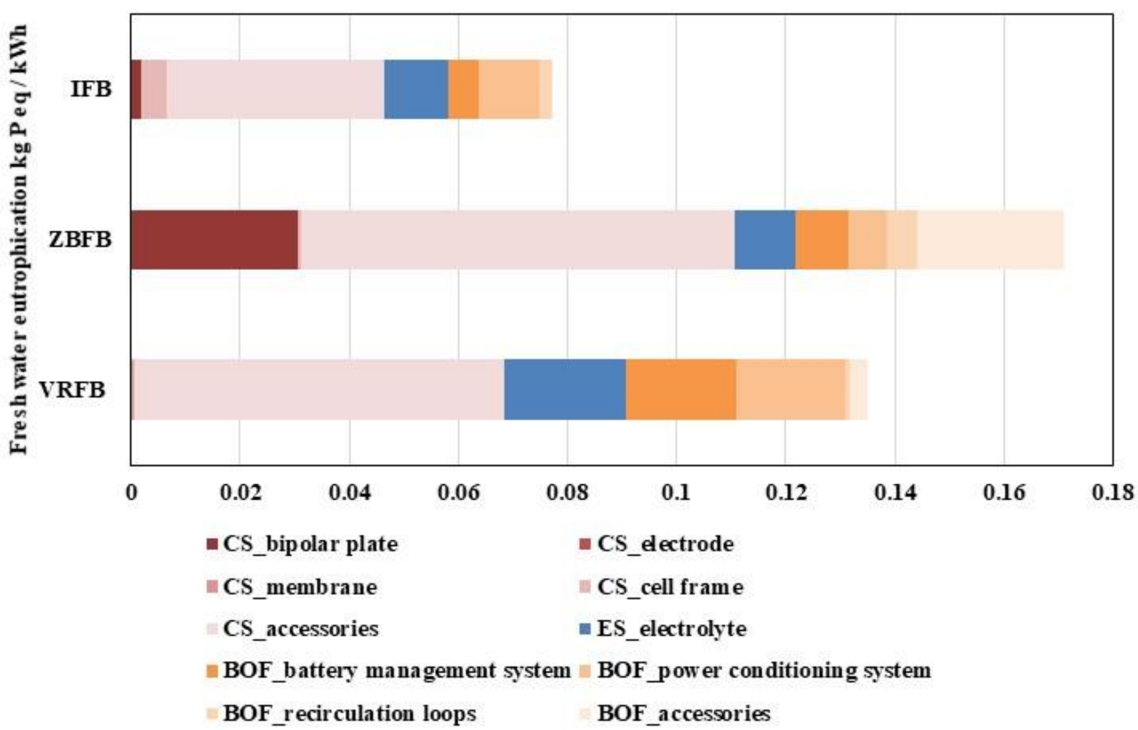


Source: UC Irvine

3.2.1.5 Eutrophication

Eutrophication results are shown in Figure 17.

Figure 17: Eutrophication Results of Each Component in Three Flow Batteries



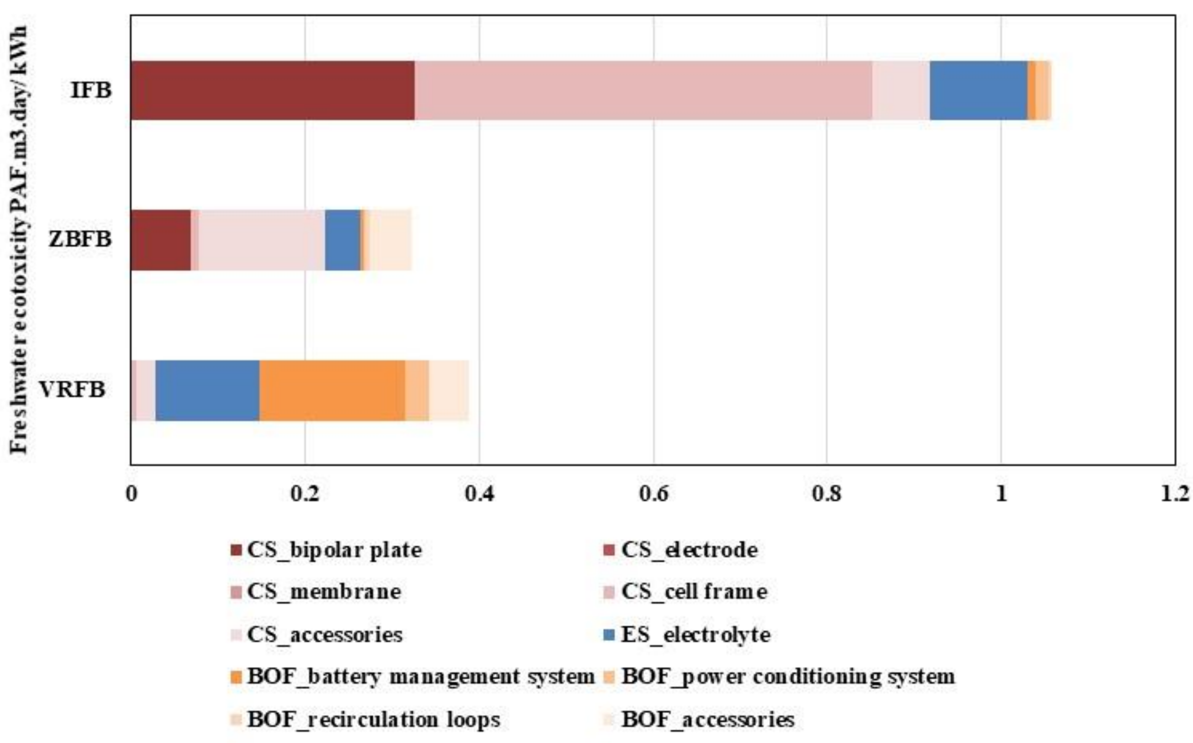
Source: UC Irvine

The results indicate the ZBFB had the highest eutrophication potential, followed by the VRFB, and the IFB had the lowest eutrophication potential. The steel production and processing used in the cell stack accessories were the major triggers for the three flow batteries. As the freshwater eutrophication in ReCiPe 2016 was only determined by the emission of phosphor-based chemicals, the amount of unit processes contributing to high eutrophication impacts was lower than other impact categories from the SPA analysis in Appendix C. Also, the major unit processes that have a high potential on eutrophication were associated with the treatment of the waste and by-product of the mining process such as the lignite mining, sulfidic mining, and hard coal mining.

3.2.1.6 Ecotoxicity

The related results of the ecological toxicity potential are shown in Figure 18. From the results, the IFB had the highest impact on ecotoxicity over the other two batteries. This was triggered by the bipolar plate and cell frame, which consisted of a graphite and vinyl ester-based bulk molding compound and a glass fiber reinforced polyester resin bulk molding compound used for injection molding. For the VRFB, the ecotoxicity was caused primarily by the battery management system, consisting of several electronic devices such as the printed wiring board and circuit and the electrolyte associated with the vanadium pentoxide production. The ZBFB showed the lowest potential impacts on ecotoxicity and the major contributors were the cell stack accessories.

Figure 18: Ecotoxicity Results of Each Component in Three Flow Batteries



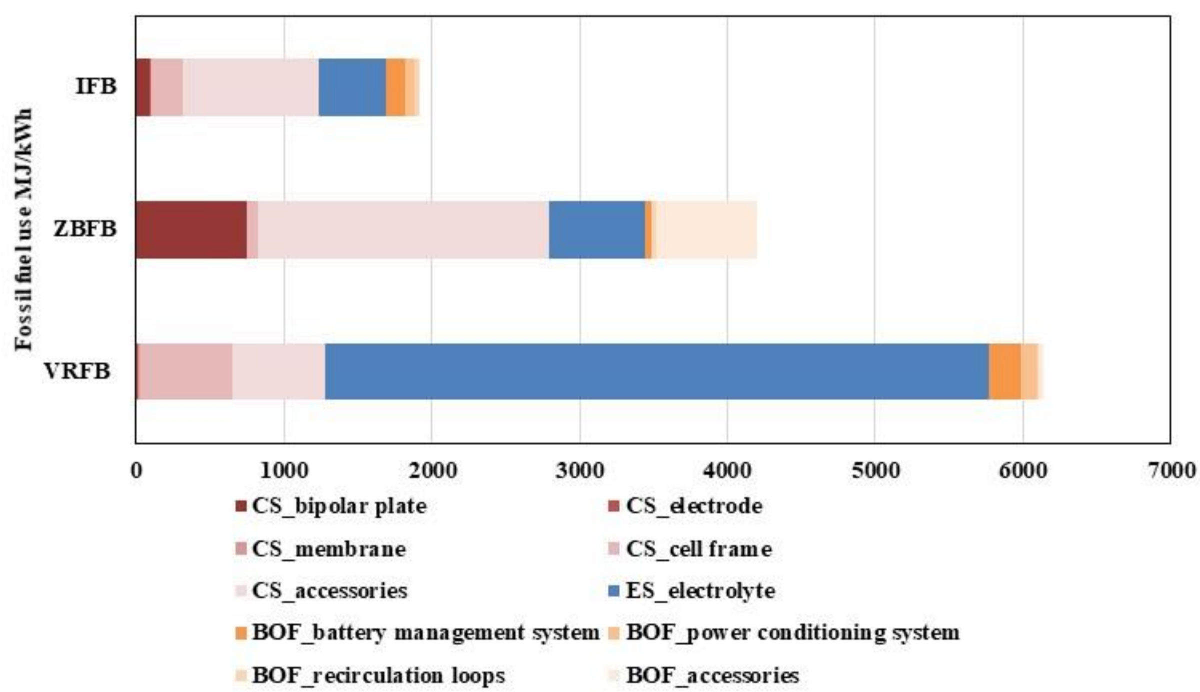
Source: UC Irvine

The SPA results in Appendix C present the unit processes that have high contributions to the ecotoxicity of the flow batteries. Overall, the unit processes that showed high ecotoxicity involve organic compounds. In IFB, there were several unit processes on organic compounds production that present high ecotoxicity potentials such as the vinyl ester resin, glass fiber reinforced polyester, phenol, and acetic anhydride. Those chemicals and compounds were used to fabricate the bipolar plate and cell frame in the IFB but for the other two batteries, their bipolar plate was made of graphite and titanium and the cell frame was made of polyethylene — both of which do not consume materials with high ecotoxicity. The P-dichlorobenzene was the unit process showing the highest ecotoxicity impact in the VRFB and it was largely used for manufacturing electronic devices. The other material in the VRFB with high ecotoxicity was soda ash which is used to produce vanadium pentoxide. For the ZBFB, the ecotoxicity potential on the associated unit processes was not as high as the IFB and VRFB. Coke production and sugarcane production are the major contributors associated with the steel manufacturing used in the cell stack accessories while another process is the titanium production used for the bipolar plate.

3.2.1.7 Cumulative Energy Demand

The CED results for the non-renewable fossil fuel component for the three flow batteries are shown in Figure 19. The results indicate the nonrenewable fossil fuel use of the VRFB and ZBFB were higher than that for the IFB. For the VRFB, the major component was the electrolyte and for the ZBFB, the major component was the cell stack accessories. Again, the SPA analysis in Appendix C indicates the unit processes associated with the vanadium pentoxide production, mining process of hard coal and lignite, and energy resources used for the steel production and processing had the highest consumption of the nonrenewable fossil-fuel use.

Figure 19: Cumulative Energy Demand Results of Each Component in Three Flow Batteries

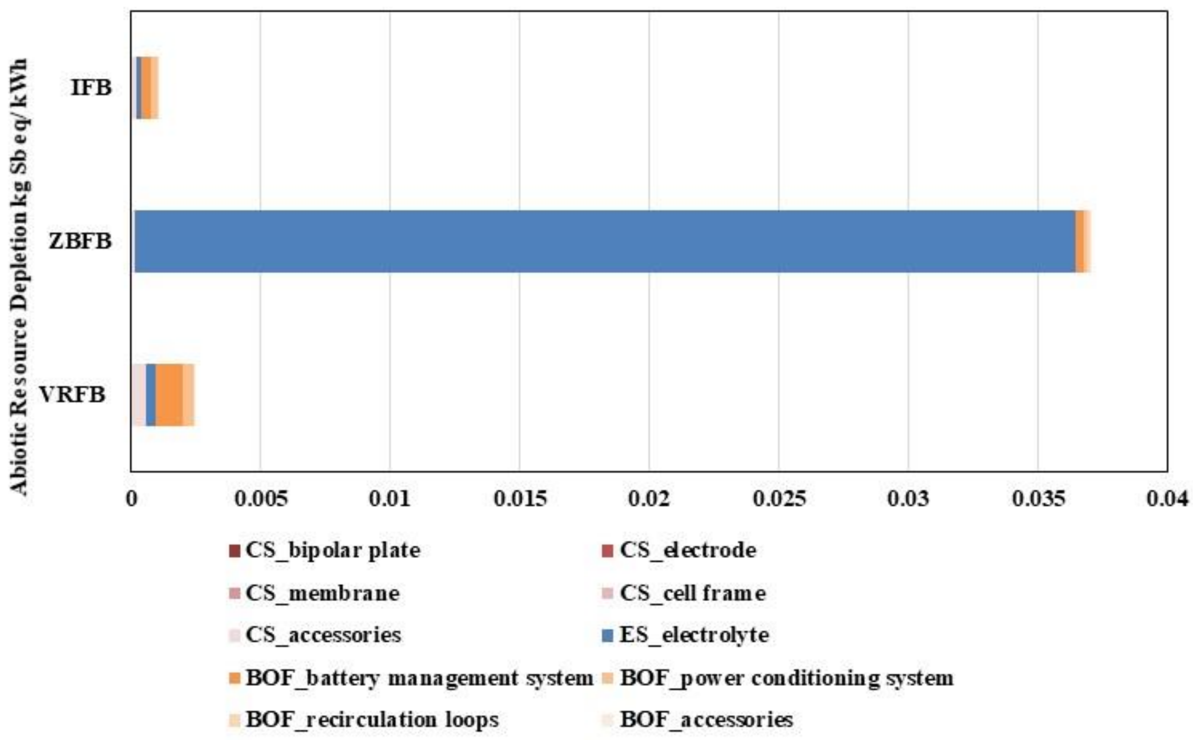


Source: UC Irvine

3.2.1.8 Abiotic Resource Depletion

Figure 20 presents the abiotic resource depletion potentials of the three flow battery technologies. The ZBFB had a significantly larger impact compare to the VRFB and IFB. The SPA results in Appendix C show that the production of bromine contributed to a much higher resource depletion potential than any other materials. To avoid the high impact of bromine production that would hide the contribution of other unit processes, the SPA results based on the 1 percent cut-off value for the ZBFB on abiotic resource depletion were calculated after the subtraction of the impact on bromine production. For the rest of unit processes, the major contributions were made by the copper production used as accessories, inverters, and precious metals such as gold contained in electronic devices or other metals mining processes which is consistent with the VRFB and IFB.

Figure 20: Abiotic Resource Depletion Results of Each Component in Three Flow Batteries



Source: UC Irvine

In the CML method, the characterization factor (CF) for the ADP was calculated as the extraction rate divided by the ultimate reserves, then the CF was normalized using the ratio of antimony as the reference material. The high ADP potential can be triggered by a high extraction rate or low reserve amount on earth. This is the case for the bromine due to its low reserve amount in the earth compared with other materials and its high amount of use as the electrolyte for the ZBFB. However, there is still uncertainty associated with using the ultimate reserves, as many researchers in this field argue that this should be replaced by considering the extractable reserves that only considers the amount available in the upper earth's crust and the anthropogenic stock by valuing their potential on fulfilling for human purposes [50]. As a large amount of bromine is refined from the dead seas on the surface of the Earth's crust and due to its usage in multiple human activities, the relative CF for bromine can vary by using different methods.

It is also important to note that based on feedback from the three flow battery manufacturers engaged in this project, all three aim to reuse electrolyte from decommissioned units as the electrolyte in new units, after minor balancing of the electrolyte chemistry. This implies that the ADP associated with flow battery electrolytes is primarily associated with new cumulative flow battery capacity only, not the replacement of decommissioned capacity. Note that since the project team performed the analysis on a lifetime-normalized per-kWh of energy capacity basis, no distinction was made between decommissioned and new capacity. Incorporating this distinction would require assumptions for energy storage deployment between now and a future period.

3.2.2 Normalized Materials and Manufacturing Life Cycle Impact Assessment Results Excluding Accessories

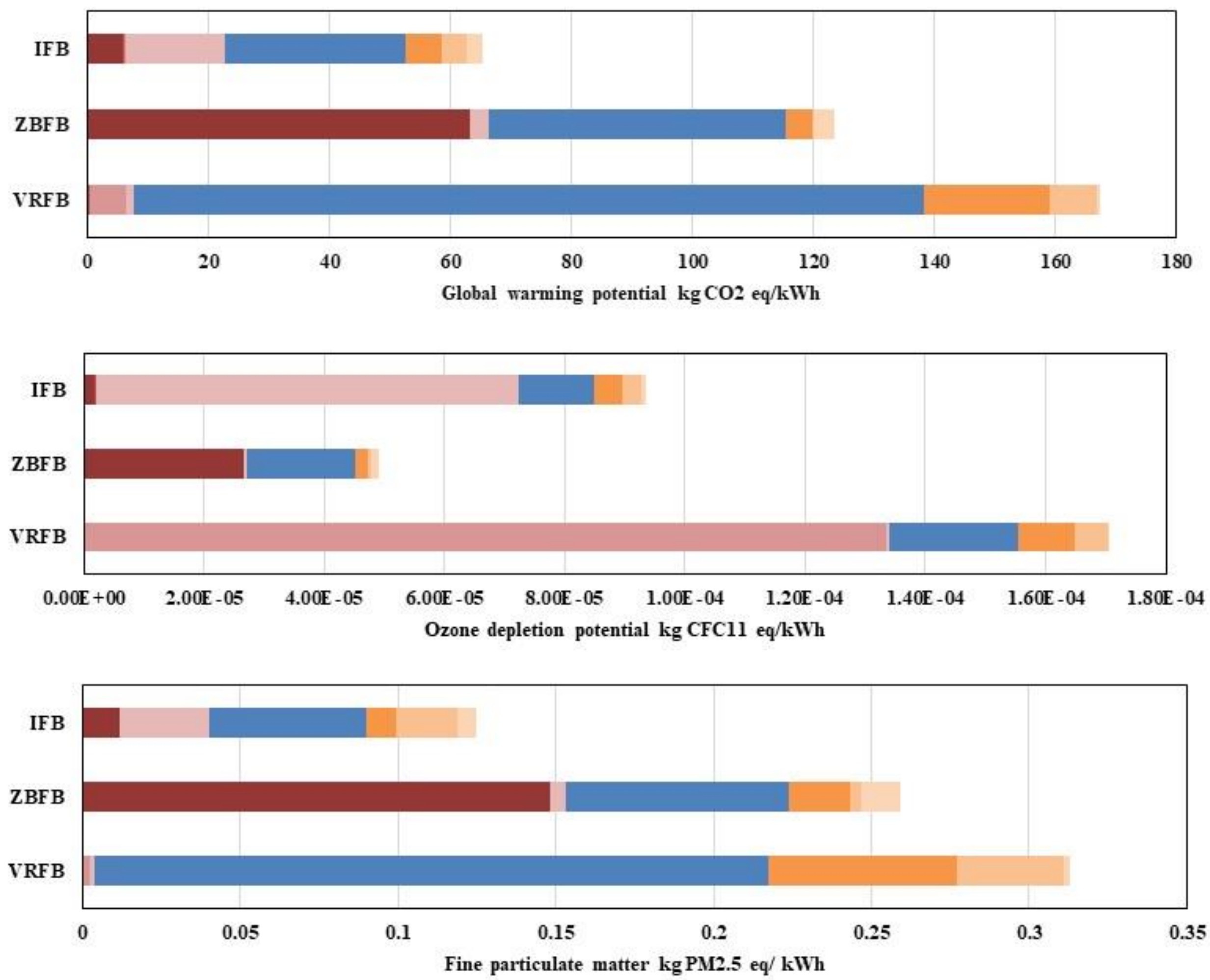
Because the details on data provided by the three manufacturers took into account different classes of components, a standardized battery system boundary with a comparable constitution of components was critical for comparison not only between different flow batteries but also with other battery technologies. The normalized LCIA results of the three flow batteries is presented when focusing only on their core components – that is, avoiding counting the environmental impacts associated with the cell stack accessories and balance of plant accessories. Cell stack and balance of plant accessories were influenced mainly by the design choices of particular flow battery units and were not necessarily a core characteristic of a given technology. Different unit design choices can change the material types and magnitudes used for battery accessories, whereas core components cannot be easily changed or substituted for a given flow battery chemistry. **Error! Reference source not found.** d isplays the results of all impact categories considered (GWP, ODP, PM, AP, EP, Ecotoxicity, CED, and ADP) in this report and provide a comprehensive sense of the three flow batteries performance on each impact category.

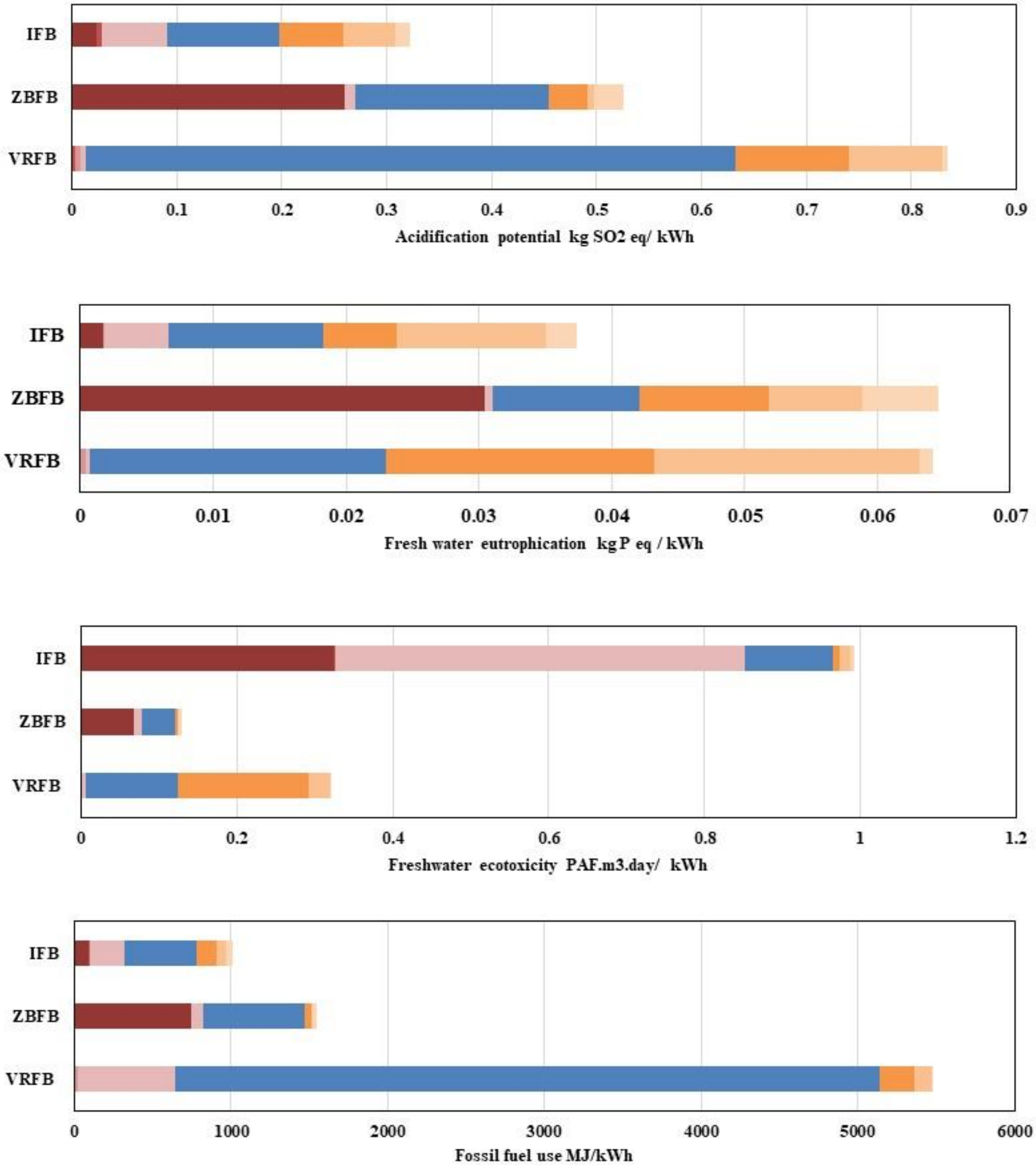
In the displayed results, the major contributions to impact categories such as the GWP, PM 2.5, AP, EP, and CED were were caused by the accessories which consume a large amount of steel. Steel in each flow battery was primarily used for the supporting structures but not for the core functioning of the battery. Manufacturers use steel for accessories because it is widely accessible, has promising mechanical behavior, and relatively low cost. However, the large amount of steel produced in developing countries using nonrenewable sources such as fossil fuels as the major component in their electricity mixes will trigger high environmental impacts. Without considering those accessories, it is clear the overall impacts for those flow batteries decreased a great deal, especially for the ZBFB.

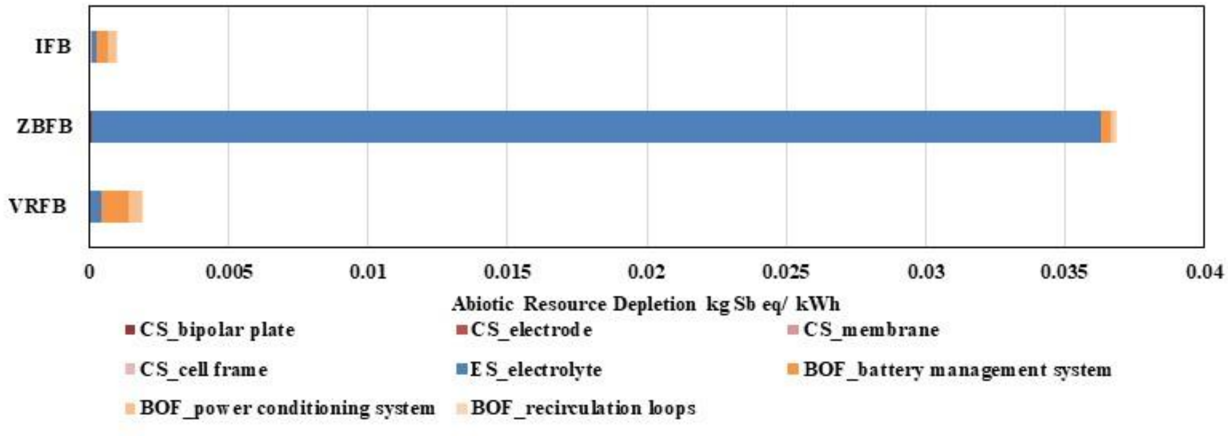
For the VRFB, the remaining issues on material intensity were primarily caused by the vanadium pentoxide production, the core materials used as the active species on electrolyte. As the vanadium pentoxide is mostly a by-product of the steel production process or crude oil production process, the impacts allocated considering those primary production processes contributed significantly to the total environmental impact. There is no established inventory data for the vanadium pentoxide production in any official LCI data source. Therefore, the project teams data source was a review of the academic and industrial literature review associated with the vanadium pentoxide production that still has uncertainties without considering the temporal and geological sensitivities. This indicates that a unified and systematic LCI data for vanadium pentoxide is urgent and greatly needed.

For the ZBFB, the remaining concerns were the bromine used in electrolyte for its high ADP and the titanium used for the bipolar plate manufacturing. The special design of the bipolar plate on ZBFB avoided the assembly of a separate electrode and cell frame, which eliminated the use of a membrane and therefore required fewer materials compared to the other two flow batteries. However, the production of titanium itself can trigger high environmental impacts as shown through the SPA, and finding alternatives materials would be beneficial to decrease the overall impact contributed by the titanium.

Figure 21: Normalized Results of Eight Impact Categories




IFB
ZBFB
VRFB
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
Acidification potential kg SO2 eq/ kWh
IFB
ZBFB
VRFB
0
0.01
0.02
0.03
0.04
0.05
0.06
0.07
Fresh water eutrophication kg P eq / kWh
IFB
ZBFB
VRFB
0
0.2
0.4
0.6
0.8
1
1.2
Freshwater ecotoxicity PAF.m3.day/ kWh
IFB
ZBFB
VRFB
0
1000
2000
3000
4000
5000
6000
Fossil fuel use MJ/kWh



Source: UC Irvine

For the IFB, the remaining issues were due to the polyester resins used as the bulk molding compound for injection molding which presents high impacts on ecotoxicity over the other two flow batteries. The choice of safer organic compounds would help to improve the overall performance of the IFB. Other than the raw materials use and processing methods that contributed to high impacts from the cell stacks and electrolyte, the impacts of the balance of plant were also not negligible on some of the impact categories. For example, the battery management system and the power conditioning system contributed to nontrivial impacts on GWP, eutrophication potential, acidification potential, abiotic depletion potential, and PM 2.5 even though their weight ratio in each battery package is not high. This was primarily caused by the inverter and electronic devices that have complex materials use on heavy metals such as copper, precious metals like gold, and several processing materials like organic materials which also indicate there is space for improvement.

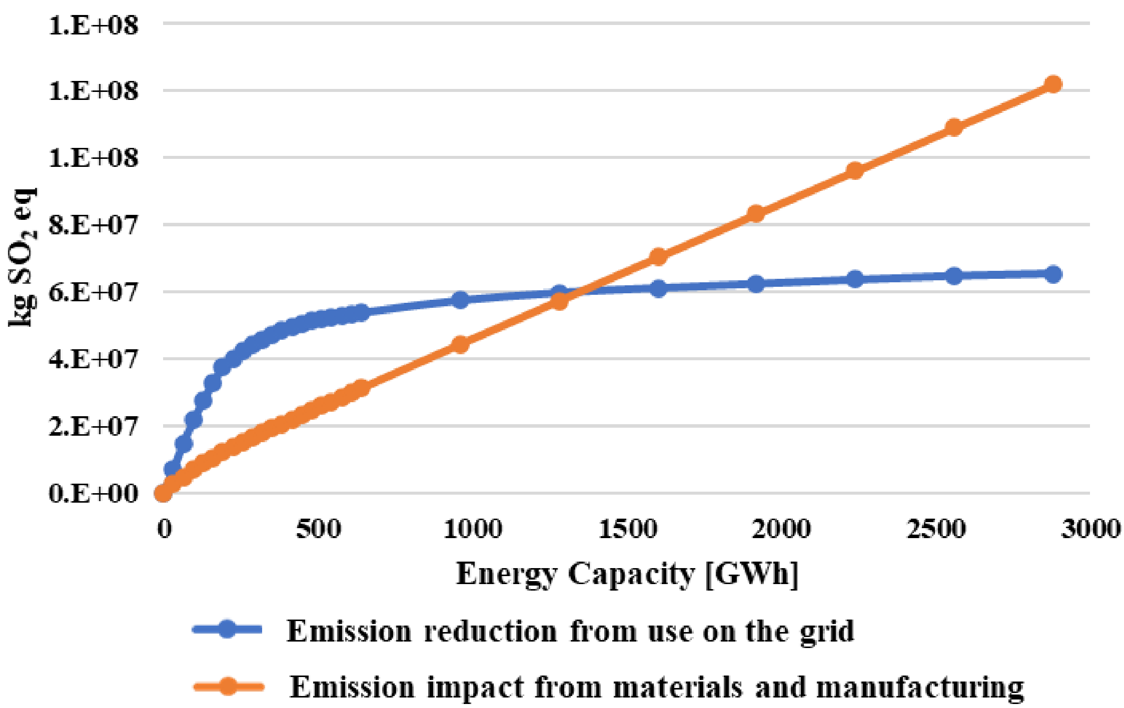
3.2.3 Use-Phase: Analysis of Flow Battery and Electric Grid Interactions

The use-phase refers to the application of batteries for capturing and shifting excess renewable electricity generation that occurs on the electric grid. These results compared the benefits provided from these systems during their operation to the impacts contributed from the materials extraction and manufacturing processes, and how these two elements scaled as more energy storage capacity was deployed. Differences in the rate at which energy storage environmental benefits and impacts scale as more energy storage is deployed indicate the potential for a capacity level where the environmental impacts of these systems outweigh their benefits. Determining whether these thresholds exist and at what capacity level these thresholds occur for different types of environmental impacts is critical for better understanding the role of energy storage in facilitating more sustainable energy infrastructure development and for ensuring that its deployment provides a net environmental benefit. The following set of results addresses this question; while all three flow batteries provide similar levels of environmental benefits through enhancing the uptake of renewable energy resources on the electric grid, VRFB is used to demonstrate this concept for different environmental impact indicators.

The following results show that the environmental impact from materials extraction and manufacturing increased linearly with the energy capacity of the battery installed on the grid. This trend was consistent across all the indicators: since the environmental impacts were assessed on a per-kWh of energy capacity basis, increasing the energy capacity of the installed battery fleet will proportionally increase the per-unit environmental impacts from manufacturing.

By contrast, the reduction in environmental impacts due to the services provided from the battery to the electric grid was more complex. For indicators such as acidification potential, PM, and fossil fuel cumulative energy demand, , the reduction in environmental impacts due to the additional uptake of renewable generation only increased slowly as energy storage capacity was increased above the lower bound of capacity (Figure 22, Figure 23, and Figure 25). This occurred since the additional uptake of renewable energy did not significantly reduce these indicators. Additionally, most of the increased renewable uptake was provided by the first units of energy storage capacity installed. ODP profits increased as the capacity increased since the main contributor of ODP of the grid — biogas usage — was significantly decreasing with the vast amount installation of batteries (Figure 24). The same was true of natural gas usage. PM also did not benefit significantly from energy storage, since the electric grid in the year 2050 configuration did not emit significant amounts of PM due to the only fossil fuel use in California power plants being natural gas, which comprises a small portion of the resource mix.

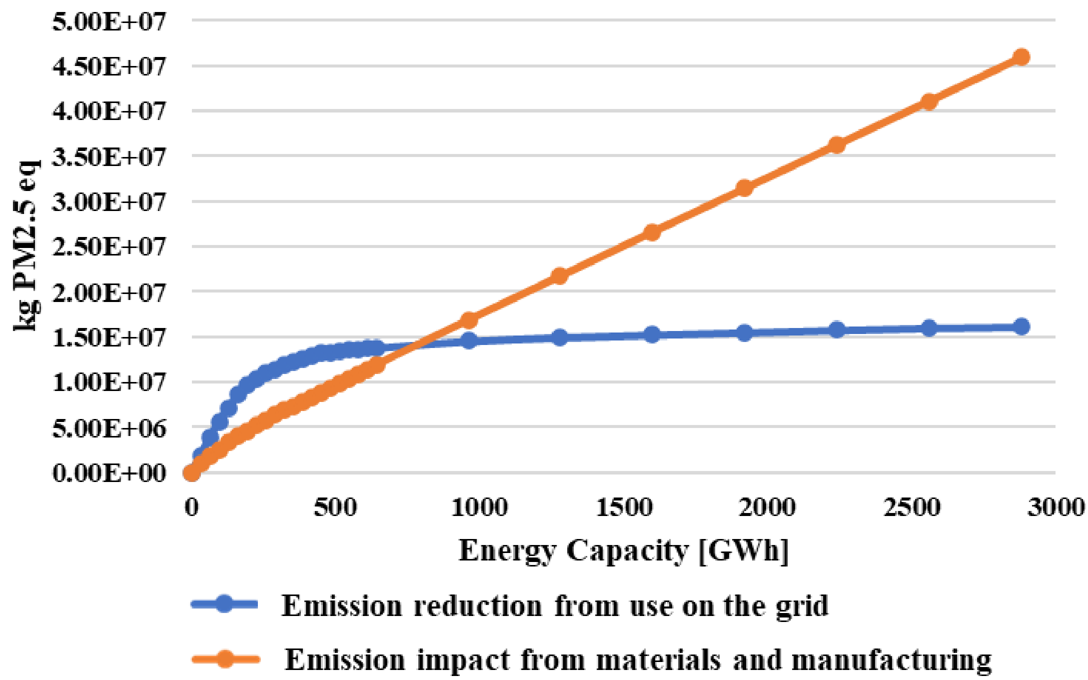
Figure 22: Vanadium-Redox Flow Battery Benefits versus Impacts (2050 Scenario) – Acidification Potential [kg SO2-eq]



Source: UC Irvine

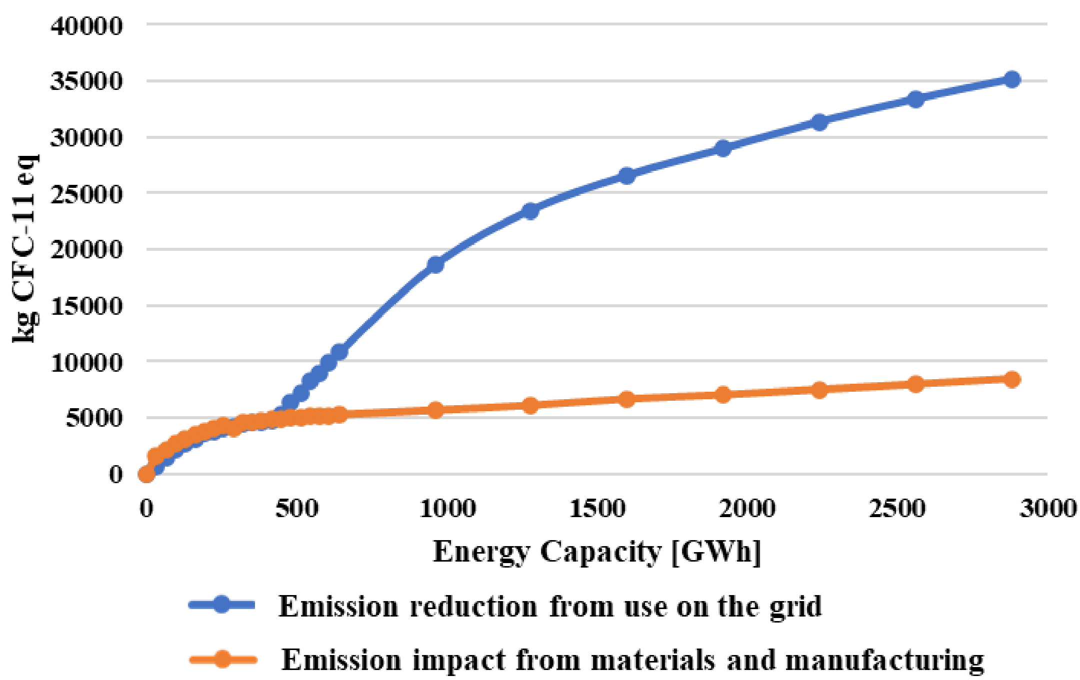
Therefore, when compared against the scaling of impacts from manufacturing, thresholds at which the manufacturing impacts exceeded the grid benefits exist. For ODP, the threshold appeared around 416 gigawatt-hours. For PM, the threshold is around 640 GWh. Fossil fuel cumulative energy demand had a threshold of 960 GWh. It is important to note, however, that while these limits exist, the numerical value of these thresholds still equated to a significant amount of battery units. For example, the threshold for ODP equated to roughly 200,000 individual commercial VRFB installations.

Figure 23: Vanadium-Redox Flow Battery Benefits versus Impacts (2050 Scenario) – Particulate Matter [kg PM2.5-eq]



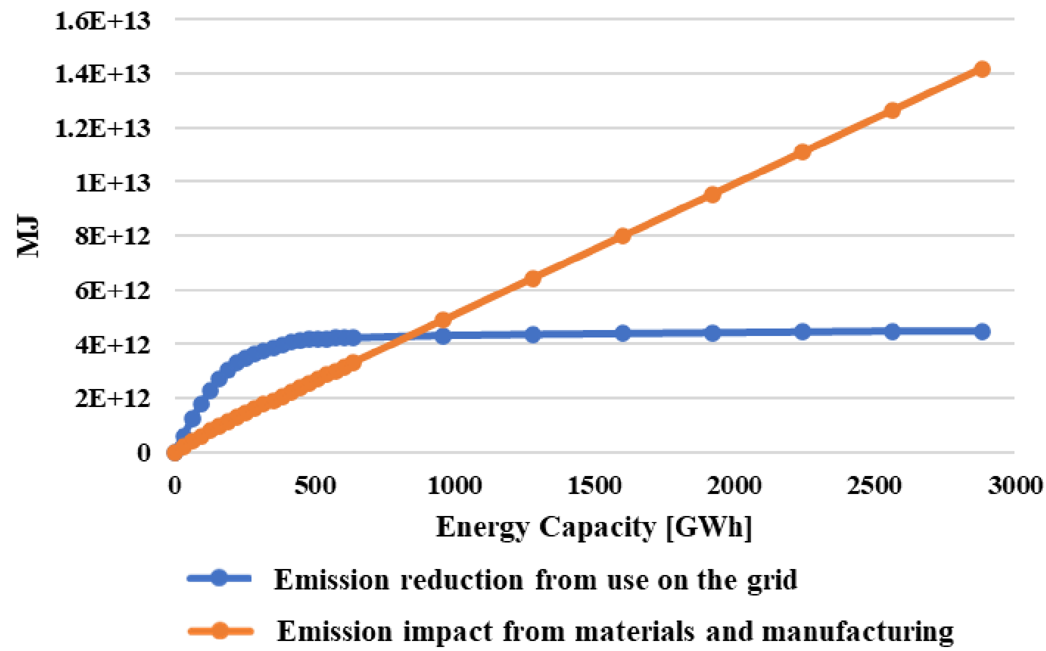
Source: UC Irvine

Figure 24: Vanadium-Redox Flow Battery Benefits versus. Impacts (2050 Scenario) – Ozone Depletion Potential [kg CFC 11-eq]



Source: UC Irvine

Figure 25: Vanadium-Redox Flow Battery Benefits versus Impacts (2050 Scenario) Fossil Fuel – Cumulative Energy Demand [MJ]



Source: UC Irvine

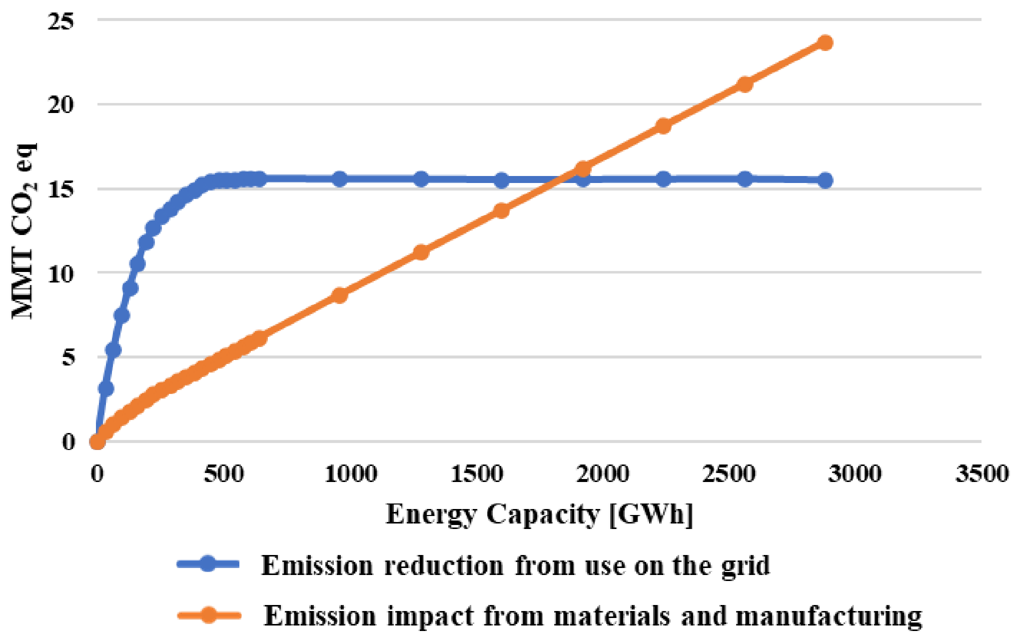
For GWP, the energy capacity threshold beyond additional capacity caused the impacts to outweigh benefits, but the threshold was much higher than for the acidification potential, PM, and cumulative energy demand indicators. The trend of impacts increasing linearly with energy storage capacity and benefits increasing up to an asymptotic point were still present, but since the GWP indicator benefits significantly from the additional uptake of otherwise curtailed renewable electricity generation displacing the use of natural gas on the electric grid, the benefits outweighed the impacts for a large range of energy storage capacities. For GWP, the threshold value was around 1920 GWh (Figure 26).

For the eutrophication and ecotoxicity indicators, the deployment of flow battery energy storage systems did provide a benefit from the displacement of natural gas usage with otherwise curtailed renewable generation, however, this benefit decreased as more energy storage capacity was installed (Figure 27 and Figure 28).

For eutrophication and ecotoxicity, the initial energy storage units that were installed cause the benefit to be negative – meaning that the use-phase contributes an impact. This occurred since biogas resources were modeled as substituting for natural gas usage in combined cycle gas turbines. The initial units of energy storage alter the electric grid dispatch such that more biogas can be used, however, biogas contributes significantly towards eutrophication and ecotoxicity impacts. As more energy storage is installed, combined cycle power plants start to be displaced by otherwise curtailed wind and solar generation, and biogas usage decreases. This caused the trend for the benefit to reverse and become positive.

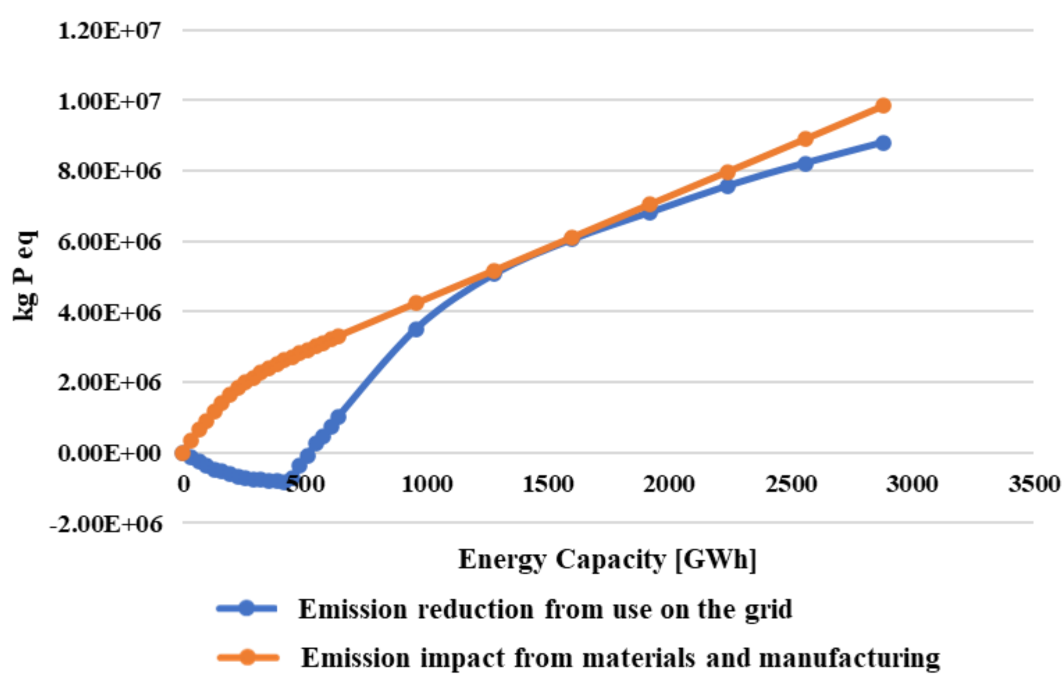
For eutrophication, an energy storage capacity of 1280 GWh allowed the use-phase benefit to offset the impacts from manufacturing and material use. However, the benefit did not exceed the impact over the range of capacities examined here. For ecotoxicity, the use-phase benefit offset the impacts from manufacturing and material use at a capacity of 640 GWh.

Figure 26: Vanadium-Redox Flow Battery Benefits versus Impacts (2050 Scenario) – Global Warming Potential [kg CO2-eq]



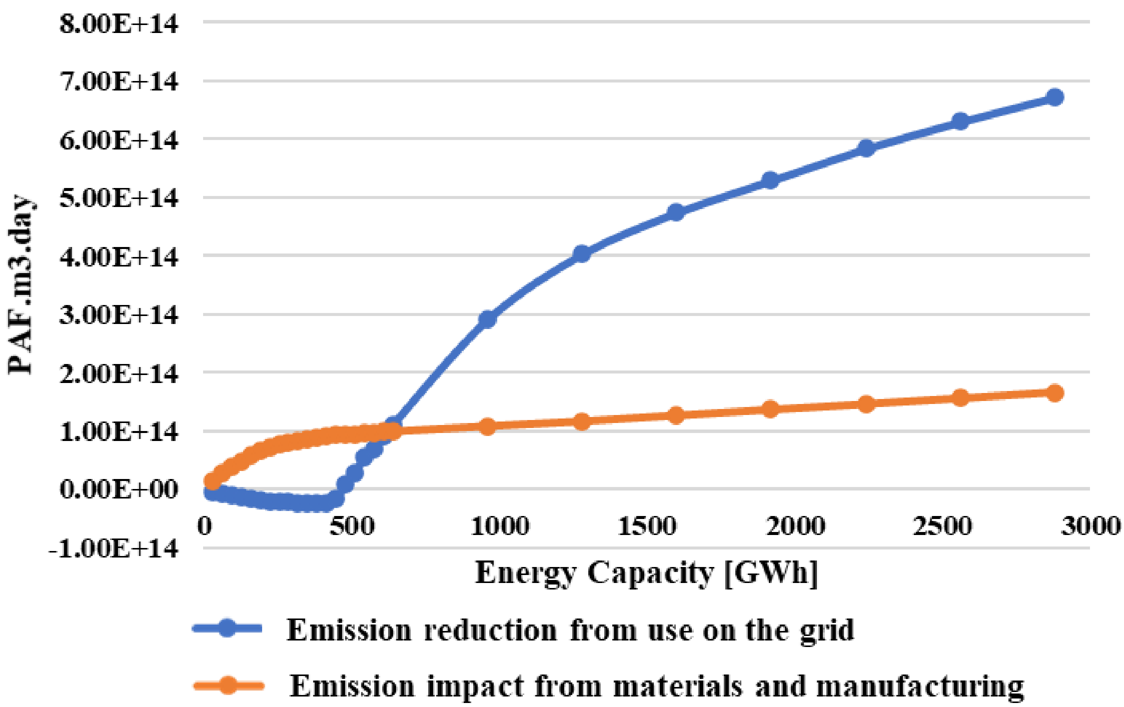
Source: UC Irvine

Figure 27: Vanadium-Redox Flow Battery Benefits versus. Impacts (2050 Scenario) – Eutrophication [kg PO4-eq]



Source: UC Irvine

Figure 28: Vanadium-Redox Flow Battery Benefits versus Impacts (2050 Scenario) – Ecotoxicity [PAF·m3/kg]



Source: UC Irvine

3.3 Human Health Impact Assessment Results

3.3.1 Endpoints Assessment for Flow Battery Production

The results for the human health impacts of the battery production processes for the different endpoint indicators are presented here. Note that for these results, the units are presented in DALY per kWh of battery energy capacity.

3.3.1.1 Human Health Effects of Global Warming Potential

The midpoint and endpoint characterization were both calculated by ReCiPe 2016 (H) and the midpoint indicator is defined in kg CO_2 eq. The endpoint indicator is DALYs, for which the midpoint to endpoint conversion factor is $9.28E10^{-7}$. The results here are normalized per kWh of battery energy capacity.

The graph in Figure 29 (a) shows that the VRFB exhibited the highest impact on human health impact from global warming potential, while the IFB exhibited the lowest impact. The biggest contribution of VRFB was from the vanadium electrolyte, which is associated with the vanadium pentoxide production. However, note that this process has uncertainty in terms of the process data used that may influence the relative impact of VRFB. For the ZBFB, the high impacts were mostly contributed by the use of energy sources such as hard coal, heat, and electricity during the bipolar plate production and processing using titanium as the primary material. The contributions to each component in the IFB were quite similar, with the cell frame and tank ranked as highest due to the production of complex polymers.

3.3.1.2 Human Health Effects Caused by Ozone Depletion Potential

The midpoint and endpoint characterization both take ReCiPe 2016 (H), the midpoint indicator is kg CFC-11 eq, and the endpoint indicator is DALYs, which the midpoint to endpoint conversion factor is $5.31E10^{-4}$. The results here were normalized per kWh of battery energy capacity.

The data presented in Figure 29 (b) show that the impact of the VRFB was higher than the ZBFB and IFB. The ZBFB impact was the lowest among the three batteries. The components that contributed towards the high ODP results were different in different flow batteries. For the VRFB, the major contributor was the membrane which used Nafion, a polymer compound. In the ZBFB, the major impact was contributed by the bipolar plate. The cell frame was the major component that contributes to the ODP and the materials used were the glass fiber reinforced polyester resin that was used as the bulk molding compound for injection molding for the IFB. It is important to note that the overall ODP impact was orders of magnitude lower compared to other categories.

3.3.1.3 Human Health Effects Caused by Particulate Matter 2.5

The midpoint and endpoint characterization both take ReCiPe 2016 (H), the midpoint indicator is kg PM2.5 eq, and the endpoint indicator is DALY, which the midpoint to endpoint conversion factor is $6.29E10^{-4}$. The results here are normalized per kWh of battery energy capacity.

The data presented in Figure 29 (c), showing the PM 2.5 results indicate that the VRFB has the highest impact due to the cell stack accessories and an electrolyte, and a similar contribution is also shown for the IFB. The ZBFB has the next higher impact due to cell stack accessories and bipolar plate which are related to the metal and alloys production and processing. The drivers of these results are very similar to those of the GWP results: the use of many metals and alloys as accessories.

3.3.1.4 Human Health Effects Caused by Human Toxicity Potential Cancer Effect

The midpoint and endpoint characterization both take USETox v2.0, the midpoint indicator is the number of cases, and the endpoint indicator is DALY, which the midpoint to endpoint conversion factor is 11.5. The results here are normalized per kWh of battery energy capacity.

The information presented in Figure 29 (d) shows that based on carcinogenesis, ZBFB had the highest human health effect among the three. The electrolyte was the major contributor due to the use of bromine. The use of metals such as titanium and steel in the bipolar plate and cell stack accessories also contributed substantially to the overall impact. VRFB and IFB had almost the same effect. The electrolyte had the highest contribution to the overall impacts of VRFB. The cell frame contributed the most to IFB. It is important to note that the overall HTP-Cancer impact was orders of magnitude lower compared to other categories.

3.3.1.5 Human Health Effects Caused by Human Toxicity Potential Non-cancer Effect

The midpoint and endpoint characterization both take USETox v2.0, the midpoint indicator is the number of cases, and the endpoint indicator is DALY, which the midpoint to endpoint conversion factor is 2.7. The results here are normalized per kWh of battery energy capacity.

The information presented in Figure 29 (e) shows that the IFB had the highest noncancer impact. The cell frame had a very high impact because of the glass fiber reinforced polyester resin bulk molding compound used for injection molding. The membrane contributed the most to the effect of VRFB and the bipolar plate was the main reason for the ZBFB effects. It is important to note that the overall HTP-Non-cancer impact was orders of magnitude lower compared to other categories.

3.3.1.6 Summarized Life-Cycle Impact Assessment Human Health Results

From the results shown above, the human health effects from global warming potential and particulate matter have a higher score than ozone depletion potential impacts. This occurs because the chemicals that battery manufacturing processes emit have low impacts in terms of ozone depletion potential.

In the comparison of three battery types, it is interesting to note that there is no specific kind of battery that is the best or worst in every category (Figure 29). For instance, the zinc-bromide flow battery has the lowest score in terms of noncancer effects, but its score for cancer-related effects was the highest among the three kinds of batteries. Different methods have different ways to characterize the emissions, which results in the VRFB having the highest score when using ReCiPe (2016), but its score is between that of the other two batteries.

3.3.2 The Endpoints Assessment for Flow Battery Use-Phase

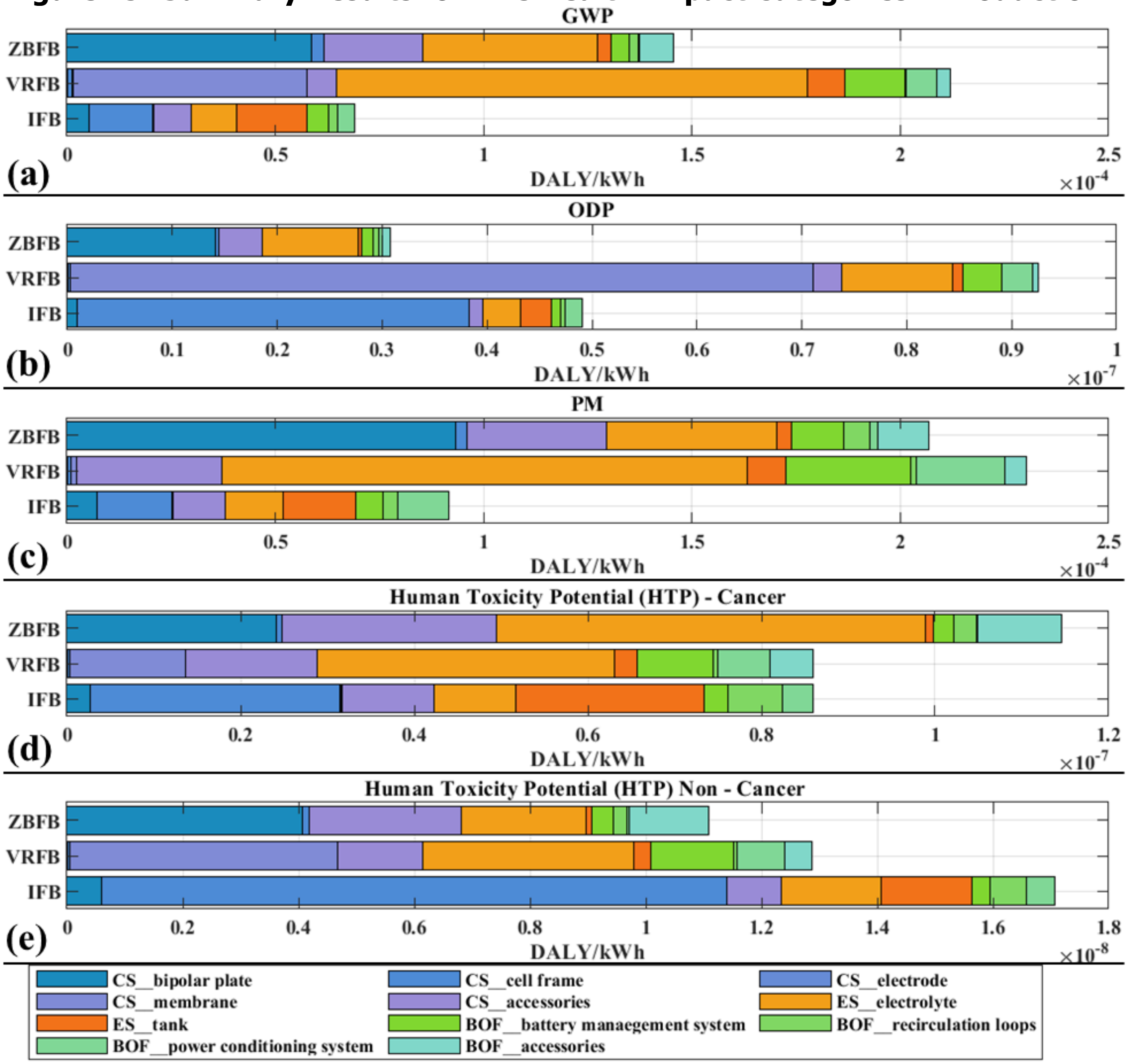
This section presents the results for the human health effect assessment of flow batteries due to the use-phase stage, and these results were compared to those for production (provided in more detail above). Note that the use-phase results do not depend on the flow battery type, but rather the grid mix, since all three flow batteries have nominally the same round-trip efficiency.

The human health impacts of flow battery use phase were translated from the environmental impacts of the flow battery use phase. The environmental impact of the batteries during the use-phase was based on the inefficiency of the battery during its charging and discharging processes. As a result, environmental impacts can be traced back to the corresponding electricity generation resources that drive these processes. Since the efficiency of the three flow battery types was assumed the same, the use-phase impact was the same for three batteries with the same energy capacity. This use-phase impact was compared to the production impact of each specific battery type. All the impacts are normalized to per-MWh so that these can be compared.

Two methods were used to calculate the endpoint indicator with the unit DALY. The impact of GWP, ODP, and PM were translated by using ReCiPe 2016 (H). USETox was used to determine cancer and noncancer human toxicological effects. The comparison of the cradle-to-gate processes and use-phase impacts are shown in Figure 30 for GWP, ODP, and PM. Two scenarios of different grid mixes by the year 2030 and the year 2050 were considered. The 2030 scenario stood for a renewable penetration of 50 percent and the 2050 scenario represented the 90 percent renewable penetration grid. The impact results in Figure 30 are normalized on a per-MWh of electricity taken in by the battery over its entire lifetime. Note that these were different units than those used for the battery cradle-to-gate results.

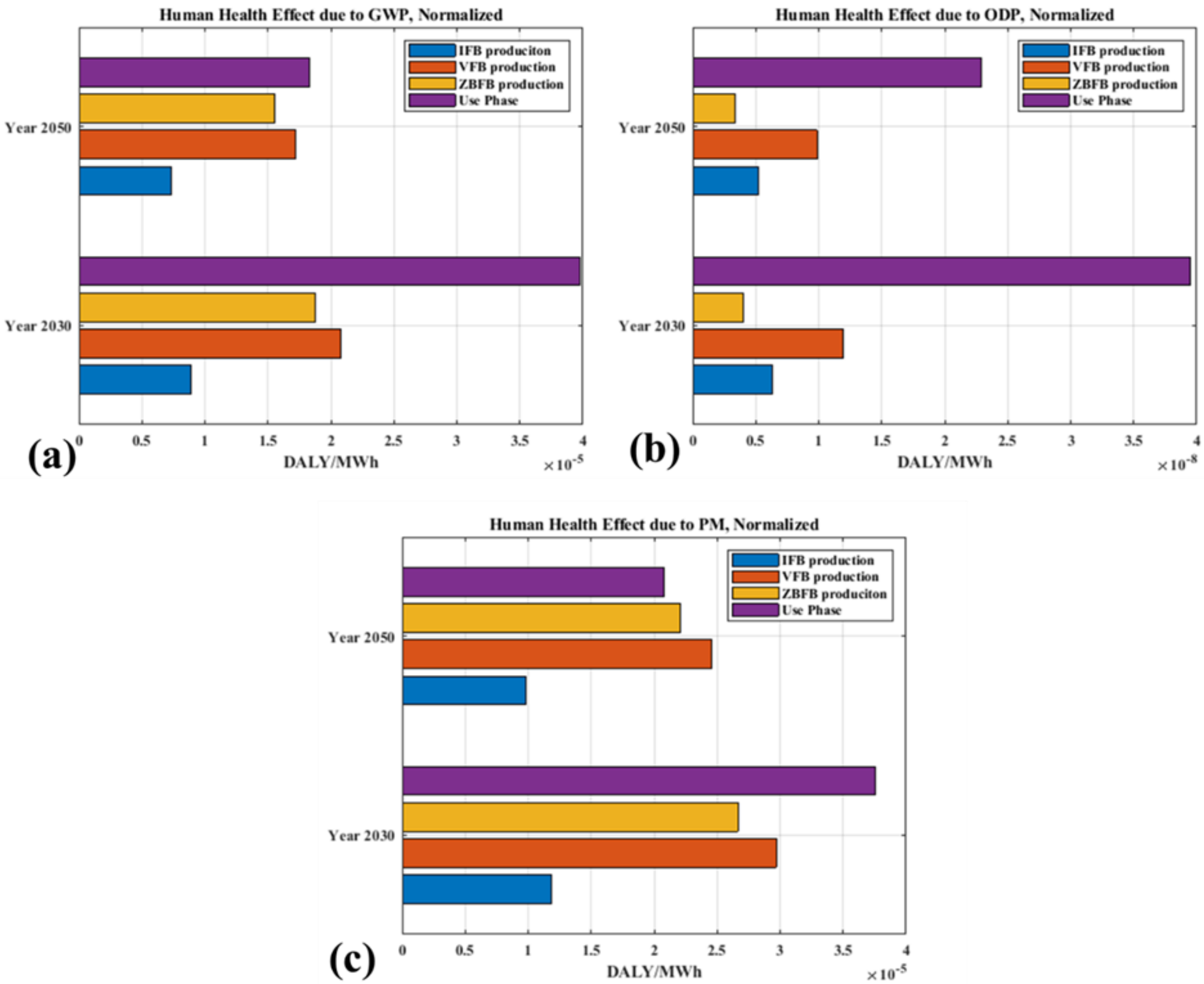
Generally, ODP did not contribute much DALYs among all the five indicators considered in this case.

Figure 29: Summary Results for Five Health Impact Categories – Production



Source: UC Irvine

Figure 30: Production versus Use-Phase Comparison for Health Impacts



Source: UC Irvine

Different energy grid mixes can vary the results. The normalization changes the relative impact of the cradle-to-gate process. The total impact of cradle-to-gate processes for a certain amount of battery capacity is assumed to be the same. However, because of the different grid scenarios in which batteries were deployed, the amount of electricity the batteries need to provide for balancing the grid is different. In the year 2050 target case, since the penetration of renewable energy resources was higher than the year 2030 target, batteries needed to provide more electricity for shifting the load. So, the overall delivered electricity was more than the case for 2030, which induced the lower normalized cradle-to-gate process impact of the year 2050.

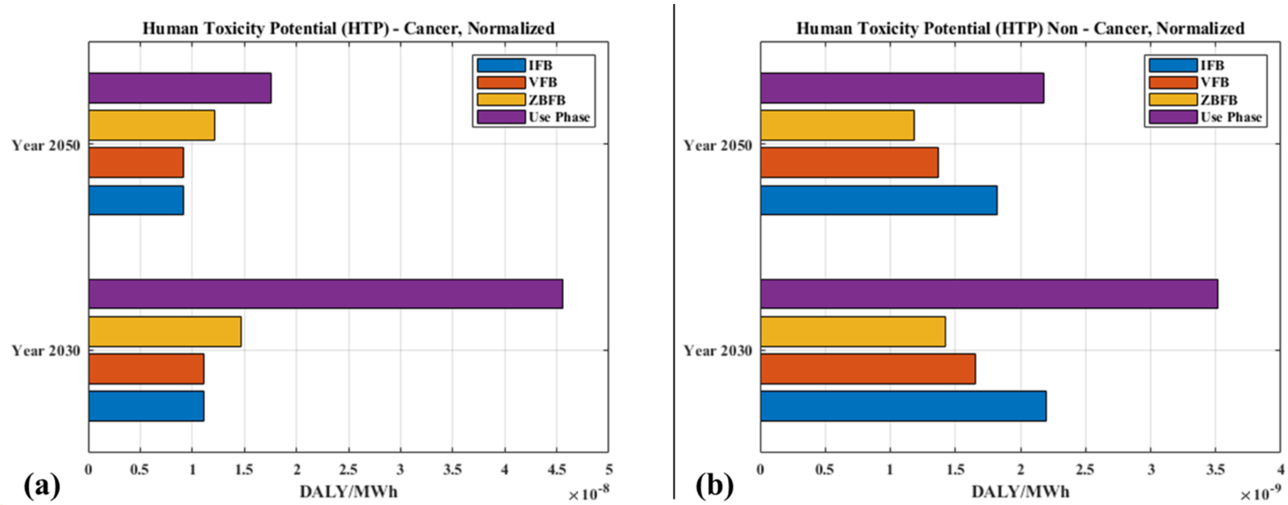
Note that for these results, the project team assumed that the battery was operating to smooth the net load profile of the electric grid and therefore assumed to charge with the grid-average mix of electricity. In 2030, natural gas was still a large part of the grid mix, causing the use-phase to contribute to health impacts from GWP. For the year 2050 case where the grid was heavily decarbonized, the use-phase impacts were comparable to those of battery production.

Among all indicators, the differences between the impact of cradle-to-gate and use-phase were the largest for ODP. Use-phase impacts were more than three times higher than the cradle-to-gate impacts for 50 percent renewable energy penetration. For the grid with high renewable penetration, use-phase impacts were still double the potential impacts attributable to the cradle-to-gate processes. The manufacturing process of the flow battery did not release many chemicals that cause ozone depletion. The use-phase impact was mainly from the biogas usage in the combined power and heat power plant, which was not a significant impact of the use-phase (Figure 32).

The relative human health impacts due to PM2.5 not only vared between different grid mixes but also changed between different kinds of flow batteries. ZBFB and VFB cradle-to-gate impacts were higher than use-phase impacts for low renewable energy penetration in the grid. Use-phase impacts were still higher than IFB impacts. Natural gas usage drove the use-phase impacts. The reduction of use-phase impacts from 2030 to 2050 helped the use-phase impact become smaller than the cradle-to-gate impact of ZBFB and VFB. The decrease in the use-phase impact came from the reduction of natural gas usage.

The comparison of the cradle-to-gate process and use-phase impact are shown in Figure 31 for HTP (cancer) and HTP (noncancer). In general, the use-phase dominated the cancer and noncancer impacts for 2030 and 2050 electric grid mixes.

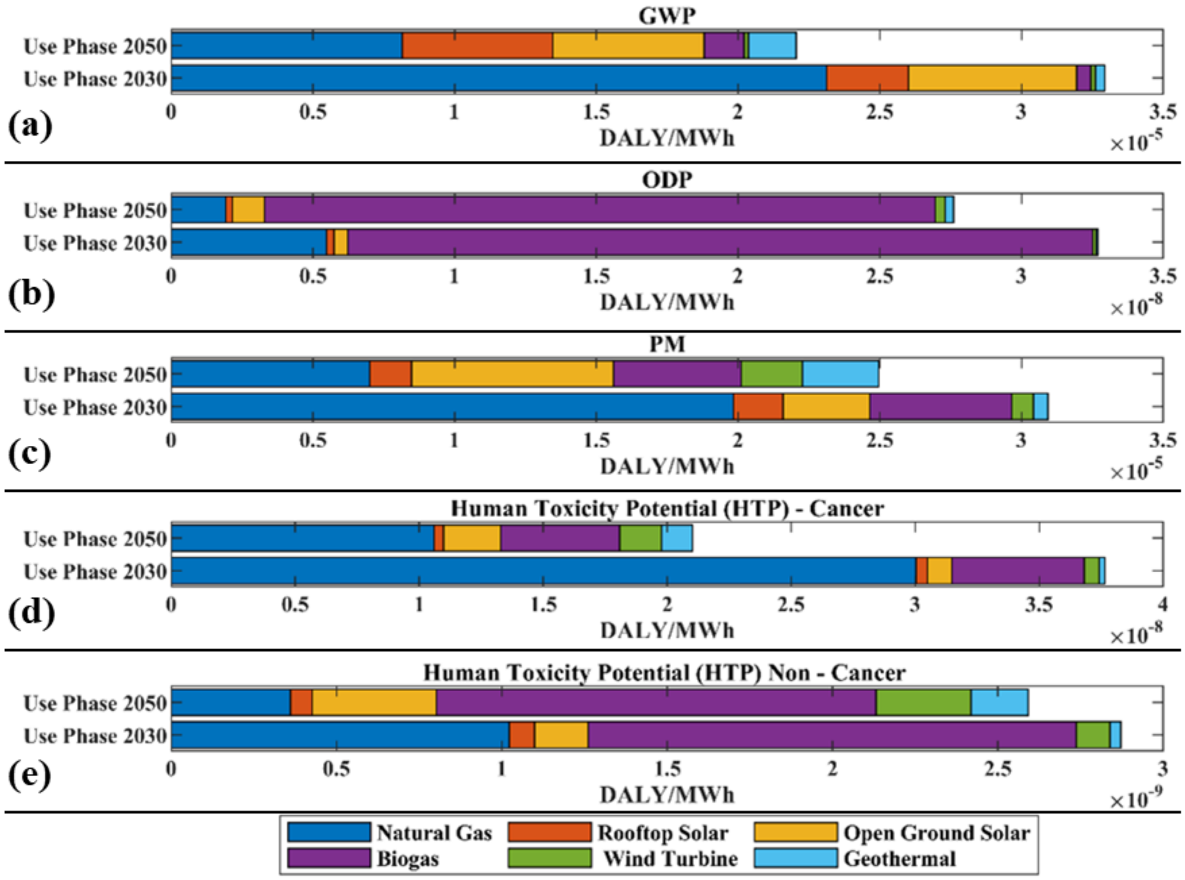
Figure 31: Production versus Use-Phase Comparison of the Human Toxicity Potential Cancer and NonCancer Effect



Source: UC Irvine

Figure 32 presents detailed graphs, including different categories, to explain the results and explore more features of the use-phase.

Figure 32: Use-Phase Contributions to the Human Health Effect



Source: UC Irvine

The flow battery use-phase cancer human toxicity impacts were higher than the cradle-to-gate stage for all three flow batteries. According to the results from SimaPro, the digester sludge treatment process [51] from the biogas usage had the highest contribution to the overall use-phase impact. Batteries were assumed to be charged with grid-average electricity, with the 2050 case representing a decarbonized grid. Even in a decarbonized grid, however, biogas was still used to a small extent as a carbon-neutral (in use) alternative to conventional natural gas for power plants to perform peaking functions. This resource, however, still had emissions from its life cycle due to effects such as leakage. Another interesting finding in the graphs is that the impacts increased because of the higher penetration of wind turbines and solar panels and the impact reduction of the natural gas and biogas were comparable in the USETox indicators. The slag process from unalloyed electric arc furnace steel treatment used in the wind turbine contributed much to the process [52]. The treatment of red mud from bauxite digestion was the primary driver for the increase of the open ground solar panel installation [53]. The biggest driver in the geothermal power plant was the slagging process. The impact growth of wind, solar, and geothermal outweighed the impact drop of natural gas and biogas usage. For noncancer human toxicity, biogas and open ground solar were the most prominent impact contributor. The influence came from the treatment of digester sludge [51] and the treatment of sulfidic tailing from open solar installation [54].

3.3.3 GreenScreen®-Based Chemical Hazard Assessment

3.3.3.1 Results for Primary Materials

The primary chemicals used in each flow battery and their GreenScreen®-based benchmark scores are provided in Table 15.

Table 15: GreenScreen®-Based Results for Primary Chemicals Used in Flow Battery Systems

Battery Type	Chemicals Name	BM Score
VRFB	Vanadium pentoxide	1
	Glass fiber (E glass)	1
	Hydrochloric acid	2
	Sulfuric acid	2
	Polyethylene	2
	Polypropylene	2
	Carbon fiber felt	3
	Graphite	4
	Nafion	U
ZBFB	Titanium	2
	Zinc bromide	2
	Bromine	2
	Polyethylene	2
IFB	Glass fiber (E glass)	1
	Manganese dioxide	2
	Hydrochloric acid	2
	Iron(II) chloride	2
	Polyvinylchloride	2
	Carbon fiber felt	3
	Graphite	4
	Polyester resin	U
	Vinyl ester resin	U
	Potassium chloride	U
	Isophthalic polyester	U

Source: UC Irvine

Based on these results, the primary materials used in the ZBFB system seem to be the least toxic as there wereno BM-1 chemicals (chemicals should be avoided) used, yet all were BM-2, for which safer substitutes should also be identified. When compared with the VRFB and IFB system, there were only four major chemicals used, which were titanium for the bipolar plate, zinc bromide and bromine for the electrolyte, and polyethylene for the cell frame, tank, and pipes. The integrated design of the titanium bipolar plate avoided the use of electrode and membrane, which reduced the number of chemicals used in the system. The chemical used for the cell frame, tank, and pipes was polyethylene, not a complex polymer or composite. For VRFB, there were two BM-1 chemicals: vanadium pentoxide was one core chemical used as the electrolyte, and glass fiber was one compositional material used in the bulk molding compound to produce the cell frame. Looking closely at the hazard endpoints that trigger the BM scores, vanadium pentoxide presented high potential on mutagenicity and the glass fiber was classified as a potential carcinogen. The graphite used to manufacture the bipolar plate was deemed as a safer chemical that receives a BM-4 and the Nafion® used as the membrane was assigned a BM-U due to lack of data.

Similar to VRFB, the glass fiber used in the cell frame in the IFB as a bulk molding compound for injection molding was classified as a BM-1 chemical. The electrolyte used in IFB contained three BM-2 chemicals (hydrochloric acid, iron chloride, and manganese dioxide) and one BM-U chemical which is potassium chloride. One important distinction on materials used in IFB is that the polymers applied in the bipolar plate, cell frame, tank, and pipes such as polyester resin, vinyl ester resin, and isophthalic polyester were synthetic polymers with complex processing routes. The use of complex polymers leads to no available toxicity data for classification as the molecular weight for polymers is too large to be biologically effective, hence they were generally considered to have low toxicity but highly persistent and very recalcitrant against biodegradation.

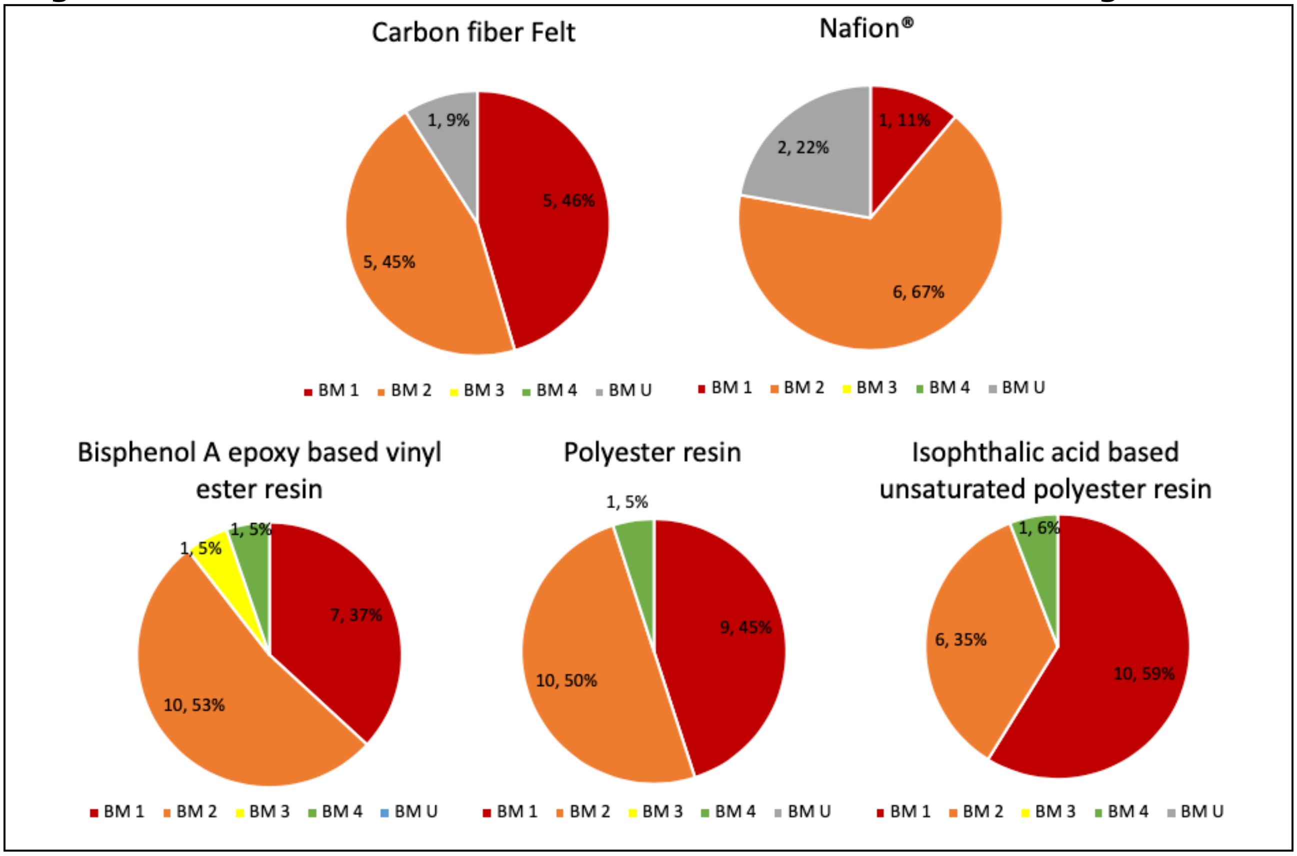
3.3.3.2 GreenScreen®-based Results for Processing Materials and Compositional Materials

To assess polymers and other complex materials with no available information, the research team expanded the system boundary by including the processing chemicals or compositional chemicals used in the production chain. By doing so, life cycle thinking was also integrated as the targeted chemicals were not only associated with the assembly and use of flow batteries, but the related materials used during the manufacturing stages were also considered. Based on the capability of ecoinvent to provide extensive data on up-stream chemicals and review of pertinent research articles and industry reports [48,51–78], the primary materials were expanded for further assessment.

The GreenScreen®-based results for selected processing materials which are carbon fiber felt, Nafion®, bisphenol-A epoxy-based vinyl ester resin, polyester resin, and isophthalic acid based unsaturated polyester are shown in Figure 33. These results indicate that many of the processing materials used in the five selected primary materials were chemicals of high concern. For clarification, each processing chemical used in one primary chemical was only counted once to avoid double-counting though it is possible for the processing chemicals to be used several times in different processing routes. There were in total eleven processing materials used to manufacture the carbon fiber felt: five of them received BM-1 (45 percent), five of them received BM-2 (45 percent) and one of them received BM-U (5 percent). In contrast, if solely looking at the carbon fiber felt, it was classified as a BM-3 chemical, which indicates the use of carbon fiber felt during the assembly and use-phase of flow battery only presents minor adverse effects. However, people working in the upstream manufacturing chains for carbon fiber felt production may be exposed to a highly hazardous environment as several of the processing chemicals were chemicals of high concern, and the use of them should be avoided. For the Nafion® membrane, six of the processing chemicals were BM-2, which accounts for 67 percent of the total chemicals used; one chemical was assigned as BM-

1. The bisphenol-A epoxy-based vinyl ester resin, polyester resin, and isophthalic acid based unsaturated polyester were both classified as BM-U because they are complex polymer resins with no toxicity information available. When broken down into the processing chemicals, many BM-1 and BM-2 chemicals were identified.

Figure 33: Distribution of Benchmark Scores for Selected Processing Materials



Source: UC Irvine

3.3.4 Occupational Health Impact Assessment

The occupational hazard assessment for each flow battery was derived based on the data from REL, PEL, CA PEL, and TLV mentioned before. The exposure limits of the primary materials with available data used in the three flow batteries are summarized in Table 16. The color scheme highlighted in each chemical represents the GreenScreen®-based BM scores based on the chemical hazard assessment. It is observed that the exposure limit of a chemical varied depending on the different standards selected. Among the four data sources, the CA PELs had set the most rigorous limit values for the hydrochloric acid, sulfuric acid, while the TLVs had the lowest threshold for manganese dioxide. For VRFB, the chemical with the lowest permissible exposure limit was the vanadium pentoxide, which is also classified as a BM-1 chemical. This indicates the use of vanadium pentoxide should be very cautious as it is a toxic chemical with high exposure potential in the workplace. For ZBFB, the bromine was the only chemical with available data and its associated exposure limit was also relatively low compared to other chemicals assessed. For IFB, the manganese oxide used in the electrolyte was the chemical with the lowest exposure limit especially in TLVs with a value of only 0.02 mg/m^3.

Table 16: Workplace Exposure Limits on Primary Materials Used in Three Flow Batteries

Materials Use		RELs (mg/m³)	PELs (mg/m³)	CA PELs (mg/m³)	TLVs (mg/m³)
VRFB	Bipolar Plate				
	Graphite	2.5	5	5	2
	Electrode				
	Carbon Felt	3.5	3.5	3.5	3
	Electrolyte				
	Vanadium Pentoxide	0.05	0.1	0.05	
	Hydrochloric acid	7	7	0.43	2.8
	Sulfuric acid	1	1	0.1	0.2
ZBFB	Electrolyte				
	Bromine	0.7	0.7	0.7	0.7
IFB	Bipolar Plate				
	Graphite	2.5	5	5	2
	Electrode				
	Carbon Felt	3.5	3.5	3.5	3
	Electrolyte				
	Manganese dioxide	1	5	0.2	0.02
	hydrochloric acid	7	7	0.43	2.8

High values are preferred. Red = BM 1, Orange = BM 2, Yellow = BM 3, Green = BM 4.

Source: UC Irvine

3.4 Material-Based Cost Analysis Results

3.4.1 Baseline Cost Analysis

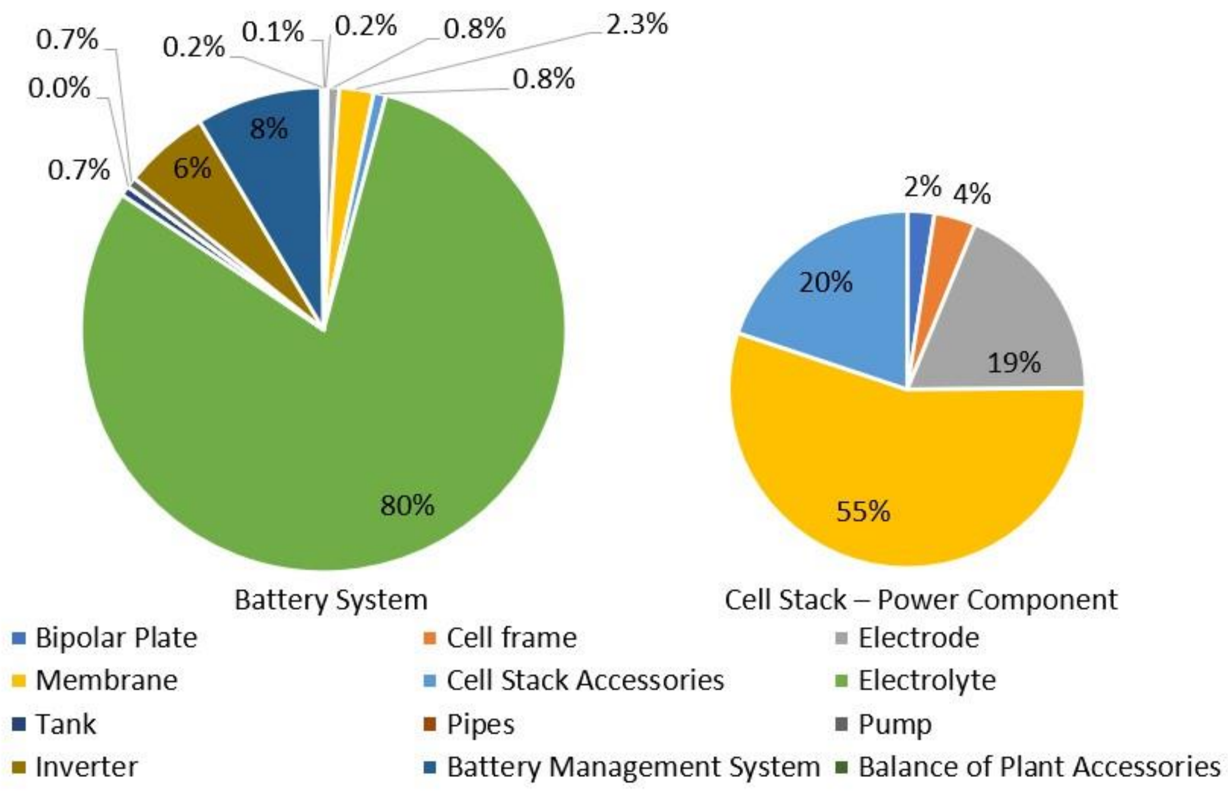
3.4.1.1 Vanadium Pentoxide Flow Battery

The material costs for the VRFB system were calculated using the unit cost input data in Appendix D. Figure 34 provides the cost distribution by component along with an expanded view for the cell stack (power components) only. Due to the high cost of vanadium pentoxide and its use as the major species in the electrolyte, the cost of electrolyte accounted for 80 percent of the total cost. Other components related to energy capacity such as tanks, pipes, and pumps accounted for only 1 percent of total costs. The second-largest share of the total cost was the battery management system (BMS) costs at 9 percent, and the inverter, which also belongs to the balance of plant, contributed 6 percent of the total cost.

Surprisingly, the cost of the whole cell stack, which is related to the power capacity, only contributed 4 percent to the total cost. When only considering the power capacity component, the Nafion® membrane was the highest contributor and accounted for 55 percent of the power capacity subsystem. The Nafion® membrane contributed 2 percent of the total cost. The electrode and cell stack accessories contributed 19 percent and 20 percent of the power capacity subsystem, respectively, but these were almost negligible relative to the total cost.

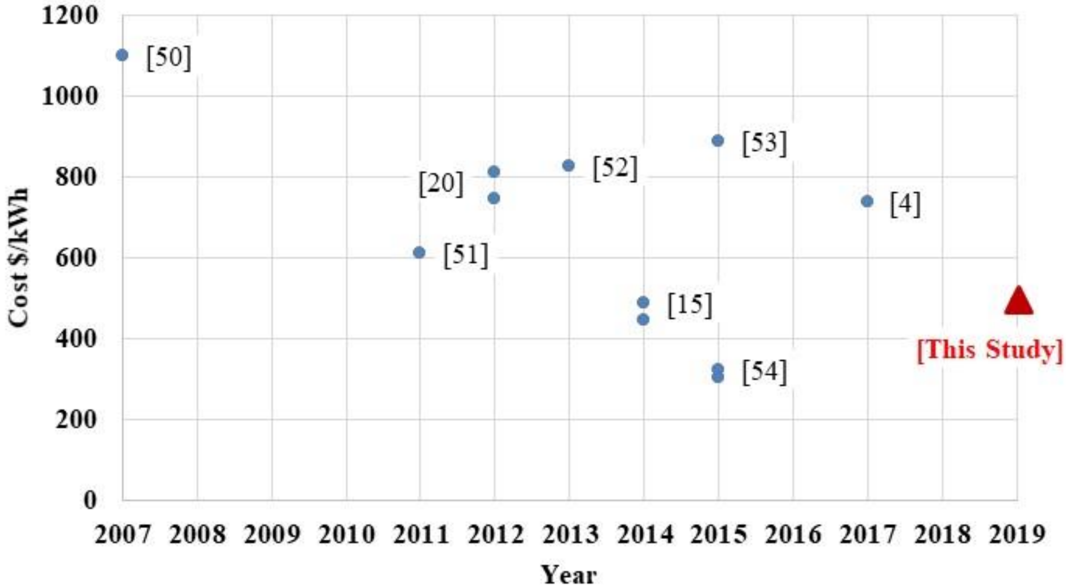
In this analysis, the cost of materials per energy capacity ($/kWh) for a 500 kWh VRFB was $491/kWh. This result was within the range of literature values as shown in Figure 35, which shows the total system cost estimates derived from the literature for an energy-to-power ratio (E/P) = 4h VRFB system. From the literature review, the cost of the VRFB system ranged from $305/kWh to $ $1100/kWh, while the system size and system components considered can vary with different battery designs. The cost information from the literature review is organized by year in Figure 9 and compared to the result of this study. The project team found that there is no clear trend as a function of time, and therefore concluded that the design of the battery system is the primary factor that determines the cost.

Figure 34: Materials Cost Distributed by Component in Vanadium-Redox System



Source: UC Irvine

Figure 35: Flow Battery Cost Literature Data for Vanadium-Redox Flow Battery with an Energy-to-Power ratio of 4 hours



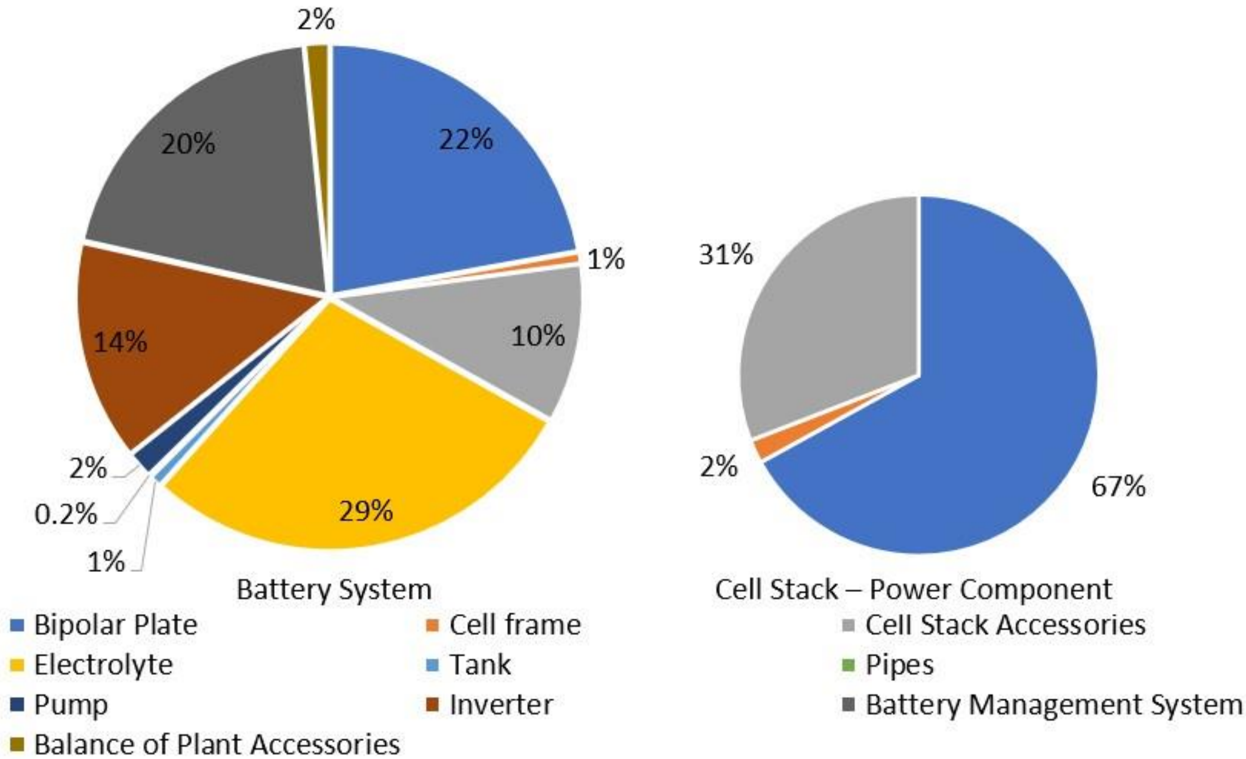
Source: UC Irvine

3.4.1.2 Zinc-Bromide Flow Battery

The cost of materials used for the ZBFB system was calculated using the unit cost input in Appendix D. Figure 36 provides the cost distribution by component along with an expanded view for the cell stack (power components) only. The power capacity components comprised the largest share of total costs as the cell stack accounted for 33 percent of the total cost, followed by components related to energy capacity with a share of 31 percent of the total cost. The BMS accounted for 20 percent of the total cost, and the percentage for the inverter was 14 percent. The electrolyte and the bipolar platewere identified as cost drivers, as they account for 29 percent and 22 percent of the total cost, respectively. The materials with high prices associated with the bipolar plate and electrolyte were titanium and bromine, respectively. The ZBFB electrolyte does not contribute as much to the total cost as the electrolyte in the VRFB system.

In the analysis, the cost of materials per energy capacity ($/kWh) for a 125 kWh ZBFB is $153/kWh. This result is within the range of literature values: $100-$1000/kWh [29,41,79]. Similar to the VRFB, the ZBFB system cost largely depends on the battery configuration, energy to power ratio, system size, and the level of details considered in the analysis. It is noted that for small residential applications ZBFB, the total installed cost could be as high as $1238/kWh -$2505/kWh for a 4-hr system [80].

Figure 36: Materials Cost Distributed by Component in Zinc-Bromide Flow Battery System



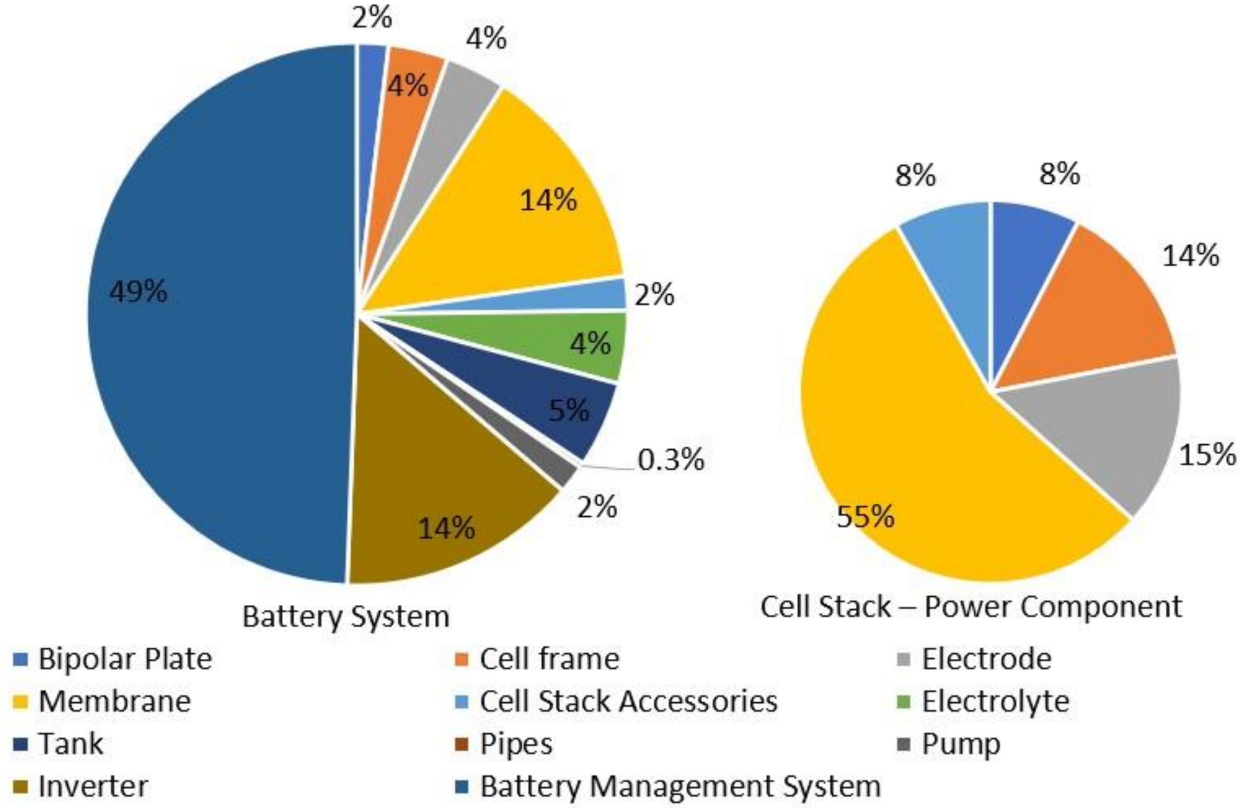
Source: UC Irvine

3.4.1.3. All-Iron Flow Battery

The material costs for the IFB system were calculated using the unit cost input data in Appendix D. Figure 37 provides the cost distribution by component along with an expanded view for the cell stack (power components) only. Contrary to the VRFB and ZBFB, the BMS in IFB contributes to the largest share of the cost at 49 percent of the total cost. The cell stack accounts for 25 percent of the total cost, while the electrolyte only accounts for 5 percent. Another supporting component, the inverter, accounts for 14 percent of the total cost. The cost distribution considering only the cell stack indicates that the membrane accounts for 55 percent, followed by the electrode and cell frame, which account for 15 percent and 14 percent, respectively.

Compared to the only existing literature figure for IFB cost of $175/kWh for a 10 kW/20 kWh IFB system with a production of 1000 units per year [34], the 50kW/ 400kWh system in this report has a similar cost estimate value of $196/kWh.

Figure 37: Materials Cost Distributed by Component in Iron Flow Battery System



Source: UC Irvine

3.4.1.4. Comparison of Three Flow Batteries

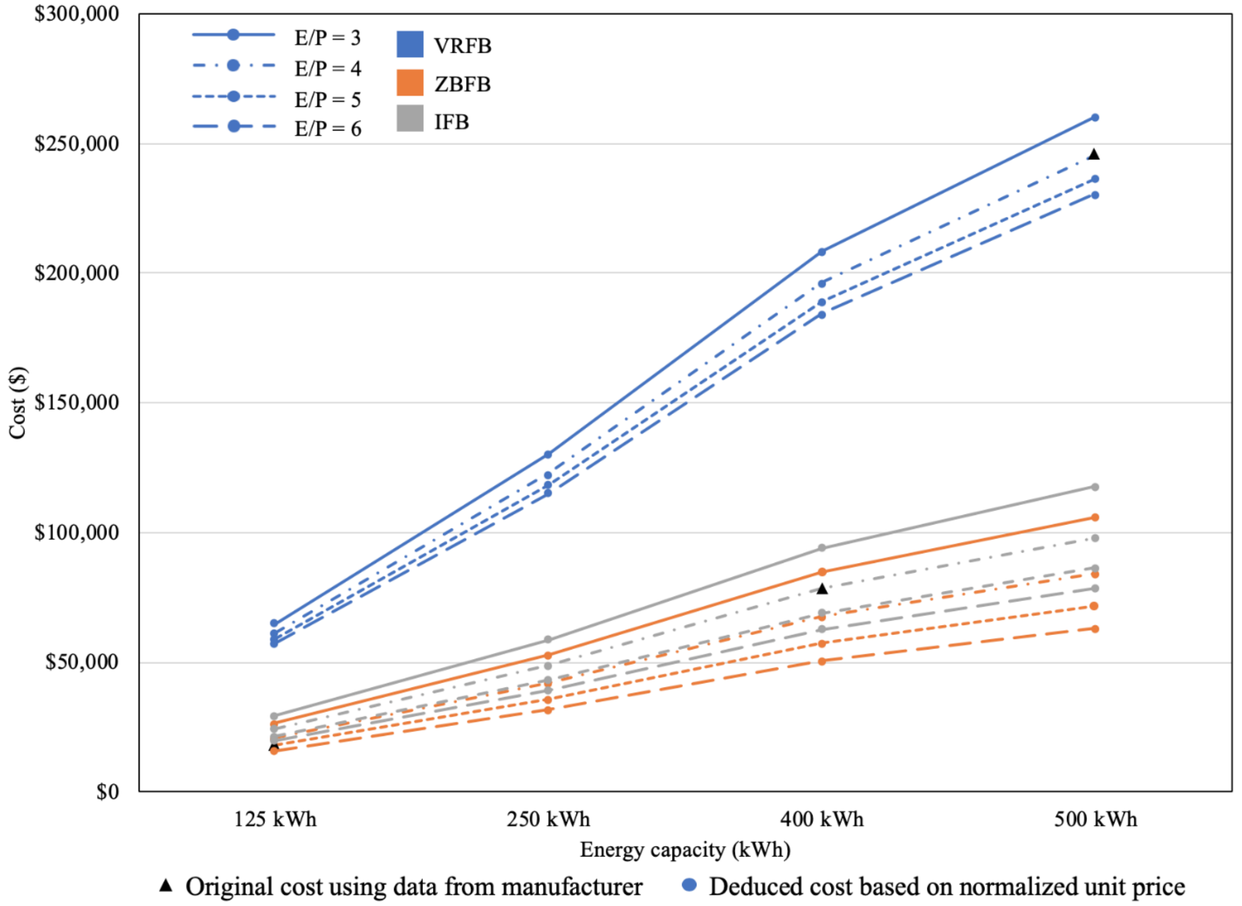
The material costs (and relative distribution by component) for the three battery systems normalized to per kWh energy capacity are compared in Figure 38. The cost per energy capacity of VRFB was significantly higher than that of the other two flow batteries due to the large use of vanadium pentoxide and its corresponding high raw material cost. The primary cost drivers vary among the flow batteries. The VRFB cost was dominated by the electrolyte with a percentage cost of over 80 percent. The largest contributor for ZBFB was also the electrolyte with a share of 29 percent but only slightly higher than the bipolar plate, which corresponds to 22 percent. By contrast, the primary cost driver for IFB is the BMS at 49 percent due to the large amount of carbon fiber felt used as the rebalancing cell as specified by the manufacturer, which is unique in the IFB system, compared to 8 percent for VRFB and 20 percent for ZBFB. Another balance of plant component, the inverter, accounted for 6 percent, 14 percent, and 14 percent of total costs for the VRFB, ZBFB, and IFB systems, respectively. These results align well with the literature results where the share of power control system varied from 8 percent to 25 percent. However, the cost comparison may be somewhat limited by the different scales and energy-to-power ratios for the flow battery systems. Further, with the fast development of newly designed battery systems, the technology readiness levels associated with different types of flow batteries may also vary. In this case, the design parameters were fixed by the manufacturer specifications.

Due to differences in the battery parameters provided by manufacturers, the project team calculated the battery system cost with normalized parameters and performed a sensitivity analysis by varying the E/P ratio and energy capacity, so that proper comparison between the different battery types can be made. Four levels of E/P ratio and energy capacity were applied to change the amount of stored energy and discharging behavior, as the related power output is fixed once the E/P ratio and energy capacity were determined. The total battery system cost associated with different E/P ratios and energy capacities for the three different flow battery types are provided in Figure 38.

The costs using the raw data and default battery parameters from manufacturerswere highlighted as black triangles, while other data points were deduced from the original data using unit cost per kWh or per kW for different components multiplying with the energy capacity and power output for various assumed battery systems. For example, since the cell stacks are primarily associated with the power output, the cost of cell stacks should be scaled up using unit data per kW. On the contrary, the electrolyte and tank determine the energy capacity, therefore the total cost of these two in the battery should be calculated using unit data per kWh. For BOP, both the power control system, pump, and inverter were categorized as power components as they are closely related to the power output, while the BOP accessories and rebalancing cells in IFB are energy subsystem components to contain and balance the electrolyte system.

From Figure 38, it is observed that with the data available for this study, the cost of the VRFB system was always higher than the ZBFB and IFB system for a given combination of energy capacity and E/P ratio. Further, the increase in material cost for VRFB was significantly higher when increasing the energy capacity of the battery system due to the high unit price and use of vanadium pentoxide compared to the electrolyte of the ZBFB and IFB. The relative material cost of the ZBFB and IFB varied depending on the different battery parameters. At similar energy capacities and E/P ratios, the material cost of the IFB was estimated to be slightly higher than that for the ZBFB, and for a 125 kWh system, the material costs of IFB and ZBFB are close and comparable. Interestingly, the material cost of the battery system is quite sensitive to the E/P ratio when the energy capacity is fixed. The smaller the E/P ratio, the higher the power output, and the influence of power output on ZBFB is more significant than for the VRFB and IFB, especially when the energy capacity is high. For example, the increase in material cost for the ZBFB from E/P = 4 to E/P =3 is higher than VRFB and IFB for a 500 kWh system. This is attributed to the high cost of the titanium bipolar plate in the cell stack as a power component for the ZBFB compared to the graphite-based bipolar plate in VRFB and IFB. This could explain why the ZBFB was designed to be smaller in energy capacity as the effect of the E/P ratio is not that insignificant for a 125 kWh system.

Figure 38: Total Flow Battery Material Cost for Different E/P Ratios and Energy Capacities



Source: UC Irvine

3.4.2 Sensitivity Analysis due to Material Price Variations

The material-based cost analyses presented in this study were driven by material prices; however, the price of raw materials used in the three flow battery systems have been subject to historical variations due to fluctuations in the global markets for these materials. Therefore, this section performs a sensitivity analysis focused on variations in raw material prices based on historical fluctuations.

The three-point estimation values (described in Section 3.1) are summarized in Table 17 for the four materials assessed. With the three price points determined, a weighted average (E) as the expected market price was calculated with a standard deviation available to reflect the variations. The larger the price gap between the pessimistic and optimistic price, the larger the standard deviation identified.

Table 17: Price Estimation for Selected Materials Used in Flow Battery

Price Information ($/kg)	Vanadium pentoxide	Titanium	Bromine	Carbon fiber felt
Current	35.75	30.00	4.90	237.60
Pessimistic	50.00	62.65	6.00	280.00
Optimistic	8.00	17.65	1.00	80.00
Weighted average (E)	32.33	33.38	4.43	218.40
Standard deviation (SD)	7.00	7.50	0.83	33.33

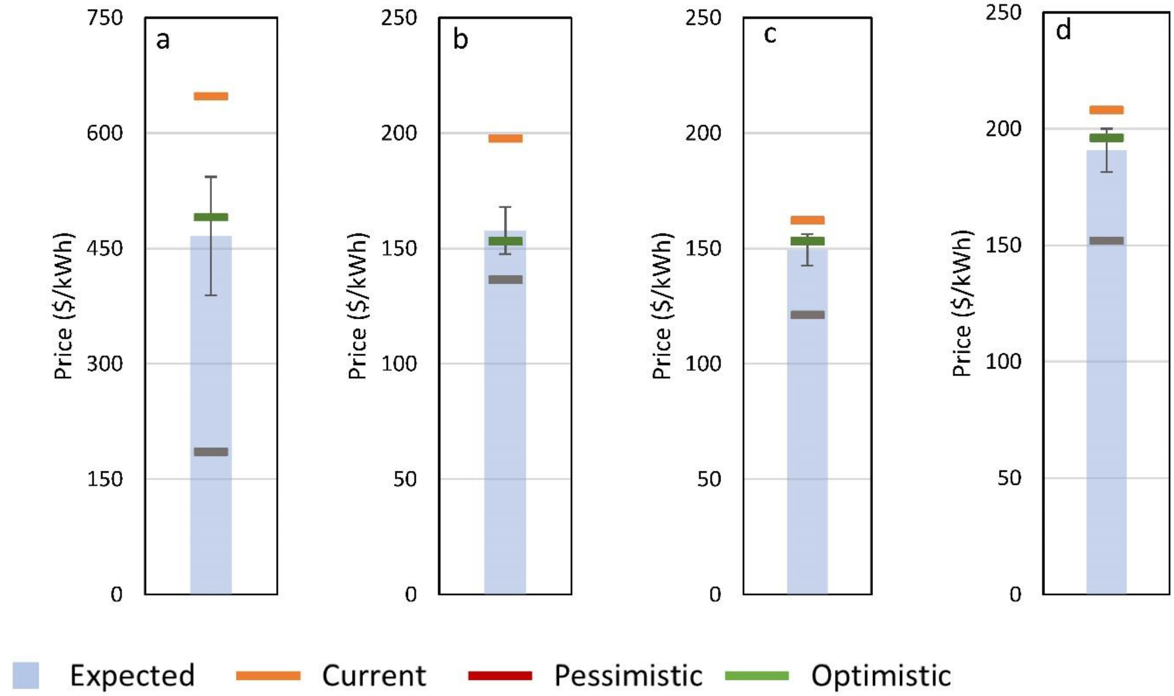
Source: UC Irvine

Figure 39 shows the results of the sensitivity analysis. The material cost of the VRFB system due to the variations in vanadium pentoxide price (Figure 13a) ranged between $185.5/kWh and $647.5/kWh when using different price points. The expected price value was estimated to be $466/kWh with a standard deviation value of $77/kWh. Thus, changes in the price of vanadium pentoxide would greatly affect the VRFB cost. The baseline value, $491/kWh, was near the upper value in the range, reflecting that recent prices for this material were higher than historical values.

The influence of titanium and bromine prices on the ZBFB material cost is shown in Figure 39b and Figure 39c, respectively. The expected ZBFB cost ($158/kWh) was higher than the baseline estimated value ($153/kWh), relative to titanium sensitivity, whereas, the expected cost for the bromine scenario ($149/kWh) was lower than the baseline estimation, but these differences are relatively small. The system cost deviations due to variations on titanium price were larger than the case of bromine, and both were relatively small compared to the vanadium pentoxide for VRFB.

For the IFB, the variations in cost due to price changes for carbon fiber felt are provided in Figure 39d. The expected cost ($191/kWh) was slightly lower than the baseline estimated value (196/kWh). The decrease in cost using the optimistic price was larger than the increase in cost when using a pessimistic value, which indicates the future price is likely to further lower the cost.

Figure 39: Sensitivity of Flow Battery Material Cost due to Variations in Material Price



a. Vanadium pentoxide for VRFB, b. Titanium, c. Bromine for ZBFB, and d. Carbon fiber felt for IFB. Source: UC Irvine

CHAPTER 4: Technology/Knowledge/Market Transfer Activities

4.1 Overview

As part of the overall project, several knowledge transfer activities occurred where the methods and results of the different tasks were presented to different audiences and stakeholders to disseminate the findings of the project. There are three specific audiences that have been engaged by the project:

1. State agency staff at the CEC and CPUC. This audience was engaged through direct briefings on project progress to CEC staff and presentations at workshops held by the project team focused on energy storage sustainability, attended by staff at both agencies. The purpose of these engagements was to inform staff involved in assessing plans for the deployment of energy storage technologies to support California's electricity decarbonization goals, specifically to provide information on flow batteries which may be used for long-duration storage functions. This information is intended to complement existing information on the environmental implications of lithium-ion battery deployment that is relatively more prevalent in the literature.
2. Academic researchers focused on better characterizing the environmental impacts of supply chains. This includes researchers focused on improving material resource sustainability through understanding and reducing materials sourcing impacts, as well as researchers focused on decarbonized energy system planning such that they can understand the environmental implications of large-scale energy storage deployment. Both classes of researchers were primarily engaged via peer-reviewed conference presentations and university seminars at which project content was presented. These activities have formed the basis for ongoing collaboration.
3. Flow battery manufacturers and the materials engineering industry. This audience was engaged primarily through direct briefings to management and technical staff during the course of the project, as well as peer-reviewed conference presentations attended by materials suppliers and flow battery manufacturers. The purpose of this engagement is to inform flow battery manufacturers of where the largest environmental impacts occur in their supply chains such that they can make better decisions regarding battery design and manufacturing techniques, and to inform materials suppliers for the potential to make better decisions regarding materials sourcing.

The following sections list the peer-reviewed conference presentations, seminars/workshops, and peer-reviewed journal publications that have resulted from this project. Note that direct briefings to state agency staff and flow battery manufacturers are not listed as items here.

The project formed the basis for a larger planning study to develop a battery energy storage sustainability roadmap funded by the University of California Office of the President which is currently ongoing. The results of this project are being incorporated with data and recommendations for other energy storage types in the development of the energy storage sustainability roadmap. The roadmap will form the basis for broader outreach to stakeholders in the energy storage industry for improving the sustainability of their supply chains.

4.2 Peer-Reviewed Conference Presentations

The results of different stages of the project have been presented or have been accepted for presentation at the following venues to academic, government, and industry audiences:

- Brian Tarroja, "*Flow Battery Energy Storage: A Flexible, Scalable Microgrid Management Resource?*", International Colloquium for Environmentally Preferred Advanced Generation 2019: Microgrid Global Summit, Irvine, CA, USA, 26 March 2019.
- Haoyang He, Shan Tian, Brian Tarroja, Oladele Ogunseitan, Scott Samuelsen, Julie M Schoenung, "*A Life cycle assessment of Flow Battery Technologies Based on Manufacturer Specifications*", 2019 MRS Spring Meeting, Phoenix, AZ, USA, 24 April 2019.
- Haoyang He, Shan Tian, Christopher Glaubensklee, Brian Tarroja, Scott Samuelsen, Oladele Ogunseitan, Julie Schoenung, "*Flow Batteries for Renewable Energy Storage in the Grid: An Investigation into the Potential Human Health Impacts of Materials and Manufacturing*", SETAC North America 40th Annual Meeting, Toronto, Canada, 7 November 2019.
- Brian Tarroja, Shan Tian, Haoyang He, Julie Schoenung Oladele Ogunseitan, Scott Samuelsen, "*Energy Storage and Zero Emissions Energy: Balancing In-Operation Emissions Benefits vs. Life Cycle Emissions Impacts*", 2019 American Geophysical Union Fall Meeting, San Francisco, CA, USA, 10 December 2019.
- Shan Tian, Haoyang He, Oladele Ogunseitan, Julie Schoenung, Scott Samuelsen, Brian Tarroja, "*Environmental Benefit-Detriment Thresholds for Flow Battery Energy Storage Systems*", Applied Energy Symposium: MIT A+B, Cambridge, MA, 17 May 2020. (Postponed due to COVID-19).
- Haoyang He, Shan Tian, Brian Tarroja, Oladele A. Ogunseitan, Scott Samuelsen, Julie M. Schoenung, "*Flow Batteries for Renewable Energy Storage: Comparative Analysis of Economic, Environmental, and Human Health Considerations*", International Symposium for Sustainable Systems and Technology 2020, Pittsburgh, PA, 8 June 2020. (Postponed due to COVID-19).

4.3 Seminars and Workshops

Certain parts of the project methods and findings were presented at a series of workshops and seminars involving academic, government, and industry audiences:

4.3.1 Seminars

- Brian Tarroja, "*Navigating the Design Space of Trajectories toward Low/Zero-Carbon Energy Systems in California*", UC Santa Barbara Institute of Energy Efficiency Annual Technology Review, 16 May 2019.
- Brian Tarroja, "*Determining the Role of Energy Storage in Zero-Emission Energy Systems: Assessing and Comparing Environmental Benefits and Impacts at Scale*", UC

Davis Energy Graduate Group Seminar Series, 11 October 2019. Video here: https://youtu.be/5r6Ie4We_oU

4.3.2 Workshops

- Brian Tarroja, "*Battery Energy Storage – Where We Are, Where We're Going, and Where We Need to Go*", UCOP MRPI: Maximizing the Environmental Utility of Battery Storage – Workshop #1. Irvine, CA, USA, 10 April 2019.
- Brian Tarroja, "*Maximizing the Environmental Utility of Battery Storage: Project Overview*", UCOP MRPI: Maximizing the Environmental Utility of Battery Storage – Workshop #2. Davis, CA, USA, 25 October 2019.

4.4 Peer-Reviewed Journal Publications

At the time of this writing, the project has resulted in 1 published peer-reviewed journal paper with an additional two currently in draft.

4.4.1 Manuscripts Accepted for Publication

- He, H., Tian, S., Tarroja, B., Ogunseitan, O., Samuelsen, S., Schoenung, J.M., "Flow Battery Production: Materials Selection and Environmental Impact". Journal of Cleaner Production. https://doi.org/10.1016/j.jclepro.2020.121740.
- Tian, S., He, H., Kendall, A., Davis, S.J., Ogunseitan, O., Schoenung, J.M., Samuelsen, S., Tarroja, B., "Environmental Benefit-Detriment Thresholds for Flow Battery Energy Storage Systems: A Case Study in California ". Applied Energy, 2021. 300, 117354. https://doi.org/10.1016/j.apenergy.2021.117354

4.4.2. Manuscripts in Draft to be Submitted

- He, H., Tian, S., Glaubensklee, C., Tarroja, B., Samuelsen, S., Ogunseitan, O., Schoenung, J.M., " A Comparative Assessment on Potential Toxicity Hazard and Health Impacts of Flow Batteries and Lithium-ion Batteries Production". (In Draft)

CHAPTER 5: Conclusions and Recommendations

5.1 Key General Findings

While each task of the project produced a range of conclusions and recommendations, the overall general findings and recommendations of the project are summarized here:

1. The lack of robust life-cycle inventories for complex compounds used in different flow battery components such as electrolytes can introduce large uncertainty into life-cycle assessment results for these emerging and early commercial technologies.
2. The vanadium pentoxide electrolyte used by the vanadium-redox flow battery is currently the dominant driver of the technology's high environmental impacts and high materials costs. For environmental impact, the production of vanadium pentoxide is currently fossil-fuel intensive as a byproduct of steelmaking in areas with strong coal dependence. For material costs, the market price for this resource drives high flow battery costs and is dependent on global markets. Therefore, more environmentally benign and less expensive sourcing of vanadium pentoxide is critical for reducing the environmental footprint and cost of vanadium-redox flow batteries.
3. The environmental impacts of the zinc-bromide flow battery are driven by the materials used in the system bipolar plate, primarily the life cycle of titanium, and the use of bromine in the electrolyte. Different system designs may substitute these materials, but as configured this allows this technology to exhibit relatively low material costs.
4. The all-iron flow battery has relatively low environmental impacts and material costs due to its use of relatively abundant and benign materials, except for the resins used for the system design analyzed in this study, which corresponds to a high contribution to ecotoxicity impacts. Alternate materials selection can potentially address this issue.
5. While all three flow batteries provide similar levels of environmental benefits through enhancing the uptake of renewable energy resources on the electric grid, these benefits can be reduced if energy storage capacity is installed to the point where the life cycle environmental impacts associated with production outweigh the benefits from their use.
6. From a human health standpoint, the zinc-bromide flow battery tends to use chemicals with fewer hazard traits with the exception of bromine, while the vanadium-redox and all-iron flow batteries incorporate some chemicals in their life cycle that present high human health hazard concerns.
7. From a human health standpoint with respect to toxicity, the zinc-bromide flow battery exhibits the lowest non-cancer toxicity effect but the highest cancer-related toxicity impact. The other two flow battery types show similar cancer-related toxicity impacts, but the iron flow battery exhibits the highest non-cancer impact.

5.2 Recommendations for Policy, Practice, and Future Research

Based on the findings of this project, the project team provide the following recommendations for relevant policy, practice, and future research regarding the life cycle characterization of flow batteries and grid energy storage as a whole:

- Policies supporting the deployment of energy storage should be based on a framework that accounts for the environmental and human health impacts from materials sourcing and manufacturing in addition to the reductions provided by their use. The benefits for emissions reductions provided from the use of energy storage are often the focus of discussions and policies incentivizing the deployment of these systems, but these are not explicitly compared against emissions generated during life cycle phases outside of their use (for example, during production) in technology assessments. The latter aspect is particularly important for environmental impact indicators such as greenhouse gas emissions that cause impacts on a global scale independent of the location of their emissions source. Such a framework will be necessary to ensure that large-scale deployment of energy storage in California provides a significant net emissions benefit.
- Further research is needed to create a consistent, standardized net benefit assessment framework for designing policies that support energy storage deployment. While this project focused exclusively on flow battery chemistries, difficulties were encountered relating to differences in detail of available data on different battery materials, selection of system boundaries for life cycle assessments of battery materials in the literature, and limited sources for data availability for these materials. These factors introduced significant uncertainty into the environmental impact footprints of the different battery types even within the category of flow batteries and can be even more influential as policymakers seek to compare these footprints across different types of energy storage technologies. Therefore, further research is needed to develop a consistent, standardized net benefit assessment framework that consists of consistent system boundaries and assumptions and harmonized life cycle inventory data for policymakers to have an effective and fair platform for evaluating the effectiveness of different energy storage technologies in supporting California's future energy system goals.
- Policies that support demand flexibility measures should be implemented to reduce the scale of energy storage needed to meet decarbonization goals. The results of this study show that while energy storage (in the form of flow batteries) do provide significant environmental benefits through their use on the grid, installing these systems to capacity levels that are too large can cause environmental impacts from materials extraction and manufacturing that reduce or even completely negate the benefits gained from using these systems in the grid. Therefore, to avoid the need to install energy storage capacities that approach these capacity thresholds, other measures that can provide electric grid flexibility such as demand response measures and dynamically-capable low and zero-carbon electricity resources should be incentivized to keep the requirements for energy storage capacity within ranges that provide significant net environmental benefits.
- Policies and programs should be developed to incentivize energy storage manufacturers to develop energy storage designs that use low-impact materials and manufacturing processes. A significant amount of attention is focused on improving the efficiency and

flexibility of energy storage systems during their use, since these improvements can increase the emissions reduction benefit provided by these systems. However, there are limits to how much these parameters can improve based on chemical and thermodynamic limits. Alternatively, the net environmental benefits provided by energy storage systems can be increased by developing designs that use lower-impact materials (either by selecting different materials or selecting more environmentally benign supply chains for the same materials) and manufacturing processes, perhaps potentially more so than by improvements in operational efficiency. However, energy storage system manufacturers often procure their materials and select their manufacturing processes based on lowest cost, especially for emerging energy storage technologies that are attempting to break into the market. Therefore, policies and programs that can monetarily incentivize or support manufacturers to develop low-environmental-and-health-impact energy storage designs can be beneficial in enabling reductions in the environmental footprint of these technologies before they are deployed to the scale needed to support California's future energy goals.

- Future work is needed to characterize and compare the recyclability and disposal options for used flow battery systems. This study did not assess the end-of-life recycling or disposal options for the three different flow batteries. One potential advantage of flow batteries in this regard compared to conventional batteries, however, is that the electrolyte and electrode assemblies are physically separate. This potentially enables flow batteries to be more easily disassembled, the resulting materials more easily sorted for recycling, and many of the balance of plant components are readily recyclable. The environmental and health impacts of the end-of-life options of flow batteries, however, will depend strongly on the handling of the flow battery electrolyte. Since the three flow battery types here use very different chemistries, some may be more amenable to environmentally-benign and low-impact end-of-life options than others. Investigating the end-of-life options for flow batteries and comparing them to incumbent energy storage options such as lithium-ion batteries is a subject for future work.

LIST OF ACRONYMS

Term	Definition
ACGIH	American Conference of Governmental Industrial Hygienists
ADP	Abiotic Depletion Potential
BM	Benchmark Score
BMS	Battery Management System
BOP	Balance of Plant
CED	Cumulative Energy Demand
CF	Characterization Factor
CFC-11	Chloroflorocarbon-11
CHA	Chemical Hazard Assessment
DALY	Disability-Adjusted Life Years
DOD	Depth of Discharge
E/P	Energy to Power Ratio
ECHA CHEM	European Chemicals Agency Registered Substances
EF	Effect Factor
EU-SVHC	European Union – Substance of Very High Concern
FF	Fate Factor
GHG	Greenhouse Gas
GHS	Globally Harmonized System of Classification and Labeling of Chemicals
GWP	Global Warming Potential
HDPE	High Density Poly-Ethylene
HiGRID	Holistic Grid Resource Integration and Deployment tool
HSDB	Hazardous Substances Data Bank
HTP	Human Toxicity Potential
IFB	Iron Flow Battery
IPCC	Intergovernmental Panel on Climate Change
IS	Impact Score
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory

Term	Definition
LCIA	Life Cycle Impact Assessment
ODP	Ozone Depletion Potential
OSHA	Occupational Safety and Health Administration
PEL	Permissible Exposure Limit
PM	Particulate Matter
REACH	European Union's Registration, Evaluation, Authorization and Restriction of Chemicals
REL	Recommended Exposure Limit
RPS	Renewable Portfolio Standard
SB100	Senate Bill 100
SOC	State of Charge
SPA	Structural Path Analysis
TEA	Techno-Economic Analysis
TEDX	The Endocrine Disruption Exchange
TLV	Threshold Limit Value
TWA	Time-Weighted Average
USGS	U.S. Geological Survey
VRFB	Vanadium-redox flow battery
ZBFB	Zinc-bromide flow battery

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APPENDIX A:
Life-Cycle Inventory Data Collection Form for Flow Battery

Data Collection Form			
Products Name		**Company Name**	
Performance			
Rated Power			
Related discharge energy at rated power			
Round trip efficiency			
Physical			
Dimensions			
Mass			
Number of cell stacks			
Constitution			
Cell Stack: **Electrolyte Storage:** **Balance of plant:**			
Material Use / Energy Consumption / Waste Stream Outputs			
Cell Stack (Unit: 1) Weight:			
Electrode Total weight: Constitution: (Material/weight / from which part/ the number of this part)		Process Materials for Assembling (Material/weight /function/process method)	

Data Collection Form			
Cell Frames Total weight: Constitution: (Material/weight / from which part/ the number of this part)		Process Materials for Assembling (Material/weight /function/ process method)	
Process Materials for Assembling (Material/weight/ function)			
Cell Stack Manufacturing Process Energy Consumption (Electricity, Heat or Fuel Input)			
Cell Stack Manufacturing Process Waste Outputs (i.e. Solvents, VOCs, etc…)			
Electrolyte storage			
Electrolyte Total weight: (Material/weight /function)		Process Materials for Manufacture (Material/weight /function/ process method)	

Data Collection Form			
Containment vessel Total weight: Constitution: (Material/weight / from which part/ the number of this part)		Process Materials for Manufacture (Material/weight /function/ process method)	
Process Materials for Assembling (Material/weight /function)			
Electrolyte Storage Manufacturing Process Energy Consumption (Electricity, Heat or Fuel Input)			
Electrolyte Storage Manufacturing Process Waste Outputs (i.e. Solvents, VOCs, etc…)			
Balance of Plant			
Pump Total weight: (Material/weight /number)		Process Materials for Assembling (Material/weight /function/process method)	
PC system Total weight: Constitution:			

Data Collection Form			
(component/ number)			
Temperature control Total weight: Constitution: (Material/weight /function)			
Sensors Total weight: Constitution: (Material/weight /function)		Process Materials for Assembling (Material/weight /function/process method)	
Shunt current interruption and sealing Total weight: Constitution: (Material/weight / from which part/ the number of this part)		Process Materials for Assembling (Material/weight /function/process method)	
Process Materials for Assembling (Material/weight /function)			
Balance of Plant Manufacturing Process Energy Consumption (Electricity, Heat or Fuel Input)			
Balance of Plant Manufacturing			

Data Collection Form	
Process Waste Outputs (i.e. Solvents, VOCs, etc…)	

End-of-Life Characterization			
Details of Components Disposed			
Details of Components Recycled			
Disposal / Recycling In-House or Contracted?		If Contracted – Name of Responsible Company	
Recycling or Disposal Process Energy Consumption (Electricity, Heat or Fuel Input)			
Recycling or Disposal Manufacturing Process Waste Outputs (i.e. Solvents, VOCs, etc…)			

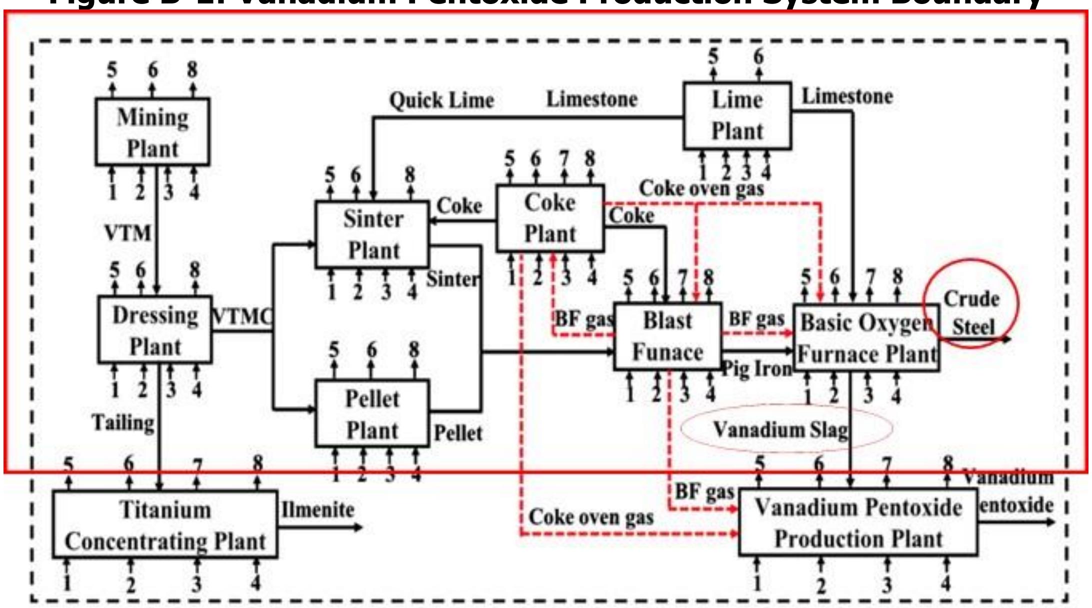
Notes:

APPENDIX B:
Life Cycle Inventory Data from Literature Review

B.1 Vanadium Pentoxide

Currently, there is no available database on vanadium pentoxide production and related LCI data is based on a published paper where the production of vanadium pentoxide is extracted as a by-product on the crude steel production process using vanadium titano-magnetite [48]. This paper, published in 2015, is the most recent paper with a clear description of the vanadium pentoxide production process with the whole system boundary shown on Figure B-1.

Figure B-1: Vanadium Pentoxide Production System Boundary



Sourced from [48]

In this flow chart, the processes described in the red box indicate the processing of the major product - crude steel by using the titano-magnetite. The intermittent materials and energy use interchanging between those processes are ignored and only the input and output connected to activities outside the boundary are considered. The titanium concentrating plant included in the system boundary is designed for titanium extraction which is not related with vanadium pentoxide production and the LCI data on this part is cut off without any impacts loaded to the vanadium pentoxide production. The LCI data related the vanadium pentoxide production plant will all be counted as this process is fully designed for vanadium pentoxide extraction. As the previous physical flows on material and energy use during the crude steel production also contribute to the production of vanadium pentoxide, the LCI data is counted through the allocation of crude steel and vanadium slag based on the weight ratio during the crude steel production processes. The final LCI data is normalized to 1 kg vanadium pentoxide production and the details are presented on Table B-1.

Table B-1: The Life Cycle Inventory Data on Vanadium Pentoxide Production

Item	Value
Input	
Energy	5.33 kwh
Raw material	
Coal	12.1 kg
Iron ores	51.55 kg
Steel	0.02 kg
Limestone	4.66 kg
Bentonite	0.08 kg
Fluorspar	0.07 kg
Ammonium sulphate	0.78 kg
Salt	0.58 kg
Sulphuric acid	0.69 kg
Soda	1.49 kg
Emissions	
CO_2	35.4 kg
SO_2	0.71 kg
CO	3.29 kg
NO_X	0.35 kg
CH_4	0.18 kg
NMVOC	0 kg
Dust	2.76 kg

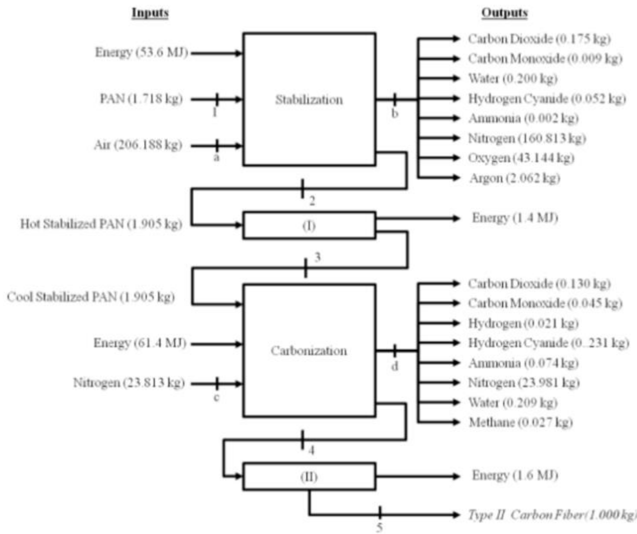
Unit: 1kg V_2O_5 production

Source: [48]

B.2 Carbon Fiber

The carbon fiber is major produced by the pyrolysis process with the use of polymer precursors such as the polyacrylonitirle (PAN). The LCI data extracted in this study is based on a study analyzing the carbon fiber manufacturing through several modeling processes. [2] The final LCI data for the production of 1 kg carbon fiber is shown on Table B-2.

Figure B-2: Process Flow of Carbon Fiber Manufacturing



Sourced from [70]

Table B-2: Life Cycle Inventory Data on Carbon Fiber Production

Item	Value
Input	
Energy	215 MJ
PAN	1.718 kg
Air	206.188 kg
Nitrogen	23.813 kg
Output	
CO_2	2 kg
CO	0.054 kg
H_2O	0.409 kg
H_2	0.021 kg
HCN	0.283 kg
NH_3	0.076 kg
N_2	184.794 kg
O_2	43.144 kg
Ar	2.062 kg
Methane	0.027 kg

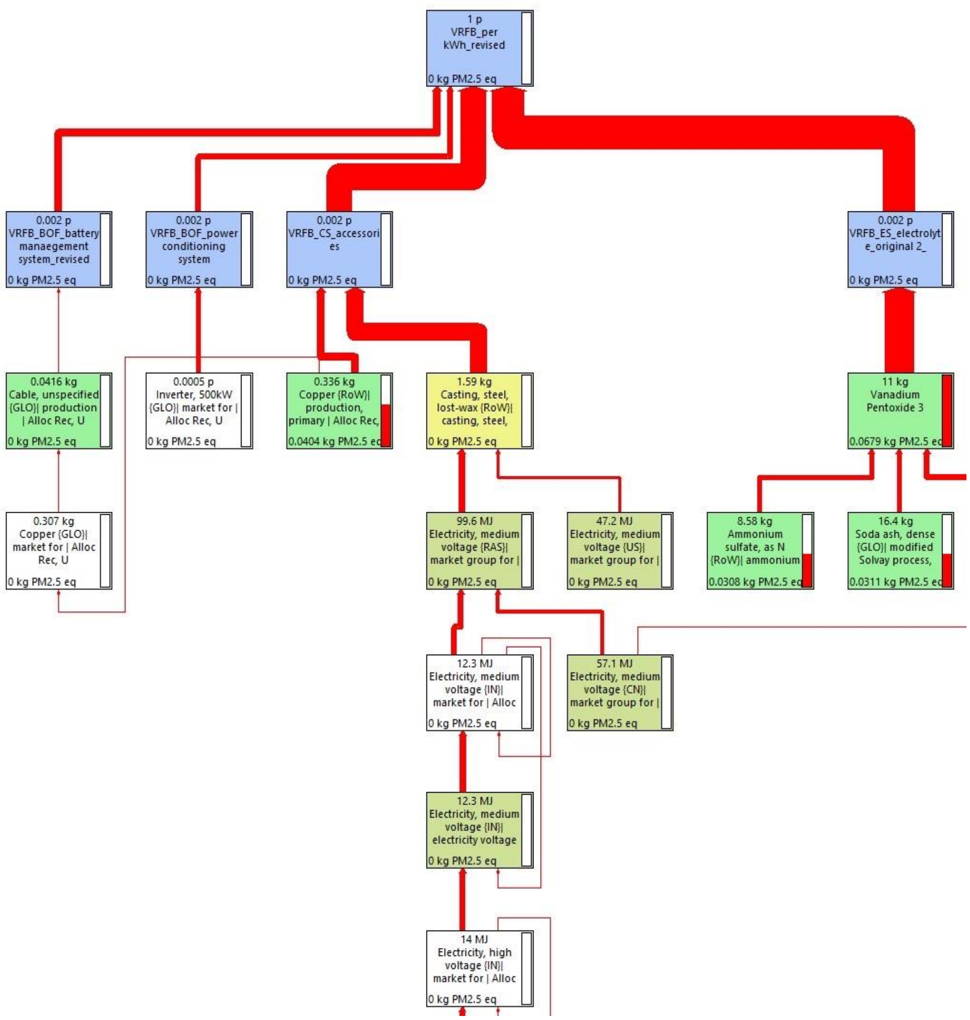
Unit: 1 kg Carbon fiber production

Source: [70]

APPENDIX C: Structural Path Analysis

The structural path analysis (SPA) was first introduced in input-output life cycle assessment studies for tracking the contribution of different components and sub-components to the overall impact of a product. For a brief introduction to SPA, here we provide an example using a flow battery. To produce the flow battery, we divide the battery system into several components: cell stacks, electrolyte storage, and balance of plant. Each of these components can also be further divided into sub-components, the manufacturing of which still requires material or energy inputs and produces emissions outputs. This process can be replicated by further dividing the sub-components into smaller parts until the cut-off threshold is met for a particular study, based on mass or energy contributions of these smaller parts. Visually, this is shown by a “tree data structure”, which displays the breakdown of each component into its contributing parts, and each tier of the structure representing a further disaggregation of components. An example is presented in Figure C-1:

Figure C-1: Example Tree Structure



Source: UC Irvine

In general, the top several tiers will contribute towards the largest share of impacts from the overall product. Within each tier, typically certain processes will comprise the larger share of impacts. It is these processes that are important to capture, while those contributing smaller impacts may not be as important to model in detail [81].

The SimaPro platform, when combined with the detailed information in the EcoInvent database, allows products to be broken down into components and sub-components, with the option to display as many tiers as desired. In this appendix, we present the unit processes which have the highest contributions to each impact category.

C.1 Global Warming Potential

Table C-1: Structural Path Analysis on Global Warming Potential for Vanadium-Redox Flow Battery (kg CO_2 eq/ kWh)

Rank	Unit Processes	Impacts	Component Contribution
1	Vanadium Pentoxide Production	56.03	Electrolyte (100%)
2	Ammonium sulfate, as N {RoW}| ammonium sulfate production | Alloc Rec, S	17.64	Electrolyte (100%)
3	Soda ash, dense {GLO}| modified Solvay process, Hou's process | Alloc Rec, S	16.96	Electrolyte (100%)
4	Hard coal {CN}| mine operation | Alloc Rec, U	15.79	Electrolyte (53.04%), Cell stack accessories (29.95%), Battery management system (10.59%)
5	Electricity, high voltage {CN-SC}| electricity production, hard coal | Alloc Rec, U	15.48	Electrolyte (98.76%)
6	Polyethylene, high density, granulate {RoW}| production | Alloc Rec, U	5.42	Electrolyte (98.13%)
7	Electricity, high voltage {IN}| electricity production, hard coal | Alloc Rec, U	3.27	Electrolyte (58.27%), Cell stack accessories (20.31%), Battery management system (13.54%)
8	Pig iron {GLO}| production | Alloc Rec, U	3.26	Cell stack accessories (51.74%), Power conditioning system (28.26%), Balance of plant accessories (12.82)

Rank	Unit Processes	Impacts	Component Contribution
9	Heat, district or industrial, other than natural gas {RoW}| heat production, at hard coal industrial furnace 1-10MW | Alloc Rec, U	2.32	Cell stack accessories (35.39%), Battery management system (33.39%), Power conditioning system (10.40%)
10	Tetrafluoroethylene {RoW}| production | Alloc Rec, U	2.30	Membrane (99.76%)
Total	224.01 (Electrolyte: 58.27%, Cell stack accessories: 23.79%, Battery management system: 9.27%)		

Source: UC Irvine

Table C-2: Structural Path Analysis on Global Warming Potential for Zinc-Bromide Flow Battery (kg CO_2 eq/ kWh)

Rank	Unit Processes	Impacts	Component Contribution
1	Hard coal {CN}| mine operation | Alloc Rec, U	28.53	Cell stack accessories (54.92%), Balance of plant accessories (18.92%), Bipolar plate (13.32%)
2	Titanium primary, triple-melt {GLO}| titanium production, primary, triple melt | Alloc Rec, S	22.38	Bipolar plate (82.35%), Cell stack accessories (17.65%)
3	Heat, district or industrial, other than natural gas {RoW}| heat production, at hard coal industrial furnace 1-10MW | Alloc Rec, U	17.39	Electrolyte (56.96%), Bipolar plate (15.48%), Cell stack accessories (14.44%)
4	Electricity, high voltage {IN}| electricity production, hard coal | Alloc Rec, U	10.90	Cell stack accessories (58.18%), Balance of plant accessories (19.66%), Bipolar plate (15.21%)
5	Heat, district or industrial, other than natural gas {RoW}| heat production, light fuel oil, at industrial furnace 1MW | Alloc Rec, U	9.96	Electrolyte (98.44%)
6	Silicon, metallurgical grade {RoW}| production | Alloc Rec, U	9.11	Cell stack accessories (75.37%), Balance of plant accessories (24.55%)
7	Pig iron {GLO}| production | Alloc Rec, U	8.52	Cell stack accessories (67.44%), Balance of plant accessories (22.45%), recirculation loops (5.81%)

Rank	Unit Processes	Impacts	Component Contribution
8	Heat, district or industrial, natural gas {RU}| heat and power co-generation, natural gas, conventional power plant, 100MW electrical | Alloc Rec, U	7.38	Electrolyte (47.79%), Cell stack accessories (34.86%), Balance of plant accessories (12.25%)
9	Hard coal {RoW}| mine operation | Alloc Rec, U	6.65	Cell stack accessories (54.22%), Balance of plant accessories (18.81%), Bipolar plate (13.24%)
10	Polyethylene, high density, granulate {RoW}| production | Alloc Rec, U	5.33	Bipolar plate (46.59%), Cell frame (34.09%), Cell stack accessories (9.69%)
11	Electricity, high voltage {RoW}| electricity production, hard coal | Alloc Rec, U	5.13	Cell stack accessories (56.64%), Balance of plant accessories (18.98%), Bipolar plate (17.80%)
12	Electricity, high voltage {CN-NM}| electricity production, hard coal | Alloc Rec, U	4.87	Cell stack accessories (58.41%), Balance of plant accessories (19.70%), Bipolar plate (14.58%)
13	Electricity, high voltage {RU}| heat and power co-generation, natural gas, conventional power plant, 100MW electrical | Alloc Rec, U	4.70	Cell stack accessories (58.56%), Balance of plant accessories (19.72%), Bipolar plate (14.53%)
14	Electricity, high voltage {RFC}| electricity production, lignite | Alloc Rec, U	4.29	Cell stack accessories (53.76%), Balance of plant accessories (19.72%), Bipolar plate (13.88%)
15	Electricity, high voltage {SERC}| electricity production, lignite | Alloc Rec, U	4.06	Cell stack accessories (52.74%), Balance of plant accessories (19.72%), Bipolar plate (13.63%)
16	Electricity, high voltage {CN-JS}| electricity production, hard coal | Alloc Rec, U	4.02	Cell stack accessories (58.41%), Balance of plant accessories (19.70%), Bipolar plate (14.58%)
17	Electricity, high voltage {CN-SD}| electricity production, hard coal | Alloc Rec, U	3.71	Cell stack accessories (58.41%), Balance of plant accessories (19.70%), Bipolar plate (14.58%)

Rank	Unit Processes	Impacts	Component Contribution
18	Heat, district or industrial, natural gas {RoW}| heat and power co-generation, natural gas, conventional power plant, 100MW electrical | Alloc Rec, U	3.68	Electrolyte (47.49%), Cell stack accessories (34.86%), Balance of plant accessories (12.25%)
Total	355.52 (Cell stack accessories: 48.70%, Bipolar plate: 17.79%, Balance of plant accessories: 16.61%)		

Source: UC Irvine

Table C-3: Structural Path Analysis on Global Warming Potential for Iron Flow Battery (kg CO_2 eq/ kWh)

Rank	Unit Process	Impact	Component Contribution
1	Hard coal {CN}| mine operation | Alloc Rec, U	10.51	Cell stack accessories (66.81%), Electrolyte (20.57%), Cell frame (11.18%).
2	Steel, low-alloyed {RoW}| steel production, converter, low-alloyed | Alloc Rec, S	6.15	Cell stack accessories (100%)
3	Electricity, high voltage {IN}| electricity production, hard coal | Alloc Rec, U	4.28	Cell stack accessories (66.48%), Electrolyte (15.22%), Cell frame (8.29%)
4	Silicon, metallurgical grade {RoW}| production | Alloc Rec, U	3.30	Cell stack accessories (99.91%)
5	Polyacrylonitrile fibres (PAN), from acrylonitrile and methacrylate, prod. mix, PAN w/o additives EU-27 S	2.80	Battery management system (89.29%), Electrode (10.71%)
6	Styrene {RoW}| production | Alloc Rec, U	2.77	Electrolyte (99.35%)
7	Heat, district or industrial, other than natural gas {RoW}| heat production, at hard coal industrial furnace 1-10MW | Alloc Rec, U	2.29	Cell stack accessories (40.12%), Electrolyte (19.08%), Cell frame (16.88%)
8	Hard coal {RoW}| mine operation | Alloc Rec, U	2.27	Cell stack accessories (65.52%), Electrolyte (16.70%), Cell frame (7.93%)
9	Bisphenol A epoxy based vinyl ester resin {RoW}| production | Alloc Rec, S	2.16	Bipolar plate (100%)
10	Polyester resin, unsaturated {RoW}| soy-based resin production | Alloc Rec, U	2.12	Cell frame (99.49%)
11	Electricity, high voltage {CN-NM}| electricity production, hard coal | Alloc Rec, U	2.04	Cell frame (67.63%), Cell stack accessories (14.75%), Electrolyte (7.87%)

12	Electricity, high voltage {RoW}| electricity production, hard coal | Alloc Rec, U	1.93	Cell stack accessories (66.77%), Electrolyte (15.00%), Cell frame (8.29%)
13	Heat, district or industrial, natural gas {RU}| heat and power co-generation, natural gas, conventional power plant, 100MW electrical | Alloc Rec, U	1.93	Cell stack accessories (63.70%), Cell frame (21.91%)
14	Electricity, high voltage {RU}| heat and power co-generation, natural gas, conventional power plant, 100MW electrical | Alloc Rec, U	1.90	Cell stack accessories (65.10%), Electrolyte (17.19%), Cell frame (8.36%)
15	Electricity, high voltage {CN-JS}| electricity production, hard coal | Alloc Rec, U	1.68	Cell stack accessories (67.63%), Electrolyte (14.75%), Cell frame (7.87%)
16	Electricity, high voltage {CN-SD}| electricity production, hard coal | Alloc Rec, U	1.55	Cell stack accessories (67.63%), Electrolyte (14.75%), Cell frame (7.87%)
17	Electricity, high voltage {RFC}| electricity production, lignite | Alloc Rec, U	1.55	Cell stack accessories (66.88%), Electrolyte (14.98%), Cell frame (8.30%)
Total	145.47 (Cell stack accessories: 55.19%, Electrolyte: 20.57%, Cell frame: 11.18%)		

Source: UC Irvine

C.2 Ozone Depletion Potential

Table C-4: Structural Path Analysis on Ozone Depletion Potential for Vanadium-Redox Flow Battery (kg CFC 11 eq/ kWh)

Rank	Unit Process	Impact	Component contribution
1	Tetrafluoroethylene {RoW}| production | Alloc Rec, U	4.98E-05	Membrane (99.76%)
2	Trichloromethane {RER}| production | Alloc Rec, U	2.62E-05	Membrane (99.74%)
3	Tetrafluoroethylene {RER}| production | Alloc Rec, U	2.30E-05	Membrane (99.76%)
4	Chlorodifluoromethane {RoW}| production | Alloc Rec, U	1.64E-05	Membrane (99.76%)
5	Trichloromethane {RoW}| production | Alloc Rec, U	1.43E-05	Membrane (99.74%)

6	Soda ash, dense {GLO}| modified Solvay process, Hou's process | Alloc Rec, S	5.98E-06	Electrolyte (100%)
7	Nitric acid, without water, in 50% solution state {RoW}| nitric acid production, product in 50% solution state | Alloc Rec, U	5.76E-06	Cell stack accessories (50.06%), Power conditioning system (22.44%), Battery management system (18.38%)
8	Ammonium sulfate, as N {RoW}| ammonium sulfate production | Alloc Rec, S	5.44E-06	Electrolyte (100%)
9	Nitric acid, without water, in 50% solution state {RER}| nitric acid production, product in 50% solution state | Alloc Rec, U	2.85E-06	Cell stack accessories (50.06%), Power conditioning system(22.44%), Battery management system (18.38%)
10	Electricity, high voltage {CN-SC}| electricity production, hard coal | Alloc Rec, U	2.71E-06	Electrolyte (98.76%)
11	Electricity, high voltage {RU}| market for | Alloc Rec, U	2.38E-06	Cell stack accessories (60.92%), Battery management system (17.93%), Electrolyte (12.95%)
12	Chlorodifluoromethane {NL}| production | Alloc Rec, U	2.35E-06	Membrane (99.76%)
Total	1.93E-04 (Membrane: 66.89%, Cell stack accessories: 11.31%, Electrolyte: 11.03%)		

Source: UC Irvine

Table C-5: Structural Path Analysis on Ozone Depletion Potential for Zinc-Bromide Flow Battery (kg CFC 11 eq/ kWh)

Rank	Unit Process	Impact	Component contribution
1	Titanium primary, triple-melt {GLO}| titanium production, primary, triple melt | Alloc Rec, S	9.88E-06	Bipolar plate (82.35%), Cell stack accessories (17.65%)
2	Electricity, high voltage {RU}| market for | Alloc Rec, U	7.96E-06	Cell stack accessories (58.56%), Balance of plant accessories (19.77%), Bipolar plate (14.53%)

Rank	Unit Process	Impact	Component contribution
3	Nitric acid, without water, in 50% solution state {RoW}| nitric acid production, product in 50% solution state | Alloc Rec, U	5.73E-06	Cell stack accessories (44.83%), Balance of plant accessories (15.92%), Battery management system
4	Electricity, high voltage {BR}| market for | Alloc Rec, U	4.34E-06	Cell stack accessories (58.35%), Balance of plant accessories (19.69%), Bipolar plate (15.29%)
5	Chlorine, gaseous {RoW}| chlor-alkali electrolysis, diaphragm cell | Alloc Rec, U	2.99E-06	Electrolyte (52.00%), Bipolar plate (38.01%), Cell stack accessories (8.46%)
6	Petroleum {RoW}| petroleum and gas production, on-shore | Alloc Rec, U	2.93E-06	Cell stack accessories (38.54%), Electrolyte (35.12%), Balance of plant accessories (13.48%)
7	Petroleum {RME}| production, onshore | Alloc Rec, U	2.90E-06	Cell stack accessories (38.54%), Electrolyte (35.12%), Balance of plant accessories (13.48%)
8	Electricity, high voltage {SGCC}| market for | Alloc Rec, U	2.84E-06	Cell stack accessories (58.81%), Balance of plant accessories (19.81%), Bipolar plate (14.63%)
9	Nitric acid, without water, in 50% solution state {RER}| nitric acid production, product in 50% solution state | Alloc Rec, U	2.83E-06	Cell stack accessories (44.83%), Balance of plant accessories (15.92%), Battery management system
10	Electricity, high voltage {AU}| market for | Alloc Rec, U	2.49E-06	Cell stack accessories (53.27%), Bipolar plate (24.86%), Balance of plant accessories (17.28%)
11	Natural gas, high pressure {US}| petroleum and gas production, on-shore | Alloc Rec, U	2.44E-06	Cell stack accessories (51.58%), Balance of plant accessories (17.58%)
12	Chlorine, gaseous {RoW}| chlor-alkali electrolysis, membrane cell | Alloc Rec, U	2.41E-06	Electrolyte (52.00%), Bipolar plate (38.01%), Cell stack accessories (8.46%)

Rank	Unit Process	Impact	Component contribution
13	Electricity, high voltage {MX}| market for | Alloc Rec, U	2.12E-06	Cell stack accessories (58.18%), Balance of plant accessories (19.62%), Bipolar plate (15.57%)
14	Heat, district or industrial, other than natural gas {RoW}| heat production, at hard coal industrial furnace 1-10MW | Alloc Rec, U	2.08E-06	Electrolyte (56.96%), Bipolar plate (15.48%), Cell stack accessories (14.44%)
15	Electricity, high voltage {RoW}| market for | Alloc Rec, U	2.00E-06	Cell stack accessories (56.71%), Balance of plant accessories (19.00%), Bipolar plate (17.81%)
16	Electricity, high voltage {ZA}| market for | Alloc Rec, U	1.91E-06	Cell stack accessories (58.37%), Balance of plant accessories (19.70%), Bipolar plate (14.68%)
17	Transport, pipeline, long distance, natural gas {RoW}| processing | Alloc Rec, U	1.74E-06	Cell stack accessories (49.24%), Electrolyte (19.83%), Balance of plant accessories (16.90%)
18	Electricity, high voltage {RoW}| electricity production, oil | Alloc Rec, U	1.67E-06	Cell stack accessories (56.72%), Balance of plant accessories (19.00%), Bipolar plate (17.80%)
19	Electricity, high voltage {IN}| electricity production, hard coal | Alloc Rec, U	1.67E-06	Cell stack accessories (58.18%), Balance of plant accessories (19.66%), Bipolar plate (15.21%)
20	Transport, pipeline, long distance, natural gas {RU}| processing | Alloc Rec, U	1.66E-06	Cell stack accessories (55.44%), Balance of plant accessories (19.00%), Bipolar plate (13.41%)
21	Heat, district or industrial, natural gas {RU}| heat and power co-generation, natural gas, conventional power plant, 100MW electrical | Alloc Rec, U	1.48E-06	Electrolyte (47.79%), Cell stack accessories (34.86%), Balance of plant accessories (12.25%)
Total	1.32E-04 (Cell stack accessories: 47.07%, Bipolar plate: 20.22%, Balance of plant accessories: 15.70%)		

Source: UC Irvine

Table C-6: Structural Path Analysis on Ozone Depletion Potential for Iron Flow Battery (kg CFC 11 eq/ kWh)

Rank	Unit Process	Impact	Component Contribution
1	Adipic acid {RoW}| production | Alloc Rec, U	3.73E-05	Cell frame (99.49%)
2	Adipic acid {RER}| production | Alloc Rec, U	1.84E-05	Cell frame (99.49%)
3	Nitric acid, without water, in 50% solution state {RoW}| nitric acid production, product in 50% solution state | Alloc Rec, U	6.25E-06	Cell frame (37.39%), Electrolyte (27.47%), Cell stack accessories (16.78%)
4	Polyacrylonitrile fibres (PAN), from acrylonitrile and methacrylate, prod. mix, PAN w/o additives EU-27 S	3.86E-06	Battery management system (89.29%), Electrode (10.71%)
5	Electricity, high voltage {RU}| market for | Alloc Rec, U	3.23E-06	Cell stack accessories (65.09%), Electrolyte (17.21%), Cell frame (8.35%)
6	Nylon 6 {RoW}| production | Alloc Rec, U	3.14E-06	Cell frame (99.42%)
7	Nitric acid, without water, in 50% solution state {RER}| nitric acid production, product in 50% solution state | Alloc Rec, U	3.09E-06	Cell frame (37.79%), Electrolyte (27.47%), Cell stack accessories (16.78%)
8	Polyester resin, unsaturated {RoW}| soy-based resin production | Alloc Rec, U	2.01E-06	Cell frame (99.49%)
9	Electricity, high voltage {BR}| market for | Alloc Rec, U	1.70E-06	Cell stack accessories (66.86%), Electrolyte (14.88%), Cell frame (8.31%)
10	Nylon 6 {RER}| production | Alloc Rec, U	1.55E-06	Cell frame (99.42%)
11	Steel, low-alloyed {RoW}| steel production, converter, low-alloyed | Alloc Rec, S	1.52E-06	Cell stack accessories (100%)
12	Petroleum {RoW}| petroleum and gas production, on-shore | Alloc Rec, U	1.22E-06	Cell stack accessories (40.63%), Electrolyte (29.75%), Cell frame (11.18%)
Total	1.22E-04 (Cell frame: 57.69%, Cell stack accessories: 23.27%, Electrolyte: 10.23%)		

Source: UC Irvine

C.3 Particulate Matter

Table C-7: Structural Path Analysis on Particulate Matter for Vanadium Redox Flow Battery (kg PM 2.5 eq/ kWh)

Rank	Unit Process	Impact	Component Contribution
1	Vanadium Pentoxide Production	6.79E-02	Electrolyte (100%)
2	Copper {RoW}| production, primary | Alloc Rec, U	4.04E-02	Cell stack accessories (90.05%), Power conditioning system (7.27%)
3	Electricity, high voltage {IN}| electricity production, lignite | Alloc Rec, U	3.75E-02	Cell stack accessories (58.16%), Battery management system (20.42%), Electrolyte (13.52%)
4	Soda ash, dense {GLO}| modified Solvay process, Hou's process | Alloc Rec, S	3.11E-02	Electrolyte (100%)
5	Ammonium sulfate, as N {RoW}| ammonium sulfate production | Alloc Rec, S	3.08E-02	Electrolyte (100%)
6	Electricity, high voltage {CN-SC}| electricity production, hard coal | Alloc Rec, U	2.24E-02	Electrolyte (98.76%)
7	Sulfuric acid {RoW}| production | Alloc Rec, S	1.55E-02	Electrolyte (100%)
8	Hard coal {CN}| mine operation | Alloc Rec, U	1.46E-02	Electrolyte (53.04%), Cell stack accessories (29.95%), Battery management system (10.59%)
9	Electricity, high voltage {ID}| electricity production, lignite | Alloc Rec, U	1.42E-02	Cell stack accessories (58.28%), Battery management system (20.23%), Electrolyte (13.53%)
10	Electricity, high voltage {RFC}| electricity production, lignite | Alloc Rec, U	1.34E-02	Cell stack accessories (42.59%), Battery management system (42.02%), Electrolyte (9.89%)

Rank	Unit Process	Impact	Component Contribution
11	Electricity, high voltage {SERC}| electricity production, lignite | Alloc Rec, U	1.23E-02	Battery management system (45.68%), Cell stack accessories (39.89%), Electrolyte (9.26%)
12	Electricity, high voltage, for internal use in coal mining {RoW}| electricity production, hard coal, at coal mine power plant | Alloc Rec, U	8.94E-03	Electrolyte (53.04%), cell stack accessories (29.95%), Battery management system (10.59%)
13	Electricity, high voltage, for internal use in coal mining {CN}| electricity production, hard coal, at coal mine power plant | Alloc Rec, U	7.35E-03	Electrolyte (53.04%), cell stack accessories (29.95%), Battery management system (10.59%)
14	Copper concentrate {RoW}| copper mine operation | Alloc Rec, U	6.94E-03	Cell stack accessories (89.45%), Power conditioning system (7.71%)
15	Electricity, high voltage {IN}| electricity production, hard coal | Alloc Rec, U	5.90E-03	Cell stack accessories (58.27%, Battery management system (20.31%), Electrolyte (13.54%)
16	Copper {RAS}| production, primary | Alloc Rec, U	5.89E-03	Power conditioning system (68.55%), Battery management system (19.36%)
17	Electricity, high voltage {WECC, US only}| electricity production, lignite | Alloc Rec, U	5.22E-03	Cell stack accessories (42.82%), Battery management system (41.71%), Electrolyte (9.94%)
18	Coke {RoW}| coking | Alloc Rec, U	5.05E-03	Cell stack accessories (65.64%), Balance of plant accessories (19.70%), Power conditioning system (9.06%)
Total	4.83E-01 (Electrolyte: 44.19%, Cell stack accessories: 33.51%, Battery management system: 12.40%)		

Source: UC Irvine

Table C-8: Structural Path Analysis on Particulate Matter for Zinc Bromide Flow Battery (kg PM 2.5 eq/ kWh)

Rank	Unit Process	Impact	Component Contribution
1	Electricity, high voltage {IN}| electricity production, lignite | Alloc Rec, U	1.25E-01	Cell stack accessories (58.17%), Balance of plant accessories (19.66%), Bipolar plate (15.21%)
2	Titanium primary, triple-melt {GLO}| titanium production, primary, triple melt | Alloc Rec, S	5.42E-02	Bipolar plate (82.35%), Cell stack accessories (17.65%)
3	Electricity, high voltage {ID}| electricity production, lignite | Alloc Rec, U	4.72E-02	Cell stack accessories (58.19%), Balance of plant accessories (19.62%), Bipolar plate (15.12%)
4	Electricity, high voltage {RFC}| electricity production, lignite | Alloc Rec, U	3.54E-02	Cell stack accessories (53.78%), Balance of plant accessories (19.72%), Bipolar plate (13.88%)
5	Heat, district or industrial, other than natural gas {RoW}| heat production, at hard coal industrial furnace 1-10MW | Alloc Rec, U	3.11E-02	Electrolyte (56.96%), Bipolar plate (15.38%), Cell stack accessories (14.44%)
6	Electricity, high voltage {SERC}| electricity production, lignite | Alloc Rec, U	3.10E-02	Cell stack accessories (52.74%), Balance of plant accessories (19.72%), Bipolar plate (13.63%)
7	Hard coal {CN}| mine operation | Alloc Rec, U	2.65E-02	Cell stack accessories (54.92%), Balance of plant accessories (18.92%), Bipolar plate (13.32%)
8	Electricity, high voltage {IN}| electricity production, hard coal | Alloc Rec, U	1.97E-02	Cell stack accessories (58.18%), Balance of plant accessories (19.66%), Bipolar plate (15.21%)
9	Electricity, high voltage, for internal use in coal mining {RoW}| electricity production, hard coal, at coal mine power plant | Alloc Rec, U	1.61E-02	Cell stack accessories (54.92%), Balance of plant accessories (18.92%), Bipolar plate (13.32%)
10	Natural gas, high pressure {RoW}| natural gas production | Alloc Rec, U	1.59E-02	Cell stack accessories (47.72%), Electrolyte (24.52%), Balance of plant accessories (16.34%)

Rank	Unit Process	Impact	Component Contribution
11	Coke {RoW}| coking | Alloc Rec, U	1.57E-02	Cell stack accessories (70.24%), Balance of plant accessories (23.20%)
12	Electricity, high voltage {RU}| heat and power co-generation, lignite | Alloc Rec, U	1.56E-02	Cell stack accessories (58.49%), Balance of plant accessories (19.75%), Bipolar plate (14.52%)
13	Natural gas, high pressure {US}| natural gas production | Alloc Rec, U	1.52E-02	Cell stack accessories (51.58%), Balance of plant accessories (17.58%), Electrolyte (17.52%)
14	Electricity, high voltage {WECC, US only}| electricity production, lignite | Alloc Rec, U	1.38E-02	Cell stack accessories (53.86%), Balance of plant accessories (19.73%), Bipolar plate (13.85%)
15	Electricity, high voltage, for internal use in coal mining {CN}| electricity production, hard coal, at coal mine power plant | Alloc Rec, U	1.33E-02	Cell stack accessories (54.92%), Balance of plant accessories (18.92%), Bipolar plate (13.32%)
16	Electricity, high voltage {TR}| electricity production, lignite | Alloc Rec, U	1.19E-02	Cell stack accessories (58.14%), Balance of plant accessories (19.81%), Bipolar plate (15.51%)
17	Electricity, high voltage {RoW}| electricity production, hard coal | Alloc Rec, U	1.11E-02	Cell stack accessories (56.64%), Balance of plant accessories (18.98%), Bipolar plate (17.80%)
18	Electricity, high voltage {MRO, US only}| electricity production, lignite | Alloc Rec, U	9.82E-03	Cell stack accessories (58.77%), Balance of plant accessories (19.79%), Bipolar plate (14.78%)
19	Electricity, high voltage {TRE}| electricity production, lignite | Alloc Rec, U	9.78E-03	Cell stack accessories (55.07%), Balance of plant accessories (19.70%), Bipolar plate (14.29%)
20	Silicon, metallurgical grade {RoW}| production | Alloc Rec, U	9.03E-03	Cell stack accessories (75.37%), Balance of plant accessories (24.55%)

Rank	Unit Process	Impact	Component Contribution
21	Electricity, high voltage {RoW}| electricity production, lignite | Alloc Rec, U	8.82E-03	Cell stack accessories (56.60%), Balance of plant accessories (18.97%), Bipolar plate (17.79%)
Total	7.94E-01 (Cell stack accessories: 49.98%, Bipolar plate: 18.69%, Balance of plant accessories: 17.36%)		

Source: UC Irvine

Table C-9: Structural Path Analysis on Particulate Matter for Iron Flow Battery (kg PM 2.5 eq/ kWh)

Rank	Unit Process	Impact	Component Contribution
1	Electricity, high voltage {IN}| electricity production, lignite | Alloc Rec, U	4.91E-02	Cell stack accessories (66.44%), Electrolyte (15.24%), Cell frame (8.29%)
2	Electricity, high voltage {ID}| electricity production, lignite | Alloc Rec, U	1.85E-02	Cell stack accessories (66.46%), Electrolyte (15.20%), Cell frame (8.29%)
3	Steel, low-alloyed {RoW}| steel production, converter, low-alloyed | Alloc Rec, S	1.47E-02	Cell stack accessories (100.00%)
4	Electricity, high voltage {RFC}| electricity production, lignite | Alloc Rec, U	1.28E-02	Cell stack accessories (66.88%), Electrolyte (14.98%), Cell frame (8.30%)
5	Electricity, high voltage {SERC}| electricity production, lignite | Alloc Rec, U	1.10E-02	Cell stack accessories (66.84%), Electrolyte (15.00%), Cell frame (8.30%)
6	Hard coal {CN}| mine operation | Alloc Rec, U	9.74E-03	Cell stack accessories (66.81%), Electrolyte (14.78%), Cell frame (7.86%)
7	Electricity, high voltage {IN}| electricity production, hard coal | Alloc Rec, U	7.72E-03	Cell stack accessories (66.48%), Electrolyte (15.22%), Cell frame (8.29%)
8	Electricity, high voltage {RU}| heat and power co-generation, lignite | Alloc Rec, U	6.36E-03	Cell stack accessories (65.00%), Electrolyte (17.26%), Cell frame (8.32%)
9	Electricity, high voltage, for internal use in coal mining {RoW}| electricity production, hard coal, at coal mine power plant | Alloc Rec, U	5.95E-03	Cell stack accessories (66.81%), Electrolyte (17.76%), Cell frame (7.86%)

Rank	Unit Process	Impact	Component Contribution
10	Natural gas, high pressure {RoW}| natural gas production | Alloc Rec, U	5.52E-03	Cell stack accessories (62.66%), Electrolyte (14.83%), Cell frame (13.23%)
11	Natural gas, high pressure {US}| natural gas production | Alloc Rec, U	5.51E-03	Cell stack accessories (64.39%), Electrolyte (14.83%), Cell frame (11.22%)
12	Electricity, high voltage {WECC, US only}| electricity production, lignite | Alloc Rec, U	5.00E-03	Cell stack accessories (66.88%), Electrolyte (14.98%), Cell frame (8.30%)
13	Electricity, high voltage, for internal use in coal mining {CN}| electricity production, hard coal, at coal mine power plant | Alloc Rec, U	4.89E-03	Cell stack accessories (66.81%), Electrolyte, (14.76%) Cell frame (7.86%)
14	Electricity, high voltage {TR}| electricity production, lignite | Alloc Rec, U	4.71E-03	Cell stack accessories (66.07%), Electrolyte (14.81%), Cell frame (9.45%)
15	Electricity, high voltage {RoW}| electricity production, hard coal | Alloc Rec, U	4.20E-03	Cell stack accessories (66.77%), Electrolyte (15.00%), Cell frame (8.29%)
16	Heat, district or industrial, other than natural gas {RoW}| heat production, at hard coal industrial furnace 1-10MW | Alloc Rec, U	4.10E-03	Cell stack accessories (40.12%), Electrolyte (19.08%), Cell frame (16.88%)
17	Electricity, high voltage {MRO, US only}| electricity production, lignite | Alloc Rec, U	3.87E-03	Cell stack accessories (67.05%), Electrolyte (14.88%), Cell frame (8.31%)
18	Coke {RoW}| coking | Alloc Rec, U	3.83E-03	Cell stack accessories (82.67%), Power conditioning system (7.14%)
19	Copper {RAS}| production, primary | Alloc Rec, U	3.83E-03	Power conditioning system (58.85%), Electrolyte (15.76%), Recirculation loops (12.08%)
20	Electricity, high voltage {TRE}| electricity production, lignite | Alloc Rec, U	3.61E-03	Cell stack accessories (66.92%), Electrolyte (14.95%), Cell frame (8.31%)
21	Electricity, high voltage {RoW}| electricity production, lignite | Alloc Rec, U	3.33E-03	Cell stack accessories (66.69%), Electrolyte (15.05%), Cell frame (8.28%)

Rank	Unit Process	Impact	Component Contribution
22	Silicon, metallurgical grade {RoW}| production | Alloc Rec, U	3.27E-03	Cell stack accessories (99.91%)
Total	3.10E-01 (Cell stack accessories: 59.71%, Electrolyte: 15.97%, Cell frame:9.16%)		

Source: UC Irvine

C.4 Acidification Potential

Table C-10: Structural Path Analysis on Acidification Potential for Vanadium-Redox Flow Battery (kg SO_2 eq/ kWh)

Rank	Unit Process	Impact	Component Contribution
1	Vanadium Pentoxide Production	2.34E-01	Electrolyte (100.00%)
2	Copper {RoW}| production, primary | Alloc Rec, U	1.39E-01	Cell stack accessories (90.05%), Power conditioning system (7.27%)
3	Ammonium sulfate, as N {RoW}| ammonium sulfate production | Alloc Rec, S	8.19E-02	Electrolyte (100.00%)
4	Electricity, high voltage {CN-SC}| electricity production, hard coal | Alloc Rec, U	7.82E-02	Electrolyte (98.76%)
5	Soda ash, dense {GLO}| modified Solvay process, Hou's process | Alloc Rec, S	7.75E-02	Electrolyte (100.00%)
6	Sulfuric acid {RoW}| production | Alloc Rec, S	5.27E-02	Electrolyte (100.00%)
7	Hard coal {CN}| mine operation | Alloc Rec, U	5.05E-02	Electrolyte (53.04%), Cell stack accessories (29.95%), Battery management system (10.59%)
8	Electricity, high voltage {IN}| electricity production, hard coal | Alloc Rec, U	2.04E-02	Cell stack accessories (58.27%), Battery management system (20.31%), Electrolyte (13.54%)
9	Copper {RAS}| production, primary | Alloc Rec, U	2.03E-02	Power conditioning system (68.55%), Battery management system (19.36%), Cell stack accessories (6.20%)

Rank	Unit Process	Impact	Component Contribution
10	Heat, district or industrial, other than natural gas {RoW}| heat production, at hard coal industrial furnace 1-10MW | Alloc Rec, U	1.44E-02	Cell stack accessories (35.49%), Battery management system (33.39%), Power conditioning system (10.40%)
11	Blasting {RoW}| processing | Alloc Rec, U	1.42E-02	Cell stack accessories (50.45%), Battery management system (23.61%), Power conditioning system (16.77%)
12	Copper {RU}| platinum group metal mine operation, ore with high palladium content | Alloc Rec, U	1.39E-02	Power conditioning system (68.55%), Battery management system (19.36%), Cell stack accessories (6.20%)
13	Polyethylene, high density, granulate {RoW}| production | Alloc Rec, U	1.37E-02	Electrolyte (98.13%)
14	Natural gas, high pressure {US}| natural gas production | Alloc Rec, U	1.34E-02	Cell stack accessories (60.99%), Battery management system (18.55%), Electrolyte (11.63%)
15	Natural gas, high pressure {RoW}| natural gas production | Alloc Rec, U	1.30E-02	Cell stack accessories (61.35%), Battery management system (16.32%), Electrolyte (12.51%)
Total	1.19E+00 (Electrolyte: 51.90%, Cell stack accessories: 28.97%, Battery management system: 9.06%)		

Source: UC Irvine

Table C-11: Structural Path Analysis on Acidification Potential for Zinc-Bromide Flow Battery (kg SO_2 eq/ kWh)

Rank	Unit Process	Impact	Component Contribution
1	Heat, district or industrial, other than natural gas {RoW}| heat production, at hard coal industrial furnace 1-10MW | Alloc Rec, U	1.08E-01	Electrolyte (56.96%), Bipolar plate (15.48%), Cell stack accessories (14.44%)
2	Titanium primary, triple-melt {GLO}| titanium production, primary, triple melt | Alloc Rec, S	9.34E-02	Bipolar plate (82.35%), Cell stack accessories (17.65%)
3	Hard coal {CN}| mine operation | Alloc Rec, U	9.12E-02	Cell stack accessories (54.92%), Balance of plant accessories (18.92%), Bipolar plate (13.32%)
4	Electricity, high voltage {IN}| electricity production, hard coal | Alloc Rec, U	6.79E-02	Cell stack accessories (58.18%), Balance of plant accessories (19.66%), Bipolar plate (15.21%)

Rank	Unit Process	Impact	Component Contribution
5	Natural gas, high pressure {RoW}| natural gas production | Alloc Rec, U	5.47E-02	Cell stack accessories (47.72%), Electrolyte (24.53%), Balance of plant accessories (16.34%)
6	Natural gas, high pressure {US}| natural gas production | Alloc Rec, U	5.23E-02	Cell stack accessories (51.58%), Balance of plant accessories (17.58%), Bipolar plate (12.06%)
7	Silicon, metallurgical grade {RoW}| production | Alloc Rec, U	4.01E-02	Cell stack accessories (75.37%), Balance of plant accessories (24.55%)
8	Electricity, high voltage {RoW}| electricity production, hard coal | Alloc Rec, U	3.82E-02	Cell stack accessories (56.64%), Balance of plant accessories (18.98%), Bipolar plate (17.80%)
9	Electricity, high voltage {ZA}| electricity production, hard coal | Alloc Rec, U	2.82E-02	Cell stack accessories (58.11%), Balance of plant accessories (19.62%), Bipolar plate (14.645)
10	Transport, freight, sea, transoceanic ship {GLO}| processing | Alloc Rec, U	2.54E-02	Cell stack accessories (58.54%), Balance of plant accessories (20.24%), Bipolar plate (8.62%)
11	Electricity, high voltage {RoW}| electricity production, oil | Alloc Rec, U	1.98E-02	Cell stack accessories (56.72%), Balance of plant accessories (19.00%), Bipolar plate (17.80%)
12	Electricity, high voltage {IN}| electricity production, lignite | Alloc Rec, U	1.97E-02	Cell stack accessories (58.17%), Balance of plant accessories (19.66), Bipolar plate (15.21%)
13	Waste natural gas, sour {GLO}| treatment of, burned in production flare | Alloc Rec, U	1.92E-02	Cell stack accessories (38.98%), Electrolyte (34.57%), Bipolar plate (10.56%)
14	Hard coal {RoW}| mine operation | Alloc Rec, U	1.77E-02	Cell stack accessories (54.22%), Balance of plant accessories (18.81%), Bipolar plate (13.24%)
15	Electricity, high voltage {CN-NM}| electricity production, hard coal | Alloc Rec, U	1.75E-02	Cell stack accessories (58.41%), Balance of plant accessories (19.70%), Bipolar plate (14.58%)
16	Electricity, high voltage {CN-SD}| electricity production, hard coal | Alloc Rec, U	1.66E-02	Cell stack accessories (58.41%), Balance of plant accessories (19.70%), Bipolar plate (14.58%)

Rank	Unit Process	Impact	Component Contribution
17	Electricity, high voltage, for internal use in coal mining {RoW}| electricity production, hard coal, at coal mine power plant | Alloc Rec, U	1.64E-02	Cell stack accessories (54.92%), Balance of plant accessories (19.70%), Bipolar plate (13.32%)
18	Sinter, iron {GLO}| production | Alloc Rec, U	1.53E-02	Cell stack accessories (67.44%), Balance of plant accessories (19.70%), Recirculation loops (5.81%)
Total	1.45E+00 (Cell stack accessories: 47.58%, Bipolar plate: 17.84%, Balance of plant accessories: 16.32%)		

Source: UC Irvine

Table C-12: Structural Path Analysis on Acidification Potential for Iron Flow Battery ($kg\ SO_2\ eq/\ kWh$)

Rank	Unit Process	Impact	Component Contribution
1	Carbon paper	4.17E-02	Battery management system (89.29%), Electrode (10.71%)
2	Hard coal {CN}| mine operation | Alloc Rec, U	3.36E-02	Cell stack accessories (66.81%), Electrolyte (14.76%), Cell frame (7.86%)
3	Electricity, high voltage {IN}| electricity production, hard coal | Alloc Rec, U	2.67E-02	Cell stack accessories (66.48%), Electrolyte (15.22%), Cell frame (8.29%)
4	Steel, low-alloyed {RoW}| steel production, converter, low-alloyed | Alloc Rec, S	2.33E-02	Cell stack accessories (100.00%)
5	Natural gas, high pressure {RoW}| natural gas production | Alloc Rec, U	1.90E-02	Cell stack accessories (62.66%), Electrolyte (14.83%), Cell frame (13.23%)
6	Natural gas, high pressure {US}| natural gas production | Alloc Rec, U	1.90E-02	Cell stack accessories (64.39%), Electrolyte (14.83%), Cell frame (11.22%)
7	Silicon, metallurgical grade {RoW}| production | Alloc Rec, U	1.45E-02	Cell stack accessories (99.91%)
8	Electricity, high voltage {RoW}| electricity production, hard coal | Alloc Rec, U	1.44E-02	Cell stack accessories (66.77%), Electrolyte (15.005), Cell frame (8.29%)

Rank	Unit Process	Impact	Component Contribution
9	Heat, district or industrial, other than natural gas {RoW}| heat production, at hard coal industrial furnace 1-10MW | Alloc Rec, U	1.42E-02	Cell stack accessories (40.12%), Electrolyte (19.08%), Cell frame (16.88%)
10	Copper {RAS}| production, primary | Alloc Rec, U	1.32E-02	Power conditioning system (58.85%), Electrolyte (15.76%), Recirculation loops (12.08%)
11	Electricity, high voltage {ZA}| electricity production, hard coal | Alloc Rec, U	1.17E-02	Cell stack accessories (66.30%), Electrolyte (15.32%), Cell frame (8.09%)
12	Copper {RoW}| production, primary | Alloc Rec, U	9.60E-03	Power conditioning system (58.85%), Electrolyte (15.76%), Recirculation loops (12.08%)
13	Copper {RU}| platinum group metal mine operation, ore with high palladium content | Alloc Rec, U	9.07E-03	Power conditioning system (58.85%), Electrolyte (15.76%), Recirculation loops (12.08%)
14	Transport, freight, sea, transoceanic ship {GLO}| processing | Alloc Rec, U	8.85E-03	Cell stack accessories (46.78%), Electrolyte, (22.83%), Cell frame (17.35%)
15	Waste natural gas, sour {GLO}| treatment of, burned in production flare | Alloc Rec, U	7.98E-03	Cell stack accessories (41.24%), Electrolyte (29.51%), Cell frame (11.22%)
16	Bisphenol A epoxy based vinyl ester resin {RoW}| production | Alloc Rec, S	7.92E-03	Bipolar plate (100.00%)
17	Electricity, high voltage {IN}| electricity production, lignite | Alloc Rec, U	7.74E-03	Cell stack accessories (66.44%), Electrolyte (15.24%), Cell frame (8.29%)
18	Polyacrylonitrile fibres (PAN), from acrylonitrile and methacrylate, prod. mix, PAN w/o additives EU-27 S	7.73E-03	Battery management system (89.29%), Electrode (10.71%)
19	Copper {RLA}| production, primary | Alloc Rec, U	7.61E-03	Power conditioning system (58.85%), Electrolyte (15.76%), Recirculation loops (12.08%)
20	Electricity, high voltage {RoW}| electricity production, oil | Alloc Rec, U	7.44E-03	Cell stack accessories (66.96%), Electrolyte (14.89%), Cell frame (8.30%)

Rank	Unit Process	Impact	Component Contribution
21	Electricity, high voltage {CN-NM}| electricity production, hard coal | Alloc Rec, U	7.32E-03	Cell stack accessories (67.63%), Electrolyte (14.75%), Cell frame (7.87%)
22	Electricity, high voltage {CN-SD}| electricity production, hard coal | Alloc Rec, U	6.96E-03	Cell stack accessories (67.63%), Electrolyte (14.75%), Cell frame (7.87%)
23	Sour gas, burned in gas turbine {RoW}| processing | Alloc Rec, U	6.56E-03	Cell stack accessories (48.73%), Electrolyte (34.26%), Cell frame (9.60%)
24	Styrene {RoW}| production | Alloc Rec, U	6.47E-03	Electrolyte (99.35%)
Total	6.44E-01 (Cell stack accessories: 49.99%, Electrolyte: 16.57%, Cell frame: 9.66%)		

Source: UC Irvine

C.5 Eutrophication

Table C-13: Structural Path Analysis on Eutrophication for Vanadium-Redox Flow Battery (kg P eq/ kWh)

Rank	Unit Process	Impact	Component Contribution
1	Sulfidic tailing, off-site {GLO}| treatment of | Alloc Rec, U	7.54E-02	Cell stack accessories (59.99%), Power conditioning system (23.18%), Battery management system (12.31%)
2	Spoil from lignite mining {GLO}| treatment of, in surface landfill | Alloc Rec, U	2.50E-02	Cell stack accessories (52.61%), Battery management system (29.32%), Electrolyte (9.58%)
3	Spoil from hard coal mining {GLO}| treatment of, in surface landfill | Alloc Rec, U	1.79E-02	Cell stack accessories (46.82%), Electrolyte (24.48%), Battery management system (17.36%)
4	Soda ash, dense {GLO}| modified Solvay process, Hou's process | Alloc Rec, S	6.78E-03	Electrolyte (100.00%)
5	Ammonium sulfate, as N {RoW}| ammonium sulfate production | Alloc Rec, S	6.75E-03	Electrolyte (100.00%)
Total	1.35E-01 (Cell stack accessories: 50.08%, Electrolyte: 16.51%, Battery management system: 14.90%)		

Source: UC Irvine

Table C-14: Structural Path Analysis on Eutrophication for Zinc-Bromide Flow Battery (kg P eq/ kWh)

Rank	Unit Process	Impact	Component Contribution
1	Spoil from lignite mining {GLO}| treatment of, in surface landfill | Alloc Rec, U	7.74E-02	Cell stack accessories (56.49%), Balance of plant accessories (19.57%), Bipolar plate (15.46%)
2	Spoil from hard coal mining {GLO}| treatment of, in surface landfill | Alloc Rec, U	5.09E-02	Cell stack accessories (54.36%), Balance of plant accessories (18.91%), Bipolar plate (15.46%)
3	Sulfidic tailing, off-site {GLO}| treatment of | Alloc Rec, U	2.46E-02	Power conditioning system (28.42%), Battery management system (26.76%), Recirculation loops (18.30%)
4	Titanium primary, triple-melt {GLO}| titanium production, primary, triple melt | Alloc Rec, S	1.14E-02	Bipolar plate (82.35%), Cell stack accessories (17.65%)
5	Basic oxygen furnace waste {RoW}| treatment of, residual material landfill | Alloc Rec, U	2.67E-03	Cell stack accessories (67.48%), Balance of plant accessories (23.44%)
Total	1.71E-01 (Cell stack accessories: 46.50%, Bipolar plate: 17.82%, Balance of plant accessories: 15.76%)		

Source: UC Irvine

Table C-15: Structural Path Analysis on Eutrophication for Iron Flow Battery (kg P eq/ kWh)

Rank	Unit Process	Impact	Component Contribution
1	Spoil from lignite mining {GLO}| treatment of, in surface landfill | Alloc Rec, U	2.97E-02	Cell stack accessories (66.66%), Electrolyte (17.03%), Cell frame (7.84%)
2	Sulfidic tailing, off-site {GLO}| treatment of | Alloc Rec, U	2.13E-02	Power conditioning system (45.92%), Battery management system (20.08%), Electrolyte (16.13%)
3	Spoil from hard coal mining {GLO}| treatment of, in surface landfill | Alloc Rec, U	1.74E-02	Cell stack accessories (65.99%), Electrolyte (15.56%), Cell frame (7.90%)
4	Steel, low-alloyed {RoW}| steel production, converter, low-alloyed | Alloc Rec, S	6.44E-03	Cell stack accessories (100.00%)
Total	7.73E-02 (Cell stack accessories: 51.59%, Electrolyte: 15.18%, Power conditioning system: 14.53%)		

Source: UC Irvine

C.6 Ecotoxicity

Table C-16: Structural Path Analysis on Ecotoxicity for Vanadium-Redox Flow Battery (PAF.m^3.day/ kWh)

Rank	Unit Process	Impact	Component Contribution
1	P-dichlorobenzene {RoW}| benzene chlorination | Alloc Rec, U	1.02E-01	Battery management system (96.46%)
2	Soda ash, dense {GLO}| modified Solvay process, Hou's process | Alloc Rec, S	7.61E-02	Electrolyte (100.00%)
3	Coke {RoW}| coking | Alloc Rec, U	2.71E-02	Cell stack accessories (65.64%), Balance of plant accessories (19.70%), Power conditioning system (9.06%)
4	P-dichlorobenzene {RER}| benzene chlorination | Alloc Rec, U	2.56E-02	Battery management system (96.46%)
5	Water discharge from petroleum/natural gas extraction, onshore {GLO}| treatment of | Alloc Rec, U	1.71E-02	Cell stack accessories (37.97%), Power conditioning system (24.83%), Battery management system (18.96%)
6	Potato, Swiss integrated production {CH}| potato production, Swiss integrated production, intensive | Alloc Rec, U	1.39E-02	Electrolyte (69.97%), Cell stack accessories (14.32%), Power conditioning system (8.84%)
7	Phenol {RoW}| production | Alloc Rec, U	1.38E-02	Battery management system (41.24%), Power conditioning system (17.65%), Cell stack accessories (13.48%)
8	Wood preservation, pressure vessel, creosote, outdoor use, ground contact {RoW}| wood preservation, pressure vessel, creosote, outdoor use, ground contact | Alloc Rec, U	1.18E-02	Balance of plant accessories (79.36%), Electrolyte (6.36%), Battery management system (6.09%)
9	Ammonium sulfate, as N {RoW}| ammonium sulfate production | Alloc Rec, S	1.05E-02	Electrolyte (100.00%)
10	Phenol {RER}| production | Alloc Rec, U	6.82E-03	Battery management system (41.24%), Power conditioning system (17.65%), Cell stack accessories (13.48%)

Rank	Unit Process	Impact	Component Contribution
11	Sugarcane {BR}| production | Alloc Rec, U	6.75E-03	Cell stack accessories (59.77%), Battery management system (18.45%), Electrolyte (13.82%)
12	Ethyl acetate {RoW}| production | Alloc Rec, U	6.72E-03	Battery management system (99.32%)
13	Sulfuric acid {RoW}| production | Alloc Rec, S	4.83E-03	Electrolyte (100.00%)
14	Polyethylene, high density, granulate {RoW}| production | Alloc Rec, U	4.56E-03	Electrolyte (98.13%)
15	Polycarbonate {RoW}| production | Alloc Rec, U	4.35E-03	Battery management system (69.33%), Power conditioning system (30.61%)
16	Sugarcane {IN}| sugarcane production | Alloc Rec, U	4.04E-03	Cell stack accessories (60.32%), Battery management system (18.74%), Electrolyte (13.39%)
Total	3.88E-01 (Battery management system: 43.20%, Electrolyte: 30.69%, Cell stack accessories: 11.54%)		

Source: UC Irvine

Table C-17: Structural Path Analysis on Ecotoxicity for Zinc-Bromide Flow Battery (PAF.m^3.day/ kWh)

Rank	Unit Process	Impact	Component Contribution
1	Coke {RoW}| coking | Alloc Rec, U	8.46E-02	Cell stack accessories (70.24%), Balance of plant accessories (23.20%)
2	Water discharge from petroleum/natural gas extraction, onshore {GLO}| treatment of | Alloc Rec, U	5.47E-02	Cell stack accessories (38.56%), Electrolyte (35.11%), Balance of plant accessories (13.48%)
3	Sugarcane {BR}| production | Alloc Rec, U	2.30E-02	Cell stack accessories (58.32%), Balance of plant accessories (19.69%), Bipolar plate (15.32%)
4	Titanium primary, triple-melt {GLO}| titanium production, primary, triple melt | Alloc Rec, S	2.02E-02	Bipolar plate (82.35%), Cell stack accessories (17.65%)
5	Hydrochloric acid, without water, in 30% solution state {RoW}| benzene chlorination | Alloc Rec, U	1.53E-02	Bipolar plate (74.98%), Cell stack accessories (17.91%)

Rank	Unit Process	Impact	Component Contribution
6	Sugarcane {IN}| sugarcane production | Alloc Rec, U	1.39E-02	Cell stack accessories (56.69%), Balance of plant accessories (19.02%), Bipolar plate (17.80%)
7	Potato, Swiss integrated production {CH}| potato production, Swiss integrated production, intensive | Alloc Rec, U	1.06E-02	Electrolyte (46.48%), Cell stack accessories (22.61%), Balance of plant accessories (18.98%)
8	Phenol {RoW}| production | Alloc Def, U	8.78E-03	Bipolar plate (57.69%), Cell frame (42.31%)
9	Phenol {RoW}| production | Alloc Rec, U	7.37E-03	Cell stack accessories (39.57%), Electrolyte (18.65%), Balance of plant accessories (18.48%)
10	Natural gas, unprocessed, at extraction {GLO}| production | Alloc Rec, U	7.02E-03	Cell stack accessories (47.72%), Electrolyte (24.52%), Balance of plant accessories (16.34%)
11	Natural gas, high pressure {US}| natural gas production | Alloc Rec, U	6.40E-03	Cell stack accessories (51.58%), Balance of plant accessories (17.58%), Bipolar plate (12.06%)
12	Sugarcane {RoW}| production | Alloc Rec, U	6.11E-03	Cell stack accessories (56.69%), Balance of plant accessories (19.02%), Bipolar plate (17.80%)
13	Coal gas {RoW}| coking | Alloc Rec, U	5.52E-03	Cell stack accessories (47.29%), Bipolar plate (32.75%)
14	Polyethylene, high density, granulate {RoW}| production | Alloc Rec, U	4.49E-03	Bipolar plate (46.59%), Cell frame (34.09%), Cell stack accessories (9.69%)
15	Hydrochloric acid, without water, in 30% solution state {RER}| benzene chlorination | Alloc Rec, U	4.37E-03	Bipolar plate (68.59%), Cell stack accessories (17.70%), Electrolyte (9.60%)
16	Phenol {RER}| production | Alloc Def, U	4.34E-03	Bipolar plate (57.69%), Cell frame (42.31%)

Rank	Unit Process	Impact	Component Contribution
17	Wood preservation, pressure vessel, creosote, outdoor use, ground contact {RoW}| wood preservation, pressure vessel, creosote, outdoor use, ground contact | Alloc Rec, U	4.02E-03	Cell stack accessories (43.89%), Electrolyte, Balance of plant accessories (18.17%)
18	Phenol {RER}| production | Alloc Rec, U	3.64E-03	Cell stack accessories (39.57%), Electrolyte (24.37%), Balance of plant accessories (18.48%)
Total	3.23E-01 (Cell stack accessories: 44.56%, Bipolar plate: 20.94%, Balance of plant accessories: 15.32%)		

Source: UC Irvine

Table C-18: Structural Path Analysis on Ecotoxicity for Iron Flow Battery (PAF.m^3.day/ kWh)

Rank	Unit Process	Impact	Component Contribution
1	Bisphenol A epoxy based vinyl ester resin {RoW}| production | Alloc Rec, S	3.04E-01	Bipolar plate (100.00%)
2	Polyester resin, unsaturated {RoW}| soy-based resin production | Alloc Rec, U	1.29E-01	Cell frame (99.49%)
3	Phenol {RoW}| production | Alloc Rec, U	1.25E-01	Cell frame (86.29%), Bipolar plate (7.67%)
4	Acetic anhydride {RoW}| production, ketene route | Alloc Rec, U	6.61E-02	Cell frame (99.49%)
5	Phenol {RER}| production | Alloc Rec, U	6.20E-02	Cell frame (86.29%), Bipolar plate (7.67%)
6	Propylene glycol, liquid {RoW}| production | Alloc Rec, U	5.85E-02	Electrolyte (77.41%), Cell frame (22.47%)
7	Polyester resin, unsaturated {US}| soy-based resin production | Alloc Rec, U	4.31E-02	Cell frame (99.49%)
8	Cyclohexanol {RoW}| production | Alloc Rec, U	3.49E-02	Cell frame (99.31%)
9	Propylene glycol, liquid {RER}| production | Alloc Rec, U	2.89E-02	Electrolyte (77.41%), Cell frame (22.47%)
10	Water discharge from petroleum/natural gas extraction, onshore {GLO}| treatment of | Alloc Rec, U	2.28E-02	Cell stack accessories (40.65%), Electrolyte (29.74%), Cell frame (11.19%)

Rank	Unit Process	Impact	Component Contribution
11	Acetic anhydride {RER}| production, ketene route | Alloc Rec, U	2.15E-02	Cell frame (99.49%)
12	Coke {RoW}| coking | Alloc Rec, U	2.06E-02	Cell stack accessories (82.67%), Power conditioning system (7.14%)
13	Cyclohexanol {RER}| production | Alloc Rec, U	1.72E-02	Cell frame (99.31%)
14	Potato, Swiss integrated production {CH}| potato production, Swiss integrated production, intensive | Alloc Rec, U	1.72E-02	Electrolyte (86.49%), Cell stack accessories (5.92%)
15	Steel, low-alloyed {RoW}| steel production, converter, low-alloyed | Alloc Rec, S	1.44E-02	Cell stack accessories (100.00%)
Total	1.06E+00 (Cell frame: 49.69%, Bipolar plate: 30.77%, Electrolyte: 10.67%)		

Source: UC Irvine

C.7 Cumulative Energy Demand

Table C-19: Structural Path Analysis on Cumulative Energy Demand, Nonrenewable Fossil, for Vanadium-Redox Flow Battery (MJ/ kWh)

Rank	Unit Process	Impact	Component Contribution
1	Vanadium Pentoxide Production	3513.84	Electrolyte (100.00%)
2	Hard coal {CN}| mine operation | Alloc Rec, U	397.42	Electrolyte (53.04%), Cell stack accessories (29.95%)
3	Soda ash, dense {GLO}| modified Solvay process, Hou's process | Alloc Rec, S	219.99	Electrolyte (100.00%)
4	Ammonium sulfate, as N {RoW}| ammonium sulfate production | Alloc Rec, S	211.22	Electrolyte (100.00%)
5	Polyethylene, high density, granulate {RoW}| production | Alloc Rec, U	187.34	Electrolyte (98.13%)
6	Hard coal {RoW}| mine operation | Alloc Rec, U	90.73	Cell stack accessories (57.56%), Battery management system (17.60%), Electrolyte (10.50%)

Rank	Unit Process	Impact	Component Contribution
7	Lignite {RoW}| mine operation | Alloc Rec, U	85.56	Cell stack accessories (50.33%), Battery management system (31.71%), Electrolyte (11.36%)
8	Hard coal {RNA}| mine operation | Alloc Rec, U	69.24	Cell stack accessories (49.34%), Battery management system (29.08%), Electrolyte (10.67%)
Total	5540.46 (Electrolyte: 81.08%, Cell stack accessories: 11.34%, Battery management system:3.95%)		

Source: UC Irvine

Table C-20: Structural Path Analysis on Cumulative Energy Demand, Non-renewable Fossil, for Zinc-Bromide Flow Battery (MJ/ kWh)

Rank	Unit Process	Impact	Component Contribution
1	Hard coal {CN}| mine operation | Alloc Rec, U	718.09	Cell stack accessories (54.92%), Balance of plant accessories (18.92%), Bipolar plate
2	Hard coal {RoW}| mine operation | Alloc Rec, U	319.93	Cell stack accessories (54.22%), Balance of plant accessories (18.81%), Bipolar plate
3	Lignite {RoW}| mine operation | Alloc Rec, U	258.50	Cell stack accessories (55.54%), Balance of plant accessories (19.39%), Bipolar plate
4	Titanium primary, triple-melt {GLO}| titanium production, primary, triple melt | Alloc Rec, S	240.97	Bipolar plate, Cell stack accessories (17.65%)
5	Hard coal {RNA}| mine operation | Alloc Rec, U	197.04	Cell stack accessories (57.68%), Balance of plant accessories (20.21%), Bipolar plate
6	Wax, lost-wax casting {GLO}| wax production, for lost-wax metal casting | Alloc Rec, U	189.47	Cell stack accessories (75.44%), Balance of plant accessories (24.56%)

Rank	Unit Process	Impact	Component Contribution
7	Polyethylene, high density, granulate {RoW}| production | Alloc Rec, U	184.55	Bipolar plate (46.59%), Cell frame (34.09%), Balance of plant accessories (9.45%)
8	Natural gas, high pressure {RU}| natural gas production | Alloc Rec, U	182.19	Cell stack accessories (50.46%), Electrolyte (19.53%), Balance of plant accessories (17.29%)
9	Petroleum {RoW}| petroleum and gas production, on-shore | Alloc Rec, U	163.84	Cell stack accessories (38.54%), Electrolyte (35.12%), Balance of plant accessories (13.48%)
10	Petroleum {RME}| production, onshore | Alloc Rec, U	161.94	Cell stack accessories (38.54%), Electrolyte (35.12%), Balance of plant accessories (13.48%)
11	Natural gas, high pressure {US}| petroleum and gas production, on-shore | Alloc Rec, U	135.99	Cell stack accessories (51.58%), Balance of plant accessories (17.58%), Electrolyte (17.52%)
12	Natural gas, high pressure {RoW}| natural gas production | Alloc Rec, U	135.58	Cell stack accessories (47.72%), Electrolyte (24.52%), Balance of plant accessories (16.34%)
13	Natural gas, unprocessed, at extraction {GLO}| production | Alloc Rec, U	119.62	Cell stack accessories (47.72%), Electrolyte (24.52%), Balance of plant accessories (16.34%)
14	Natural gas, high pressure {US}| natural gas production | Alloc Rec, U	114.39	Cell stack accessories (51.58%), Balance of plant accessories (17.58%), Electrolyte (17.52%)
15	Lignite {RER}| mine operation | Alloc Rec, U	72.77	Cell stack accessories (59.85%), Balance of plant accessories (20.22%), Bipolar plate (14.57%)
16	Petroleum {RU}| production, onshore | Alloc Rec, U	70.69	Cell stack accessories (38.54%), Electrolyte (35.12%), Balance of plant accessories (13.48%)

Rank	Unit Process	Impact	Component Contribution
17	Polyethylene, high density, granulate {RER}| production | Alloc Rec, U	69.38	Electrolyte (99.10%)
18	Petroleum {RoW}| petroleum and gas production, off-shore | Alloc Rec, U	66.84	Cell stack accessories (38.54%), Electrolyte (35.12%), Balance of plant accessories (13.48%)
19	Hard coal {ZA}| mine operation | Alloc Rec, U	64.29	Cell stack accessories (53.69%), Balance of plant accessories (18.62%), Bipolar plate (13.23%)
20	Hard coal {AU}| mine operation | Alloc Rec, U	58.21	Cell stack accessories (51.07%), Balance of plant accessories (17.86%), Electrolyte (14.53%)
21	Natural gas, high pressure {RoW}| petroleum and gas production, on-shore | Alloc Rec, U	53.27	Cell stack accessories (47.72%), Electrolyte (24.52%), Balance of plant accessories (16.34%)
22	Natural gas, high pressure {DE}| natural gas production | Alloc Rec, U	48.61	Cell stack accessories (55.07%), Balance of plant accessories (18.56%), Bipolar plate (16.87%)
23	Hard coal {RU}| mine operation | Alloc Rec, U	48.40	Cell stack accessories (53.01%), Balance of plant accessories (18.53%), Electrolyte (13.14%)
24	Hard coal {PL}| mine operation | Alloc Rec, U	42.73	Cell stack accessories (58.04%), Balance of plant accessories (20.40%), Bipolar plate (14.17%)
Total	4198.99 (Cell stack accessories: 46.98%, Bipolar plate: 17.72%, Balance of plant accessories: 16.10%)		

Source: UC Irvine

Table C-21: Structural Path Analysis on Cumulative Energy Demand, Nonrenewable Fossil, for Iron Flow Battery (MJ/ kWh)

Rank	Unit Process	Impact	Component Contribution
1	Hard coal {CN}| mine operation | Alloc Rec, U	264.45	Cell stack accessories (66.81%), Electrolyte (14.76%), Cell frame (7.865)
2	Hard coal {RoW}| mine operation | Alloc Rec, U	109.01	Cell stack accessories (65.52%), Electrolyte (16.70%), Cell frame (7.93%)
3	Lignite {RoW}| mine operation | Alloc Rec, U	96.71	Cell stack accessories (67.09%), Electrolyte (15.06%), Cell frame (8.13%)
4	Natural gas, high pressure {RU}| natural gas production | Alloc Rec, U	77.98	Cell stack accessories (54.26%), Electrolyte (26.89%), Cell frame (11.50%)
5	Wax, lost-wax casting {GLO}| wax production, for lost-wax metal casting | Alloc Rec, U	68.56	Cell stack accessories (100.00%)
6	Petroleum {RoW}| petroleum and gas production, on-shore | Alloc Rec, U	68.22	Cell stack accessories (40.63%), Electrolyte (29.75%), Cell frame (11.18%)
7	Hard coal {RNA}| mine operation | Alloc Rec, U	68.20	Cell stack accessories (67.44%), Electrolyte (14.63%), Cell frame (7.62%)
8	Petroleum {RME}| production, onshore | Alloc Rec, U	67.43	Cell stack accessories (40.63%), Electrolyte (29.75%), Cell frame (11.18%)
9	Styrene {RoW}| production | Alloc Rec, U	65.56	Electrolyte (99.35%)
10	Steel, low-alloyed {RoW}| steel production, converter, low-alloyed | Alloc Rec, S	60.74	Cell stack accessories (100.00%)
11	Carbon paper	60.20	Battery management system (89.29%), Electrode (10.71%)
12	Polyacrylonitrile fibres (PAN), from acrylonitrile and methacrylate, prod. mix, PAN w/o additives EU-27 S	54.53	Battery management system (89.29%), Electrode (10.71%)
13	Natural gas, high pressure {US}| petroleum and gas production, on-shore | Alloc Rec, U	49.38	Cell stack accessories (64.39%), Electrolyte (14.83%), Cell frame (11.22%)

Rank	Unit Process	Impact	Component Contribution
14	Natural gas, high pressure {RoW}| natural gas production | Alloc Rec, U	47.17	Cell stack accessories (62.66%), Electrolyte (14.83%), Cell frame (13.23%)
15	Xylene {RoW}| production | Alloc Rec, U	43.74	Electrolyte (58.85%), Cell frame (40.53%)
16	Natural gas, unprocessed, at extraction {GLO}| production | Alloc Rec, U	41.62	Cell stack accessories (62.66%), Electrolyte (14.83%), Cell frame (13.23%)
17	Natural gas, high pressure {US}| natural gas production | Alloc Rec, U	41.54	Cell stack accessories (64.39%), Electrolyte (14.83%), Cell frame (11.22%)
18	Bisphenol A epoxy based vinyl ester resin {RoW}| production | Alloc Rec, S	38.00	Bipolar plate (100.00%)
19	Natural gas, high pressure {DE}| natural gas production | Alloc Rec, U	37.26	Electrolyte (55.90%), Cell stack accessories (34.42%)
20	Polyester resin, unsaturated {RoW}| soy-based resin production | Alloc Rec, U	32.39	Cell frame (99.49%)
21	Styrene {RER}| production | Alloc Rec, U	32.38	Electrolyte (99.35%)
22	Lignite {RER}| mine operation | Alloc Rec, U	30.20	Cell stack accessories (65.31%), Electrolyte (22.35%), Cell frame (6.92%)
23	Petroleum {RU}| production, onshore | Alloc Rec, U	29.44	Cell stack accessories (40.63%), Electrolyte (29.75%), Cell frame (11.18%)
24	Petroleum {RoW}| petroleum and gas production, off-shore | Alloc Rec, U	27.83	Cell stack accessories (40.63%), Electrolyte (29.75%), Cell frame (11.18%)
25	Propylene {RoW}| production | Alloc Rec, U	25.78	Electrolyte (72.68%), Cell frame (25.86%)
26	Hard coal {ZA}| mine operation | Alloc Rec, U	22.41	Cell stack accessories (65.50%), Electrolyte (15.18%), Cell frame (8.07%)
27	Natural gas, high pressure {NL}| petroleum and gas production, on-shore | Alloc Rec, U	19.76	Electrolyte (43.85%), Cell stack accessories (42.73%), Cell frame (8.38%)

Rank	Unit Process	Impact	Component Contribution
Total	1921.20 (Cell stack accessories: 47.36%, Electrolyte: 23.90%, Cell frame: 11.38%)		

Source: UC Irvine

C.8 Abiotic Resource Depletion

Table C-22: Structural Path Analysis on Abiotic Resource Depletion for Vanadium-Redox Flow Battery (kg Sb eq/ kWh)

Rank	Unit Process	Impact	Component Contribution
1	Copper concentrate {RoW}| copper mine operation | Alloc Rec, U	5.18E-04	Cell stack accessories (89.45%), Power conditioning system (7.71%)
2	Silver {RoW}| silver-gold mine operation with refinery | Alloc Rec, U	2.51E-04	Battery management system (98.49%)
3	Copper {RoW}| gold-silver-zinc-lead-copper mine operation and refining | Alloc Rec, U	2.35E-04	Power conditioning system (68.55%), Battery management system (19.36%), Cell stack accessories (6.20%)
4	Gold {RoW}| production | Alloc Rec, U	1.88E-04	Battery management system (92.46%)
5	Ammonium sulfate, as N {RoW}| ammonium sulfate production | Alloc Rec, S	1.84E-04	Electrolyte (100.00%)
6	Soda ash, dense {GLO}| modified Solvay process, Hou's process | Alloc Rec, S	1.35E-04	Electrolyte (100.00%)
7	Tin {RoW}| production | Alloc Rec, U	1.14E-04	Battery management system (99.39%)
8	Zinc concentrate {GLO}| zinc-lead mine operation | Alloc Rec, U	9.22E-05	Power conditioning system (43.96%), Battery management system (29.00%), Electrolyte (8.81%)
9	Copper, from solvent-extraction electro-winning {GLO}| copper production, solvent-extraction electro-winning | Alloc Rec, U	8.22E-05	Cell stack accessories (68.09%), Power conditioning system (23.32%), Battery management system (6.58%)
10	Copper concentrate {RAS}| copper mine operation | Alloc Rec, U	6.51E-05	Power conditioning system (68.55%), Battery management system (19.36%), Cell stack accessories (6.20%)

Rank	Unit Process	Impact	Component Contribution
11	Tin {RER}| production | Alloc Rec, U	5.61E-05	Battery management system (99.39%)
12	Copper concentrate {RLA}| copper mine operation | Alloc Rec, U	4.93E-05	Power conditioning system (68.55%), Battery management system (19.36%), Cell stack accessories (6.20%)
13	Gold {ZA}| production | Alloc Rec, U	4.42E-05	Battery management system (92.46%)
14	Gold {US}| production | Alloc Rec, U	4.24E-05	Battery management system (92.46%)
15	Gold {AU}| production | Alloc Rec, U	4.15E-05	Battery management system (92.46%)
16	Silver {RoW}| gold-silver-zinc-lead-copper mine operation and refining | Alloc Rec, U	4.13E-05	Battery management system (98.49%)
17	Chromite ore concentrate {GLO}| production | Alloc Rec, U	3.92E-05	Balance of plant accessories (38.78%), Cell stack accessories (20.84%), Power conditioning system (18.19%)
18	Copper concentrate {RNA}| copper mine operation | Alloc Rec, U	3.56E-05	Power conditioning system (68.55%), Battery management system (19.36%), Cell stack accessories (6.20%)
19	Lead concentrate {GLO}| zinc-lead mine operation | Alloc Rec, U	3.23E-05	Battery management system (71.82%), Membrane (8.77%), Cell stack accessories (7.38%)
20	Copper concentrate {RER}| copper mine operation | Alloc Rec, U	2.89E-05	Power conditioning system (68.55%), Battery management system (19.36%), Cell stack accessories (6.20%)
Total	2.49E-03 (Battery management system: 40.60%, Cell stack accessories: 23.21%, Power conditioning system: 17.32%)		

Source: UC Irvine

Table C-23: Structural Path Analysis on Abiotic Resource Depletion for Zinc-Bromide Flow Battery (kg Sb eq/ kWh)

Rank	Unit Process	Impact	Component Contribution
1	Bromine {RoW}| production | Alloc Rec, U	3.61E-02	Electrolyte (100.00%)
2	Copper concentrate {RER}| copper mine operation | Alloc Rec, U	2.75E-04	Battery management system (96.44%)
3	Copper {RoW}| gold-silver-zinc-lead-copper mine operation and refining | Alloc Rec, U	1.08E-04	Recirculation loops (35.00%), Battery management system (26.62%), Cell stack accessories (11.67%)
4	Copper concentrate {RoW}| copper mine operation | Alloc Rec, U	1.06E-04	Power conditioning system (76.60%), Recirculation loops (8.88%), Battery management system (6.76%)
5	Chromite ore concentrate {GLO}| production | Alloc Rec, U	9.50E-05	Balance of plant accessories (49.32%), Recirculation loops (26.65%), Cell stack accessories (18.26%)
6	Zinc concentrate {GLO}| zinc-lead mine operation | Alloc Rec, U	8.94E-05	Electrolyte (27.84%), Cell stack accessories (22.28%), Balance of plant accessories (13.20%)
7	Copper concentrate {RAS}| copper mine operation | Alloc Rec, U	3.01E-05	Recirculation loops (35.00%), Battery management system (26.62%), Cell stack accessories (11.67%)
8	Gold {RoW}| production | Alloc Rec, U	2.69E-05	Electrolyte (53.15%), Cell stack accessories (20.06%), Bipolar plate (19.61%)
9	Copper concentrate {RLA}| copper mine operation | Alloc Rec, U	2.28E-05	Recirculation loops (35.00%), Battery management system (26.62%), Cell stack accessories (11.67%)
10	Titanium primary, triple-melt {GLO}| titanium production, primary, triple melt | Alloc Rec, S	2.08E-05	Bipolar plate (82.35%), Cell stack accessories (17.65%)
11	Molybdenite {GLO}| mine operation | Alloc Rec, U	1.70E-05	Cell stack accessories (56.64%), Balance of plant accessories (18.70%), Recirculation loops (18.51%)

Rank	Unit Process	Impact	Component Contribution
12	Lead concentrate {GLO}| zinc-lead mine operation | Alloc Rec, U	1.70E-05	Cell stack accessories (43.81%), Electrolyte (29.11%)
13	Copper concentrate {RNA}| copper mine operation | Alloc Rec, U	1.64E-05	Recirculation loops (35.00%), Battery management system (26.62%), Cell stack accessories (11.67%)
14	Copper, from solvent-extraction electro-winning {GLO}| copper production, solvent-extraction electro-winning | Alloc Rec, U	1.29E-05	Recirculation loops (35.00%), Battery management system (26.62%), Cell stack accessories (11.67%)
15	Ferronickel, 25% Ni {GLO}| production | Alloc Rec, U	9.73E-06	Balance of plant accessories (44.54%), Cell stack accessories (27.47%), Recirculation loops (21.68%)
16	Molybdenite {RLA}| copper mine operation | Alloc Rec, U	9.49E-06	Cell stack accessories (56.64%), Balance of plant accessories (18.70%), Recirculation loops (18.51%)
Total	3.71E-02 (Electrolyte: 97.75%, Battery management system: 0.91%, Recirculation loops: 0.34%, Cell stack accessories: 0.32%)		

Source: UC Irvine

Table C-24: Structural Path Analysis on Abiotic Resource Depletion for Iron Flow Battery (kg Sb eq/ kWh)

Rank	Unit Process	Impact	Component Contribution
1	Gold {RoW}| production | Alloc Rec, U	1.98E-04	Battery management system (77.52%), Electrolyte (18.23%)
2	Copper {RoW}| gold-silver-zinc-lead-copper mine operation and refining | Alloc Rec, U	1.53E-04	Power conditioning system (58.85%), Electrolyte (15.76%), Battery management system (7.73%)
3	Zinc concentrate {GLO}| zinc-lead mine operation | Alloc Rec, U	1.33E-04	Electrolyte (38.06%), Battery management system (21.83%), Power conditioning system (17.73%)
4	Steel, low-alloyed {RoW}| steel production, converter, low-alloyed | Alloc Rec, S	9.14E-05	Cell stack accessories (100.00%)
5	Gold {ZA}| production | Alloc Rec, U	4.65E-05	Battery management system (77.52%), Electrolyte (18.23%)

Rank	Unit Process	Impact	Component Contribution
6	Gold {US}| production | Alloc Rec, U	4.46E-05	Battery management system (77.52%), Electrolyte (18.23%)
7	Gold {AU}| production | Alloc Rec, U	4.36E-05	Battery management system (77.52%), Electrolyte (18.23%)
8	Copper concentrate {RAS}| copper mine operation | Alloc Rec, U	4.23E-05	Power conditioning system (58.85%), Electrolyte (15.76%), Battery management system (7.73%)
9	Copper concentrate {RoW}| copper mine operation | Alloc Rec, U	3.79E-05	Power conditioning system (58.85%), Electrolyte (15.76%), Battery management system (7.73%)
10	Chromite ore concentrate {GLO}| production | Alloc Rec, U	3.58E-05	Recirculation loops (26.70%), Cell stack accessories (22.36%), Electrolyte (20.18%)
11	Copper concentrate {RLA}| copper mine operation | Alloc Rec, U	3.21E-05	Power conditioning system (58.85%), Electrolyte (15.76%), Battery management system (7.73%)
12	Copper concentrate {RNA}| copper mine operation | Alloc Rec, U	2.31E-05	Power conditioning system (58.85%), Electrolyte (15.76%), Battery management system (7.73%)
13	Gold {RoW}| silver-gold mine operation with refinery | Alloc Rec, U	2.19E-05	Battery management system (77.52%), Electrolyte (18.23%)
14	Gold {CA}| production | Alloc Rec, U	2.15E-05	Battery management system (77.52%), Electrolyte (18.23%)
15	Copper concentrate {RER}| copper mine operation | Alloc Rec, U	1.88E-05	Power conditioning system (58.85%), Electrolyte (15.76%), Battery management system (7.73%)
16	Gold {PE}| gold-silver mine operation with refinery | Alloc Rec, U	1.86E-05	Battery management system (77.52%), Electrolyte (18.23%)
17	Copper, from solvent-extraction electro-winning {GLO}| copper production, solvent-extraction electro-winning | Alloc Rec, U	1.82E-05	Power conditioning system (58.85%), Electrolyte (15.76%), Battery management system (7.73%)
18	Gold {RoW}| gold-silver mine operation with refinery | Alloc Rec, U	1.74E-05	Battery management system (77.52%), Electrolyte (18.23%)

Rank	Unit Process	Impact	Component Contribution
19	Lead concentrate {GLO}| zinc-lead mine operation | Alloc Rec, U	1.43E-05	Electrolyte (44.53%), Cell frame (25.35%), Cell stack accessories (21.69%)
Total	1.10E-03 (Battery management system: 36.57%, Power conditioning system: 21.98%, Electrolyte: 18.71%)		

Source: UC Irvine

APPENDIX D: Material Pricing Data

The price of materials (in $/kg) used for the baseline cost analysis are provided in Tables D1-D3. Prices per kW for the pumps and inverters are also included. Historical pricing data for vanadium pentoxide, titanium, bromine and carbon fiber felt are provided and discussed below.

D.1 Summary of Price Parameters

Table D-1: Material Price Information for Materials used in Vanadium-Redox Flow Battery System

Battery Technology	**VRFB**			
Component	**Price**	**Unit**	**Data type**	**Data source**
Bipolar Plate				
Graphite	1.58	$/kg	2015 MARKET AVERAGE	USGS [82]
Polyethylene, low density	1.22	$/kg	2017 IMPORT AVERAGE	Plastics Insight [83]
Cell frame				
Polypropylene	1.84	$/kg	2017 IMPORT AVERAGE	Plastics Insight [84]
Glass fiber	2	$/kg	ESTIMATED VALUE	Lotfi et al. [85]
Electrode				
Carbon felt paper	237.6	$/kg	LITERATURE VALUE	Minke et al. [27]
Membrane				
Nafion®	937.53	$/kg	LITERATURE VALUE	Minke et al. [27]
Cell Stack Accessories				
Steel, low alloyed	0.69	$/kg	2019 MARKET AVERAGE	Worldsteelprice [86]
Copper	6.61	$/kg	2018 VENDOR VALUE	USGS [87]
Polyvinylchloride	0.97	$/kg	2019 MARKET AVERAGE	Investing.com [88]
Electrolyte				
Vanadium pentoxide	35.75	$/kg	2019 MARKET AVERAGE	USGS [80]
Hydrochloric acid	0.13	$/kg	2018 MARKET INSTANT	ICIS [89]
Sulfuric acid	0.06	$/kg	LITERATURE VALUE	Minke et al. [26]

Battery Technology	**VRFB**			
Component	**Price**	**Unit**	**Data type**	**Data source**
Water	0.00241	$/kg	GOVERNMENT VALUE	[90]
Tank				
Polyethylene, high density	1.26	$/kg	2017 IMPORT AVERAGE	Plastics Insight [91]
Pipes				
Polyethylene, high density	1.26	$/kg	2017 IMPORT AVERAGE	Plastics Insight [91]
Pump	13.46	$/kW	LITERATURE VALUE	Minke et al. [30]
Inverter	112.13	$/kW	LITERATURE VALUE	Minke et al. [26]
Battery Management System				
Aluminum	2.54	$/kg	2018 IMPORT AVERAGE	USGS [92]
Titanium	30	$/kg	2019 MARKET INSTANT	TRICORMETALS [93]
Power Control System	150	$/kW	LITERATURE VALUE	Minke et al. [30]
Balance of Plant Accessories				
Steel, low alloyed	0.69	$/kg	2019 MARKET AVERAGE	Worldsteelprice [86]

Source: UC Irvine

Table D-2: Material Price Information for Materials used in Zinc-Bromide Flow Battery System

Battery Technology	**ZBFB**			
Component	**Price**	**Unit**	**Data Type**	**Data Source**
Bipolar Plate				
Titanium	30	$/kg	2019 MARKET INSTANT	TRICORMETALS [93]
Polyethylene, high density	1.26	$/kg	2017 IMPORT AVERAGE	Plastics Insight [91]
Cell frame				
Polyethylene, high density	1.26	$/kg	2017 IMPORT AVERAGE	Plastics Insight [91]
Cell Stack Accessories				

Battery Technology	ZBFB			
Component	**Price**	**Unit**	**Data Type**	**Data Source**
Steel, low alloyed	0.69	$/kg	2019 MARKET AVERAGE	Worldsteelprice [86]
Titanium	30	$/kg	2019 MARKET INSTANT	TRICORMETALS [93]
Polyethylene, high density	1.26	$/kg	2017 IMPORT AVERAGE	Plastics Insight [91]
Electrolyte				
Bromine	4.9	$/kg	2017 IMPORT AVERAGE	USGS [94]
Zinc	3.2	$/kg	2018 IMPORT AVERAGE	USGS [95]
Water	0.0029	$/kg	GOVERNMENT VALUE	[96]
Tank				
Polyethylene, high density	1.26	$/kg	2017 IMPORT AVERAGE	Plastics Insight [91]
Pipes				
Polyethylene, high density	1.26	$/kg	2017 IMPORT AVERAGE	Plastics Insight [91]
Pump	13.46	$/kW	LITERATURE VALUE	Minke et al. [30]
Inverter	112.13	$/kW	LITERATURE VALUE	Minke et al. [26]
Battery Management System				
Steel, low alloyed	0.69	$/kg	2019 MARKET AVERAGE	Worldsteelprice [86]
Aluminum	2.54	$/kg	2018 IMPORT AVERAGE	USGS [92]
Copper	6.61	$/kg	2018 VENDOR VALUE	USGS [87]
Power control system	150	$/kW	LITERATURE VALUE	Minke et al. [30]
Balance of Plant Accessories				
Steel, low alloyed	0.69	$/kg	2019 MARKET AVERAGE	Worldsteelprice [86]
Aluminum	2.54	$/kg	2018 IMPORT AVERAGE	USGS [92]
Titanium	30	$/kg	2019 MARKET INSTANT	TRICORMETALS [93]

Source: UC Irvine

Table D-3: Material Price Information for Materials used in Iron Flow Battery System

Battery Technology	**IFB**			
Component	**Price**	**Unit**	**Data type**	**Data source**
Bipolar Plate				
Graphite	1.58	$/kg	2015 MARKET AVERAGE	USGS [82]
Polypropylene	1.84	$/kg	2017 IMPORT AVERAGE	Plastics Insight [84]
Cell frame				
Polyester resin	3.36	$/kg	2017 IMPORT AVERAGE	Plastics Insight [97]
Glass fiber	2	$/kg	ESTIMATED VALUE	Lotfi et al. [85]
Electrode				
Carbon felt paper	237.6	$/kg	LITERATURE VALUE	Minke et al. [27]
Membrane				
UHMW polyethylene	595.88	$/kg	2019 VENDOR VALUE	Sigma Aldrich [98]
Cell Stack Accessories				
Steel, low alloyed	0.69	$/kg	2019 MARKET AVERAGE	Worldsteelprice [86]
Aluminum	2.54	$/kg	2018 IMPORT AVERAGE	USGS [92]
EPDM Gasket	2.5	$/kg	LITERATURE VALUE	Viswanathan et al. [37]
Electrolyte				
Iron chloride	0.35	$/kg	2001 MARKET INSTANT	ICIS [99]
Potassium chloride	0.27	$/kg	2019 MARKET AVERAGE	Indexmundi [100]
Manganese dioxide	2.21	$/kg	2015 IMPORT AVERAGE	USGS [101]
Hydrochloric acid	0.13	$/kg	2018 MARKET INSTANT	ICIS [89]
Water	0.00186	$/kg	GOVERNMENT VALUE	[102]
Tank				

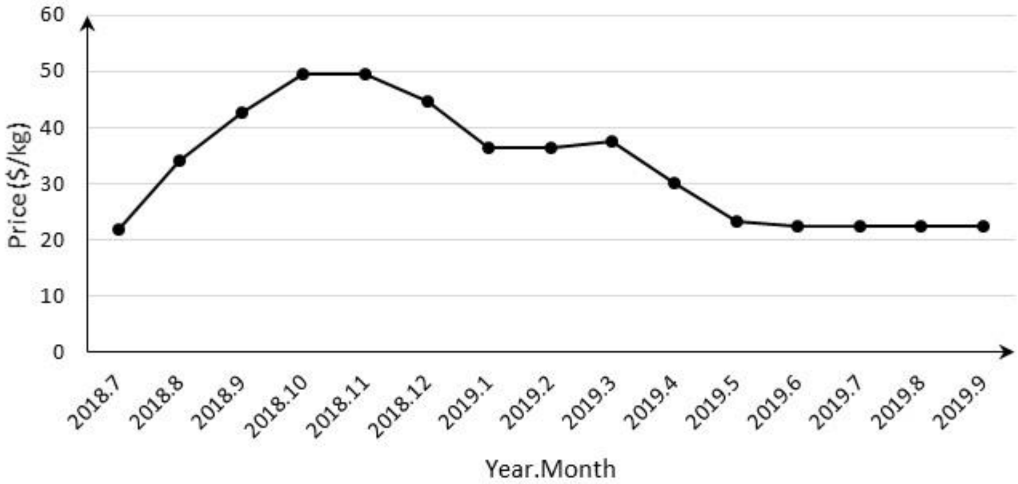
Battery Technology	IFB			
Component	**Price**	**Unit**	**Data type**	**Data source**
Polyester resin	3.36	$/kg	2017 IMPORT AVERAGE	Plastics Insight [97]
Pipes				
Polyvinylchloride	0.97	$/kg	2019 MARKET AVERAGE	Investing.com [88]
Pump	13.46	$/kW	LITERATURE VALUE	Minke et al. [30]
Inverter	112.13	$/kW	LITERATURE VALUE	Minke et al. [26]
Battery Management System				
Carbon felt paper	237.6	$/kg	LITERATURE VALUE	Minke et al. [27]
Power control unit	150	$/kW	LITERATURE VALUE	Minke et al. [30]
Balance of Plant Accessories	None			

Source: UC Irvine

D.2 Vanadium Pentoxide Price Data

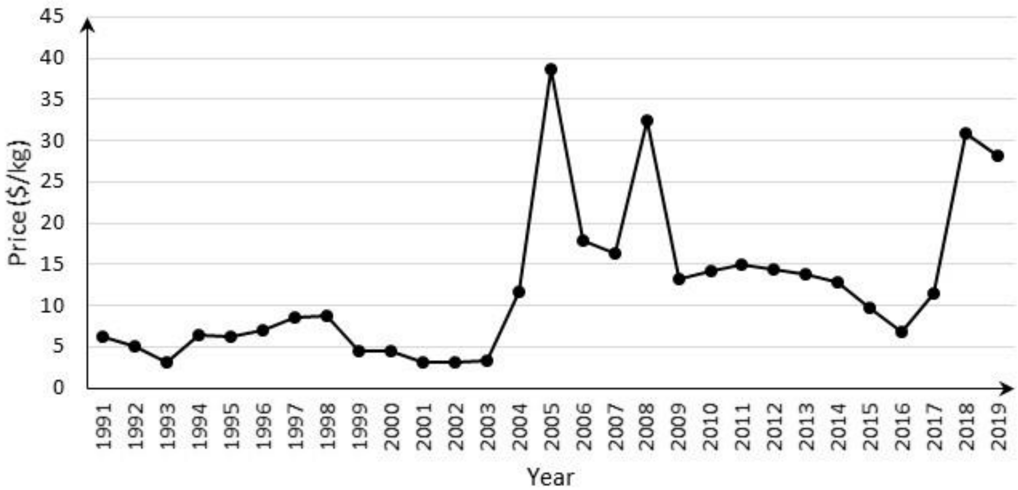
Vanadium pentoxide is the major contributor to cost for the VRFB system as the electrolyte corresponds to more than 80% of the total cost and is also a primary driver of VRFB environmental impacts. The price of vanadium pentoxide is monitored by several organizations such as USGS. It is reported that the vanadium pentoxide produced in the US is based on secondary sources such as catalysts, ashes, and petroleum residues which are 100% import reliant [79]. The market price of vanadium pentoxide varies over time. Figure D-1 [103] presents the variation in the monthly price, while Figure D-2 presents a year-to-year variation [80]. The prices for vanadium pentoxide have ranged from 20 – 50 $/kg in the past year and the peak price is observed from November to December 2018, when prices reached as high as 49.60 $/kg. For year-to-year prices, there are no clear trends. Before 2004, the price of vanadium pentoxide varied between 3 – 9 $/kg, while after 2004, the price seldom dropped below 10 $/kg and the price variability increased. It is also noted that the price of vanadium pentoxide increased sharply in certain years such as 2005 and 2008, with average prices of 38.60 $/kg and 32.50 $/kg respectively. According to USGS, the price spike in 2005 was attributed to strong demand in the steel and aerospace industries and the inability of the producers to increase production in a timely manner [104]. In the year 2008, the price increase was caused by a sharp reduction in production volume due to power shortages in South Africa and bad weather in China, which are both primary countries with vanadium reserves and production [105].

Figure D-1: Monthly Price of Vanadium Pentoxide since 2018



Sourced from [80]

Figure D-2: Average Yearly Price of Vanadium Pentoxide from 1991 – 2019



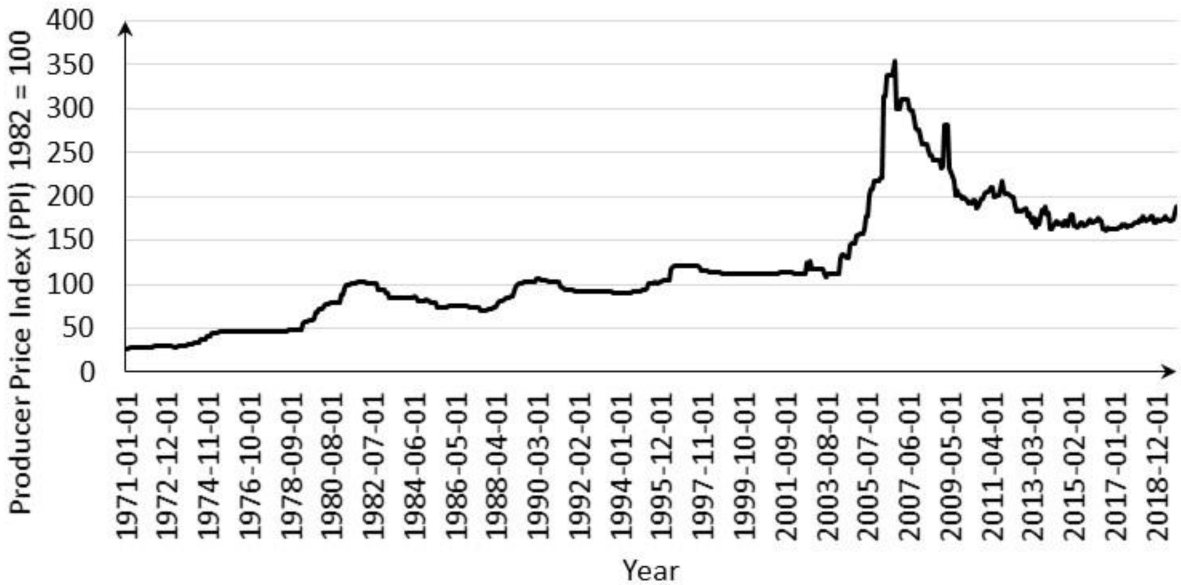
Sourced from [80]

Due to the large variations, estimating a single point for the price of vanadium pentoxide may not be representative. With the application of the three-point estimation method, the current price is set to be 35.75 $/kg, which is the average price during the past year from July 2018 to June 2019. The pessimistic price is estimated to be 50 $/kg, which is close to the highest price observed in October 2018. The optimistic price is chosen to be 8 $/kg, which is extracted from the literature [27] and closely matches the yearly price between 1991 – 2004.

D.3 Titanium Price Data

In the ZBFB, the titanium is a core material used to manufacture the bipolar plate that contributes about 22% of the total system cost. Titanium is also used in the cell stack accessories in support of the cell stack structure. The price of titanium products such as titanium mineral concentrates, titanium sponge, and titanium dioxide are monitored by USGS. However, the type of titanium products used in the ZBFB specifically is a titanium milled product for which price data over time are unavailable. Thus, the producer price index (PPI) for the titanium mill product is shown in Figure D-3 [106]. The PPI reflects the relative change in the market price of materials compared to the baseline year – the year 1982 in this case. From Figure 5, the current PPI value is close to 170 and the peak value is 355 in the year 2006. Our data search indicates that the current price for the titanium milled product is approximately 30 $/kg when the PPI is approximately 170 [106]. Based on the current price and the PPI index over the years, the pessimistic price is converted from the current price using the point when the PPI index was at its peak value of 355, and the optimistic price is determined at the point when PPI index is 100. Thus, pessimistic and optimistic prices are calculated to be 62.65 $/kg and 17.65 $/kg, respectively.

Figure D-3: Producer Price Index of Titanium Milled Production from 1971 to 2019

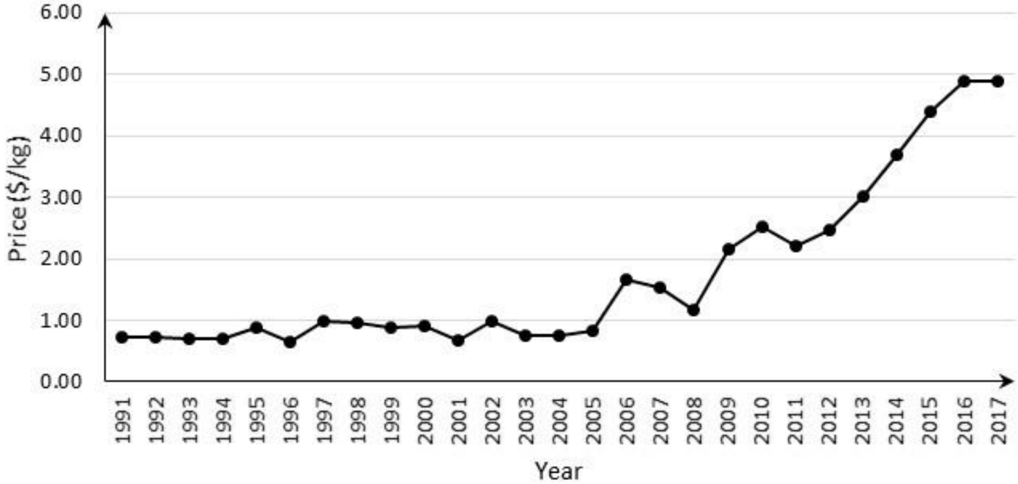


Sourced from [106]

D.4 Bromine Price Data

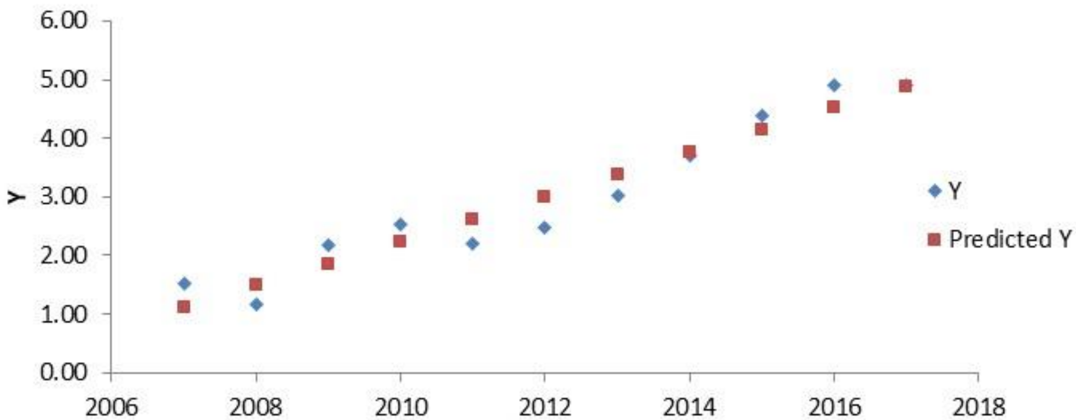
Bromine is one of the active species used as the electrolyte in the ZBFB system, which also contributes to over 20% of the total system cost. Statistical information on bromine prices has been researched by the USGS. However, the price data are not kept up to date to protect company proprietary information, as the scale of the bromine market is relatively small and only a few suppliers are identified [94]. The yearly price for bromine from 1991 to 2017 is presented in Figure D-4 [94]. The current price used in the three-point estimation is set to be 4.90 $/kg, which is from the year 2017 – the most updated information available. The optimistic price is 1 $/kg since the market price had stagnated at a value of approximately 1 $/kg for a long period from 1991 – 2005. It is noted that the market price for bromine has slowly increased after the year 2006, and the peak price cannot be determined since no decreasing trend is observed. This renders estimation of pessimistic price difficult as it is unknown how much higher the price of bromine can reach. To predict a possible future (pessimistic) price, a simple linear regression is performed (Figure D-5) using price data from 2007 to 2017 as the price increase rate is relatively steady during this time. With the simulation, the pessimistic price is set to be 6 $/kg, corresponding to the predicted value in the year 2020.

Figure D-4: Average Yearly Price of Bromine from 1991 – 2017



Sourced from [94]

Figure D-5: Regression Analysis for Bromine Using Price Data from 2007-2017



Source: UC Irvine

D.5 Carbon Fiber Felt Price Data

In this analysis, the carbon fiber felt is largely used in the IFB battery management system as a rebalancing cell and contributes strongly to the total system cost of the IFB system. The market price of carbon fiber felt is not continuously monitored since it is a material used in very specific applications and has a complex production chain. To acquire three price points for estimation, all the data are extracted from the literature. The current price is estimated to be 237.60 $/kg, the pessimistic price is set to be 280 $/kg, and the optimistic price is estimated to be 80 $/kg [27].