EFFECT OF BATTERY STORAGE TECHNOLOGY ON THE CONSTRUCTION OF ELECTRIC VEHICLE CHARGING STATIONS

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ABSTRACT

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Battery storage has become a critical component of electric vehicle (EV) charging infrastructure. However, whether and how battery storage may serve a crucial role in enabling fast-charging stations (FCSs) to fulfill customer demand and provide a profit for charging station operators is unclear. This thesis provides a better understanding of how to construct FCSs with integrated battery storage systems. The work is threefold. First, an in-depth literature review discusses EVs, details the types of charging stations and standards, and evaluates battery technologies. The review indicates that lithium-ion batteries are most promising for charging station applications followed by lead-acid and vanadium-redox batteries. Second, processes and considerations for installation of an FCS and battery storage unit are conducted. The results provide a cost estimation for various configurations of FCSs and battery storage costs based on battery size, type, and vendor. Third, a discrete event simulation (DES) model is developed to evaluate battery storage costs and characteristics for a network of FCSs in Southeast Michigan. The simulation finds that when considering network costs (i.e., the cost of setting up a new distribution line), no exchange of energy occurs and each of the FCSs requires more than one battery. When network costs are not considered, less exchange of energy occurs, and two-thirds of the FCSs require a battery. For this network, lithium-ion batteries cost the most whereas zinc-air batteries cost the least. Owing to high network costs, a highly condensed FCS network would provide higher benefit and result in lower total cost through battery units connected to a microgrid. This model is useful to stakeholders in this area (e.g., charging station operators, battery manufacturers, and vendors) to evaluate the battery costs and characteristics that fit their FCS network best.

This thesis is dedicated to my parents, who have nurtured me into what I am.
To my sister, who inspired me to learn.
To all my friends, who have constantly supported and been with me through all times.

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KEY TO ABBREVIATIONS

AESC	Alternative Energy Systems Consulting
BEV	Battery Electric Vehicle
CCS	Combined Charging Standard
CHAdeMO	Charge de Move
DES	Discrete Event Simulation
DCFC	DC Fast Charger
DOE	Department of Energy
EV	Electric Vehicle
EPRI	Electric Power Research Institute
EVCS	EV Charging Station
EVSE	EV Supply Equipment
FCS	Fast-Charging Station
HEV	Hybrid Electric Vehicle
NEC	National Electric Code
PHEV	Plug-in HEV
SAE	Society of Automotive Engineers
UL	Underwriters Laboratories

Chapter 1

Introduction

1.1 Background

Owing to the exhaustion of fuels used for transportation and increased environmental awareness, many countries have been electrifying their transportation system. The transportation sector contributes roughly 27 percent of total U.S. greenhouse gas (GHG) emissions and 63 percent of petroleum consumption (United States Environmental Protection Agency, 2012). Electric vehicles (EVs) can reduce current dependence on fossil fuels as well as emissions (Institute for Energy Research, 2013). By doing so for the personal vehicle fleet in the United States, EVs may alleviate national and global concerns about energy security and climate change (Office of the Press Secretary, 2009). The U.S. government has pledged $22 million in funding to accelerate the development of plug-in EVs (National Labs, 2016). According to the Electric Drive Transportation Association, EV sales in the United States jumped by 37% in 2016 with total sales of 159,139 vehicles (Association, 2016). EVs include hybrid EVs (HEVs), plug-in hybrid EVs (PHEVs), and battery EVs (BEVs). In addition, greater adoption of EVs may help address climate change and bring energy savings (Chandler, 2016).

As an increased number of EVs enter the market, the buildout of proper charging infrastructure has become critical. An EV charging station supplies electricity for the recharging of PHEVs and BEVs. The distance that an EV can travel is as critical as whether a facility for refueling exists when battery power dwindles (McDonald, 2016). Currently, three types of EV charging stations exist: Level 1 (Residential), Level 2 (Public), and Level 3 (DC Fast). As of 2015, approximately 70% of all public EV charging outlets are of the Level 2 type, 21.5% are Level 1, and 8.5% are

Level 3 (Flores, 2016). The literature review (Section 2.2) details charging station types Levels 1, 2, and 3. Despite being the least-adopted charger type, Level 3 charging stations, often termed fast-charging stations (FCSs), can charge a PHEV battery up to 80% within minutes. Residential charging stations enable drivers to charge in their homes, but drivers prefer to charge quickly and conveniently on the road to avoid range anxiety (Detwiler, 2014). Among the various types of charging stations, FCSs are particularly required to boost EV sales.

There are many concerns about the strain that FCSs exert on the power grid owing to their large load and short charging time. The extent of this impact depends on the EV penetration rate, charging requirements, and time of day the EV is charged at the FCS. Nevertheless, deploying large-scale FCSs may lead to grid instability (Bayram et al., 2013). Various studies have been conducted to examine the future impact of EV charging on the electrical grid. A study by Schneider (2008) finds that for a 240V rapid-charging station, storage devices are necessary for any level of penetration. The simulation results in Lin (2010) show that the high penetration of PHEV charging from the grid increase the feeder and fault currents. A DC FCS quickly charges a battery in minutes but requires a huge amount of power. In some situations, peak power demand from the grid may become so high that the contracted maximum power from the grid may not be sufficient for a charging station to serve all EVs at the charging station (Aziz, 2016). A functioning FCS must be able to cater to peak load demands and maintain a steady power supply throughout the day. This can be established by using battery storage technology to support the power demands of a charging station. Equipping FCSs with energy storage devices can reduce the impact of EV charging on the electric grid (Bashiri & Bahadori, 2016).

Utility-scale battery storage technologies and applications are becoming an integral part of a national strategy to modernize the nation’s electric system to meet future energy demand; integrate increasingly disparate renewable energy facilities; address climate change issues; and enhance overall reliability, safety, and security (Akhil, 2015). In this study, battery technology implies the types of batteries available on the market and studied in this report. By improving the operational capabilities of the grid, energy storage can play an important role in contributing to system reliability and emergency preparedness with backup power, potentially lowering costs and reducing infrastructure investments. The U.S. Department of Energy has indicated that electric utilities have a diverse suite of energy storage technologies available for consideration, including pumped hydro, compressed air energy storage, various types of batteries, flywheels, and electrochemical capacitors. Potential storage applications include energy management, backup power, load-leveling, frequency regulation, voltage support, and grid stabilization (U.S. Department of Energy, 2013). Energy storage can be deployed at different stages of the electric power system: generation, transmission, distribution, and consumption. Storage plays a role at the consumer level by allowing consumers to store energy when excess capacity (or low-cost electricity) is available, and the stored energy is used when capacity is limited (or electricity is costly; Carnegie, 2013). Battery storage can become a buffer to abate the adverse effects of the charging station on the grid and may be realized in coordination with FCSs.

1.2 Need statement

As EVs gain traction, energy storage is becoming a necessary infrastructure component (John, 2015). However, it is still unclear whether and how battery storage can serve a crucial role in enabling FCSs to fulfill customer demand and seem a profitable investment to charging station operators. With several battery storage technology options available in the market and each claiming to be competitive in terms of safety, cost, and technical performance, determining the most-appropriate technology for a particular application is critical. Many factors are involved in assessing the optimal sizing of storage as well as which charging station locations are suitable for deployment. An increased need then exists for tools and analysis that evaluate the financial benefits and projected cost of a battery storage project under a given scenario (DiOrio, 2015).

Little research has addressed the construction of battery storage technology on a network of FCSs. Deng (2016) presented a method for creating high-power fast-charging batteries controllable using two energy storage units. His study addresses only the energy regulation problem. Rogge (2015) conducted an analysis on real-world bus network data in Germany and explained the tradeoff between battery capacity and charging power. His study does not consider the economic implications of employing energy storage units for that network. Ding (2015) proposed a mixed-integer non-linear programming formulation to extract the monetary value of energy storage used in coordination with an FCS but did not extend this study to a real-time network of FCSs. Bashiri and Bahadori (2016) present an FCS with a flywheel energy storage system to meet demand charge, improve and develop the load profile, and minimize the operational costs of an FCS. Although the authors use a lifecycle cost analysis approach to compare different storage systems, operational costs using fast chargers were not discussed. The work of Momtazpour (2014) demonstrates a systematic data-mining methodology that can be used to identify locations for placing charging and storage infrastructure. However, several measures were not considered, such as battery life, energy storage, and an economic analysis. Therefore, the construction process and economics of battery storage and FCSs have not been analyzed in most studies.

1.3 Problem statement

Problem 1: The effect of battery storage technology on the construction of individual EV FCSs is unclear.

The economic implications of grid-scale energy storage technologies are obscure for power grid operators, storage manufacturers, and regulators (Zakeri, 2014). From a utility standpoint, investigating whether a battery storage system would be cheaper than upgrading the electric grid to accommodate FCSs is critical. The step-by-step process of battery storage and FCS installation as well as the roles of relevant stakeholders is not clearly defined (Schroeder, 2012). Different studies (ZhuD, 2013; Bradbury, 2014; Evans, 2013) have suggested that a lack of adequate information regarding the installation process and economies of utility scale of energy storage systems at the distribution or consumer level are major barriers to widespread use of these technologies.

Thus, a meticulous techno-economic analysis is required with updated cost data and a holistic installation process framework for use of these technologies with respect to FCSs.

Problem 2: The effect of battery storage technology on the construction of EV FCSs in a microgrid network is unknown.

The energy savings and financial benefit of adopting battery technology to support an operating network of EV charging stations are unclear. With charging network operators rapidly installing hundreds of DC fast chargers on their open network, understanding whether battery storage deployed at certain stations can benefit the entire network is vital (PlugShare, 2017). Installing storage at every FCS may not be necessary, as the utilization rates of each station vary. Hence, to assess viability, a detailed study must be conducted to estimate the changes in cost and power supply using battery storage in a network of FCSs.

1.4 Research objectives

The long-term goal of this research is to facilitate the adoption of EVs by better equipping charging stations to meet customer needs. Using battery storage as a buffer, customers are provided high-power charging that allows them to recharge an EV in a limited timeframe (Sbordonea, 2014), reducing range anxiety. This research evaluates battery systems to meet future needs for FCS applications. This study aids electric utilities, charging station network operators, battery manufacturers, and vendors to provide insights into the financial risks and benefits as well as potential energy savings when using energy storage for a network of fast chargers.

Objective 1: To provide a better understanding of battery technology and its associations with FCSs for EVs.

This objective addresses Problem 1 as follows:

(A) To review and evaluate the present state of battery-sourced storage technologies, storage systems, and applications, manufacturers, and vendors of battery systems for FCSs of EVs.

(B) To analyze and compare different battery systems' performance, cost, and siting considerations, including an assessment of potential safety, environmental, and financial impacts.

Objective 2: To identify the construction cost and process of an FCS that includes battery storage.

This objective address Problem 1 through the following specific aims:

(A) Identify and prepare a list of project actions prior to construction as well as during construction and installation phase of an FCS and battery storage system.

(B) Identify the costs for installation of FCSs, cost metrics used for battery storage, and battery storage costs.

Objective 3: To determine the optimal battery storage system for supporting a given network of FCSs.

In this study, battery storage system configuration means the size, number, and type of battery storage units.

This objective address Problem 2 through the following specific aims:

(A) Evaluate the energy supply in a network of FCSs assisted by the battery storage system through discrete event simulation (DES).

(B) Identify the size and optimum number of battery storage system units that minimize the cost of the entire system and reduce energy load on the grid.

1.5 Methodology

1.5.1 Research plan and strategy

This study was divided into three phases. The first phase provides a general overview of electric charging stations and battery storage technologies, examining their pros and cons and determining the best technologies for use with an FCS. The second phase lists project activities and cost information for the installation of an FCS and a battery storage system, using cost reports and installation guides from various charging-station network operators and battery companies. The third phase models the energy supply in a network of battery assisted FCSs using a case study of the greater Detroit area in Michigan. A DES model has been implemented in Python to identify the optimum configuration of battery units that result in the lowest energy supply cost. Figure 1.1 shows the research plan for each phase.

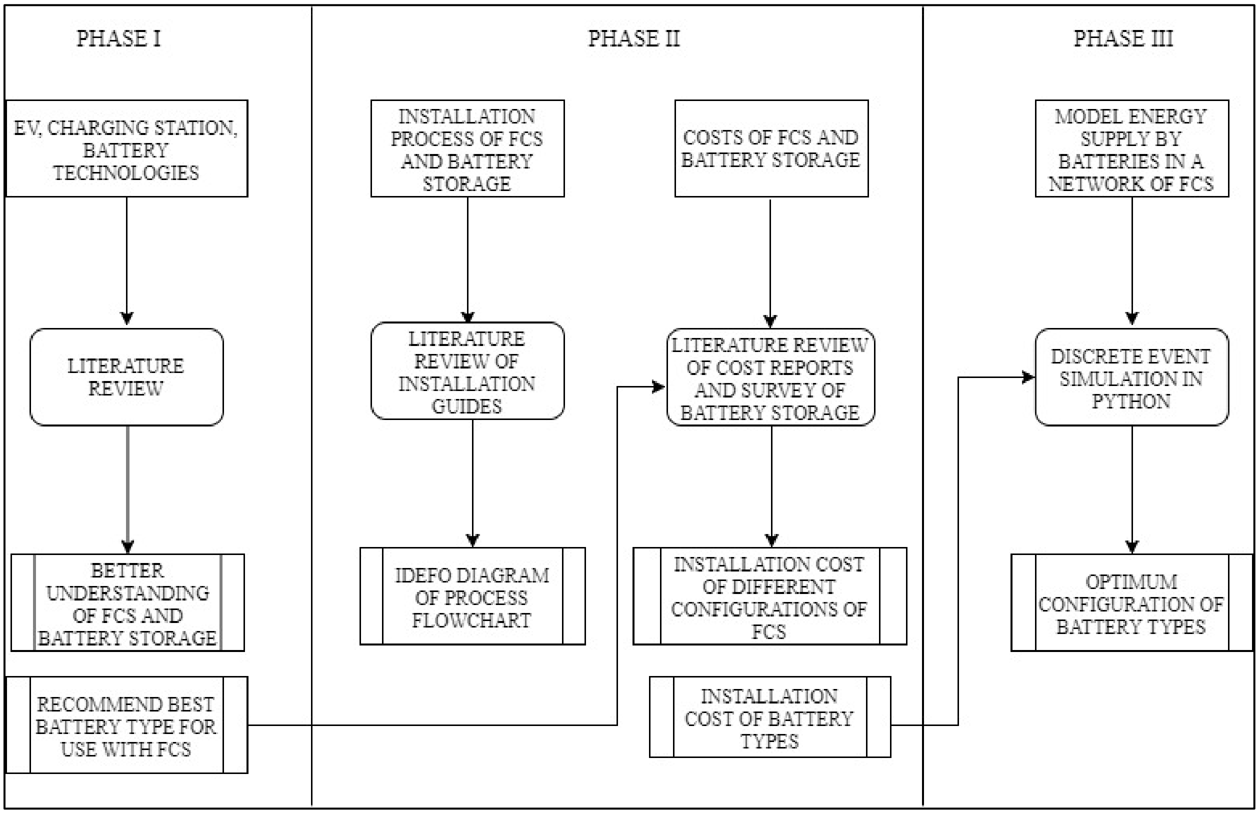


Figure 1.1 Research plan flowchart for each study phase

1.5.2 Methods for objective 1

An extensive literature review was conducted to provide a better understanding of EV charging and battery storage technology. The literature review comprised journal articles, reports, conference proceedings, and websites over 2010–2016 in the areas of electrical engineering, energy fuels, transportation science, and technology. This phase included the following reviews:

(A) Types of EVs, charging station types, and charging station standards, including their advantages and disadvantages.

(B) Existing and near-term battery storage technologies and their associations with FCSs. This includes a discussion of the different battery types (e.g., lithium ion, lead acid, and vanadium redox) used in utility scale applications:

   (1) A comparison of various battery types based on lifecycle, temperature effects, and number of past projects.

   (2) Feasibility of utilizing each battery type for charging station applications, such as peak shaving and backup power.

   (3) The safety of each battery type and environmental impacts, including siting, operation, and end-of-life disposal.

1.5.3 Methods for objective 2

Construction of FCS & Battery Storage

This study phase reviewed the installation process and costs of FCS and battery storage construction. A qualitative analysis of the literature sources included review of recent installation guides, handbooks, technical reports, and cost reports published by charging station operators and installers, U.S. Department of Energy, Electric Power Research Institute, battery manufacturers and installers, and the Clean Energy Council.

1. Installation process

   (A) Present the decision-making and process flow of installing FCS and battery storage using the IDEF0 diagram. IDEF0 is explained in Section 2.7.1.
   (B) Based on the literature review, outline site considerations for deployment, activities prior, during, and post installation, applicable codes, and standards governing installation processes.

2. Costs of FCS and battery technologies

(A) Provide cost estimates for different configurations of FCSs based on literature sources.

(B) Compare costs of various battery technologies discussed in Chapter 1 based on literature sources. Define the cost metrics used for evaluating the costs of battery storage.

(C) Compare the cost of battery systems provided by vendors using a cost survey conducted by Michigan State University and Consumers Energy on distribution-scale battery storage.

Function modeling: In systems engineering, a function model is a structured graph for representing activities, processes, and operations in a defined context (Zhao et al., 2016). The function model provides a visual platform to accommodate process information and uncover associated mechanisms and constraints. Furthermore, this model supports collaboration and project team communication during the design and construction stages.

IDEF0 diagram: The IDEF0 diagram is a function-modeling tool (Grover and Kettinger, 2000) for creating a flow diagram comprising function boxes and arrows. Fig. 1.2 shows a basic IDEF block, in which the function box represents a decision-making process and the arrows represent movements and directions (inputs/outputs and controls/mechanisms, respectively). Typically, input arrows face the function box from the left and indicate the origin of the decision; output arrows face out of the box from the right and indicate the decision made; control arrows face the box from the top and represent an internal or external constraint; and mechanism arrows point outward from the bottom and represent supporting resources (Zhao et al., 2016). A decision-making chain diagram is formed by connecting a certain number of IDEF0 blocks. This diagram allows researchers to visualize decision-making chains and discover critical decision constraints.

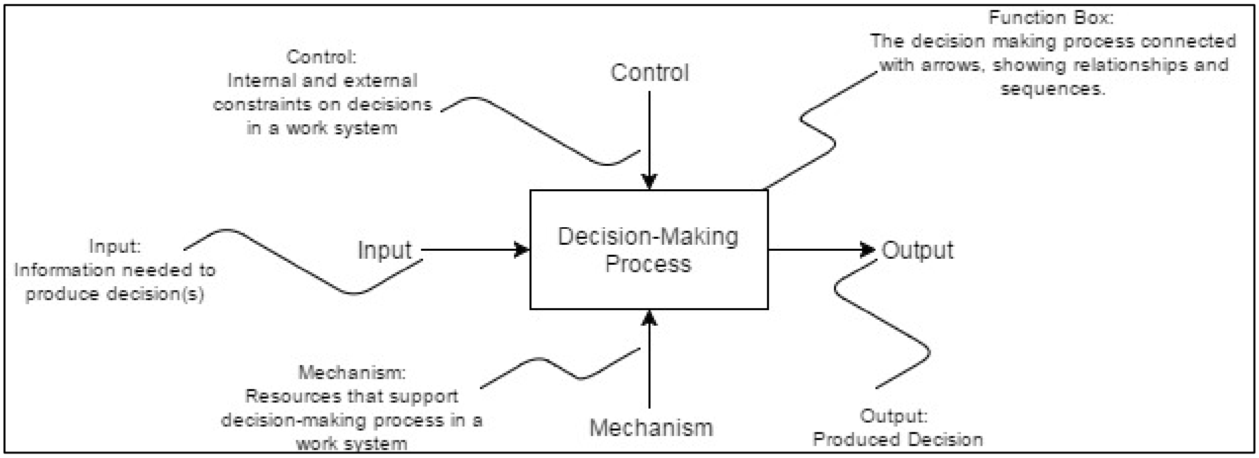


Figure 1.2 Basic IDEF0 block consisting of function box and arrows

1.5.4 Methods for objective 3

In this phase, a DES model of an FCS was created in Python 2.7.13 by varying energy demand using different battery units. See Section 2.8 for a description on DES. The installation cost range of each battery type and vendor (see Chapter 3) were used as model inputs, and the model parameters (i.e., location and power output) are based qualitatively on the network of fast chargers near Detroit. To address the FCS energy gap, battery units are introduced that can supply energy to nearby FCSs and exchange stored energy. The model evaluates the optimal configuration of battery units required to meet the energy gap of the network at minimum cost by simulating these network structures for different battery sizes, types, and exchange ranges.

Discrete event simulation: DES models a system as a chronological sequence of events where each event can be defined as an instant in which a significant state change occurs in the system (Robinson, 2004). DES has been used to tackle a wide range of problems, including project planning (Rizk and Wales, 1997; Lee and Arditi, 2006), optimization of construction operations (Hassan and Gruber, 2008; Zhang et al., 2006), resource allocation (Martinez et al., 2001), and strategic construction management (Han et al., 2011). The fundamental components of DES are as follows:

(A) Entities – Entities are items that flow through the simulation (Caro, 2005). In the model in Chapter 4, FCSs are entities.

(B) Events – Events are another major element of a DES. These are broadly defined as anything that can happen during the simulation (Caro, 2005). In Model #1 implemented in this study, the addition of each battery unit marks an event in the simulation.

(C) Time – Another major component of a DES is time. The simulation clock tracks the passage of time (Caro, 2005).

(D) Resources – A major element for economic evaluation is handling of resources, which are incorporated directly into a DES. An entity may consume a resource, and this consumption involves a defined number of resource units (Caro, 2005). In the model in this study, energy units are resources.

Implementation of DES: Most of the steps in a DES are common to all modeling approaches. First, formulate the problem and include the simulation goals (Caro, 2005). For a DES, processing the events is the most crucial step. This is best done using a general-purpose programming language such as Fortran or Python, where the software conducts the simulation by applying the given logic to each entity. The model is run until the system stabilizes to a steady state or a pre-specified condition.

Monte carlo simulation: In a Monte Carlo simulation, each simulation run generates random numbers that determine whether an event occurs. Scikit-monaco is a library for Monte Carlo integration in Python. In this study, scikit-monaco version 0.2.1 is used for inputting the cost values of a range based on a lognormal distribution. In contrast to a normal distribution that can take both positive and negative values, a lognormal distribution is commonly used for distribution of financial assets (e.g., prices), as they cannot be negative (Zucchi, 2014).

Chapter 2

Literature review

2.1 EVs

EVs refers to the broad category of vehicles that use electricity as a portion of their energy to drive the vehicle. The types of EVs on the market are as follows:

Hybrid EVs (HEVs) combine an internal combustion engine propulsion system with an electric propulsion system, and they do not plug into an electricity source. HEVs transfer the energy created through braking into electricity, which is stored in a battery. The electricity then helps the engine achieve maximum fuel efficiency and minimize operating costs (Energy, 2015). HEVs are thus completely dependent on gasoline or diesel coupled with regenerative braking.

Plug-in HEVs (PHEVs) utilize both electricity and gasoline to power the vehicle. They mostly run on a battery that is recharged by plugging into the power grid (Energy, 2015). They operate on electricity for a limited range and switch to a traditional engine for an extended range. They are referred to as ‘extended-range EVs’ and typically have a mileage range of 30–40 miles on battery (Corporation, 2016).

Battery EVs (BEVs) are propelled by electricity stored in a battery and used by an electric motor without an internal combustion engine. They are charged by plugging into an electricity source, typically the power grid. BEVs require a large DC motor and a large battery pack. They are also called ‘pure EVs’ and typically have a range of 100–200 miles (Corporation E. , 2016).

2.2 EV charging

EV charging is generally performed at three current and voltage levels: AC Level 1, AC Level 2, and Level 3 DC charging (Shuhui Li K. B., 2014). Batteries in EVs must be periodically recharged from the power grid at home or at a charging station. According to the US Department of Energy, the United States now has between 6,000 and 7,000 electric charging stations, of which the majority (more than 5,000) are privately owned. Moreover, nearly 80% of all existing charging stations are Level 2.

AC Level 1 charging uses a standard 120-V, 15A, or 20A circuit, has a maximum charging power of 1.44kW, and requires 8 to 14 hours to fully charge a vehicle (Yu Nie, 2013). Most PEVs come with a Level 1 cordset. Level 1 charging stations can be wall mounted or pedestal mounted at parking spots. Depending on the EV battery type, battery size, and charging control, this station adds approximately 2–5 miles of range per hour of charging time. Level 1 charging typically requires a long charging time and is intended to be used at home or where the vehicle can sit for an extended period. The advantages of such charging are low installation costs and low impact on electric utility peak-demand charges.

AC Level 2 charging uses a 208V (typical in commercial applications) to 240-V (typical in residential applications), single-phase outlet, provides 40A of current, has a maximum charging power of 10kW, and can fully charge a vehicle in 4 to 6 hours (Ghamami, 2016). In addition to the charging equipment of a Level 1 charging station, a dedicated 20–80A must be installed. Depending on the battery type, circuit capacity, and charging control, this type adds 10–20 miles of range per hour of charging time (Smith, 2015). The advantages of such charging are that the charge time is significantly faster than Level 1 and that a variety of manufacturers provide differentiated products for distinct markets and requirements (Vermont Energy Investment Co., 2014). The disadvantages of such charging are that installation costs are higher than Level 1 and that costs are highly variable depending on equipment and installation issues.

Level 3 DC charging is also called fast charging. It uses 480-V, up to 400-A, three-phase electrical service for fast charging of EVs in minutes instead of hours. These chargers enable rapid charging and are normally located at public fueling stations and sites along heavy traffic corridors. They typically add 50–70 miles of range in approximately 20 minutes, and an 80% charge can be provided in 30 minutes or less for most EVs. As Level 3 chargers operate with high voltage, they are generally much more expensive to build and are available only at commercial charging stations (Morrow, 2008). Level 3 is the most practical for installation in public commercial areas, and it enables greater integration of EVs into the market because of quick charging. Fast charging attracts EV users as it replicates the ease of conventional refueling and attracts potential operators because it promises interesting business options (Andreas Schroeder, 2012). According to ABB, a leading power and automation technology company, the market for charging infrastructure solutions is worth $1 billion in 2017 and will be approximately $4 billion by 2020. There are currently nearly 2,200 high-speed chargers in the United States (McDonald, 2016). The prime advantage of Level 3 charging is that charge time is drastically reduced. The disadvantages are that equipment and installation costs are very high depending on onsite power availability, and fast charging may strain the grid or incur high ‘demand charges’ for pulling power off the grid at peak times (Gartner, 2012). DC FCSs are intended for locations where vehicles are parked (primarily near major roads) for short periods of approximately 30 minutes, such as service stations, fast-food restaurants, cafés, and some urban parking areas.

2.3 DC fast-charging standards

Charge de Move (CHAdeMO), Combined Charging Standard (CCS or SAE Combo), and the Tesla Super Charger are the three charging standards in use in the United States.

CHAdeMO: In 2010, Toyota, Nissan, and Mitsubishi partnered to establish the CHAdeMO quick-charge standard (McDonald, 2016). The maximum charging power specified by the CHAdeMO standard is 62 kW. CHAdeMO ports do not support AC charging, and cars must have two charging ports: one for AC Level 2, the other for CHAdeMO (Herron, 2014). CHAdeMO is compatible with Nissan, Mitsubishi, and Kia.

Combined Charging System (CCS): CCS is built on the existing J1772 Level 2 charge standard to allow for all three charging speeds from a single port. CCS chargers improved several of the practicality and cost issues associated with CHAdeMO while allowing for a higher potential rate of charge. Although existing CCS chargers typically run at the same speeds as CHAdeMO, the standard allows for a theoretical maximum of 350 kW through the port—more than twice as fast as a Tesla Supercharger (McDonald, 2016). CCS is compatible with BMW, Volkswagen, Chevrolet, and all upcoming electric cars in the United States.

Tesla Supercharger: The Tesla Supercharger system is rated at 120kW. Tesla also sells an add-on adapter to enable Tesla owners to charge their vehicle using CHAdeMO or J1772 standards. As of 2017, there are currently 828 Supercharger stations and 5,339 Superchargers in use (Tesla, 2017).

2.4 Battery technologies

There exist many battery technologies with applications in utility power production and distribution, such as lithium ion, sodium sulfur, lead acid, vanadium redox flow, nickel cadmium, nickel metal hydride, sodium nickel chloride, zinc air, zinc bromine, and iron-chromium (Akhil et al., 2015). The emerging development of battery technology in recent years has presented new possibilities with applications in electric utility transmission and distribution, renewable energy, smart grids, and EVs. Installing energy storage also provides capacity for additional EV charging without expensive utility upgrades.

Table 2.1 provides a comparison of performance attributes of the various battery technologies later detailed.

Table 2.1 Performance comparison of various battery technologies

Battery Storage Type	Discharge Duration	Size	Nominal Voltage	Number of Cycles	Number of Projects ≤ 1 MW
Lithium-ion	10 min – 9h 21 min	1 kW – 48 MW	3.7 V	~5,000	430
Sodium-sulfur	6h – 8h	400 kW – 50 MW	2.1 V	500–10,000	14
Lead-acid	50s – 9h 36 mins	2 kW – 36 MW	2.0 V	~1,500	72
Vanadium redox flow	16 min – 20h	5 kW – 20 MW	1.6 V	~10,000	48
Nickel-cadmium	5 min – 15 min	3 MW – 27 MW	1.2 V	~500–3,000	0
Nickel metal hydride	15 min	300 kW	1.2 V	~600–1,200	1
Sodium-nickel-chloride	42 min – 5h	20 kW – 5 MW	2.6 V	~1,000	24
Zinc-bromine	2h – 6h	3 kW – 25 MW	1.8 V	> 2,000	32
Zinc-air	2h – 48h	250 kW – 10 MW	1.65 V	~5,000	0
Iron-chromium	4h	250 kW	1.18 V	> 5,000	0

Lithium-ion battery: Lithium-ion (Li-ion) batteries were first commercialized in the early 1990s and have become one of the most-preferred storage technologies in many applications owing to their high energy density, high voltage ratings, high efficiency, low self-discharge, lack of cell ‘memory,’ and fast response (Puget Sound Energy, 2015). Moreover, Li-ion batteries do not need to be discharged completely (Oswal M., 2010).

However, Li-ion batteries have some disadvantages, such as short cycle life, high cost, heat management issues, and narrow operating temperatures (International Electrotechnical Commission, 2011). More than 300 energy storage projects with Li-ion batteries are currently in operation worldwide. Li-ion batteries can adapt to a range of power and energy ratings, and the rated power of the operational projects varies from 1 kW to 48 MW. Li-ion batteries are mostly used in projects with rated power below 5 MW. Li-ion batteries have several subtypes based on cathode material, including lithium manganese oxide (LMO), lithium iron phosphate (LFP), lithium nickel cobalt aluminum (NCA), lithium titanate (LTO) and lithium nickel manganese cobalt (NMC).

Sodium sulfur battery: Sodium-sulfur (NaS) battery technology was first invented in the 1960s by Ford Motor Company, and the first mega-watt-class system of NaS batteries in the United States was installed in 2006. After decades of development and support by companies like NGK Insulators, Ltd., and Tokyo Electric Power Co. (TEPCO) and its utilities, there are approximately 30 operational NaS projects worldwide (U.S. Department of Energy, 2016). According to the DOE Global Energy Storage database, most utility-scale operational projects have rated power greater than 1 MW (varying from 100 kW to 50 MW), and the duration at rated power is between 3 to 8 hours. NaS batteries are projected to have a calendar life of 15 years (DOE-EPRI 2013 Energy Storage Handbook).

The advantages of NaS batteries are long discharge period (approximately 6 to 7.2 hours), relatively high energy densities, fast response, and commercial maturity. Moreover, the NaS battery uses inexpensive, non-toxic materials and is thus highly recyclable (Gonzales et al., 2012;

Kawakami et al., 2010). One drawback of the NaS battery is that the internal heating unit uses the battery's own stored energy and thus reduces battery performance. Another downside is the risk of fire and that the system must be protected from water and oxidizing atmospheres.

Lead-acid battery: Lead-acid (LA) batteries have been commonly used in many applications, including stationary and mobile ones (IEC, 2011). Stationary LA batteries are more efficient than starter batteries but cost more. Two main types of LA batteries exist, that is, carbon LA technologies and advanced LA technologies (Sandia, 2007). The service life of a LA battery is typically in the 6- to 15-year range and has a cycle life of 1,500 cycles and a discharge depth of 80%. Moreover, the efficiency of LA batteries is within the 80 to 90% range. LA advantages include fast recharge rates, simple charging technology, long cycle life in deep-discharge applications, favorable cost/performance ratio, and little maintenance (IEC, 2011; Sandia, 2007; Axion, 2016). LA batteries have high commercial maturity and relatively low disposal cost, total installed cost, and relocation cost (Sandia, 2007). More than 70 LA projects exist globally, most having rated power less than 1 MW.

Vanadium redox flow battery: Vanadium redox flow batteries (VRFB) are a relatively mature type of flow battery being used in various stationary applications. The power of flow batteries is defined by the size and design of the electrochemical cell, whereas the energy depends on the size of the tanks (IEC, 2011). These batteries are inherently safe, with no thermal runaway. The electrolyte is aqueous and non-flammable, and they are environmentally friendly and recyclable. Furthermore, the electrolyte is reusable and provides an emission-free energy supply. These batteries have high energy efficiency, short response time, long cycle life, independently tunable power rating and energy capacity, and consistently stable performance (Cunha, 2014). The DOE

Global Energy Storage database indicates that more than 30 operational VRFB projects exist worldwide, most with rated power less than 1 MW.

Nickel cadmium battery: Nickel cadmium (Ni-Cd) and nickel metal hydride (NiMH) batteries are the two main members of the nickel-based battery family.

Ni-Cd batteries have been commercially used since 1915 and are therefore a relatively mature technology, but few grid-scale deployments exist. This type of battery performs well even at low temperatures (in the -20 °C to -40 °C range). Nickel-based batteries have higher power density, slightly greater energy density, and a higher number of cycles than LA batteries do (IEC, 2011). Ni-Cd batteries also pose several disadvantages. For example, cadmium is prohibited for customer use because it is very toxic and dangerous to the environment.

Nickel metal hydride battery: NiMH batteries were developed as an alternative for NiCd because of the toxicity of cadmium. Although NiMH batteries share almost all the advantages of NiCd batteries, the maximal nominal capacity is still 10 times less than that of NiCd and LA (IEC, 2011). Furthermore, they charge slower than NiCd and cannot withstand very low operating temperatures (Puget Sound Energy, 2015). At present, only one operational NiCd project exists (in Japan) with 300 kW rated power.

Sodium nickel chloride battery: Sodium nickel chloride (NaNiCl) batteries are also known as zero-emission battery research activities (ZEBRA). Like NaS batteries, they are high-temperature (HT) batteries, but they use nickel chloride instead of sulfur for the positive electrode. According to the DOE Global Energy Storage database, approximately 20 operational ZEBRA projects exist globally and approximately 10 are announced or under construction. Most of the utility-scale operational projects are from 20 kW to 5MW, and the duration at rated power is between 42 minutes to 5 hours.

Some advantages of NaNiCl over NAS chemistry include overcharge and discharge tolerance, potentially better safety characteristics, and higher cell voltage. Other beneficial features of ZEBRA are its low environmental impact owing to fully recyclable materials as well as its fast response, long cycle life, tolerance of short circuits, constant performance and cycle life in harsh operating environments, high energy density (five times higher than LA), and scalability. This battery type has been shown to have relatively low intrinsic risks during normal operation. Sodium nickel technology is maintenance-free and has zero ambient emissions. However, ZEBRA units have limited utility grid application, and, therefore, the technology is currently used in the transportation and military equipment industries and in limited grid-scale applications in North America (Chen et al., 2009; IEC, 2011; Dustman, 2004).

Zinc bromine battery: Zinc-bromine batteries (ZBBs) are a promising and emerging technology. This battery is still in early stages of field deployment and demonstration trials for utility applications. According to the DOE Energy Storage database, 10 projects are operational and 10 are contracted or under construction. The rated power is not very high as most projects are below 500 kW, but the duration at rated power is relatively long, from 2 to 6 hours. The features of a conventional battery and flow battery are combined, and, thus, higher power and energy densities are allowed than in other types of flow batteries. Furthermore, ZBBs have long estimated lifetimes (20 years), because the active materials themselves do not degrade and the lifetime is not strongly dependent on the number of cycles or the depth of discharge but on the number of hours of operation (DOE-EPRI 2013 Energy Storage Handbook). Other advantages of ZBBs include long cycle lives, operational AC-to-AC efficiencies of approximately 65%, 100% depth of discharge, ambient temperature range, and no shelf life. One disadvantage of ZBBs is that it contains potentially contaminating materials.

Zinc-air battery: This type of battery offers low material cost and high specific energy. This technology is far more stable and less dangerous than other battery technologies and has up to three times the energy density of Li-ion, the most-competitive battery technology. Moreover, zinc-air batteries are very environmentally friendly because they do not produce potentially toxic or explosive gases and contain no toxic or environmentally dangerous components. A downside of zinc-air batteries is that they are sensitive to extreme temperatures and humid conditions. These batteries are still in early stages of utility applications, and no zinc-air projects are currently operational but two contracts for such projects exist in California.

Iron-chromium battery: This battery is still in the R&D stage and only one demo project has been conducted. Iron-chromium batteries are safer than integrated cell storage architectures (e.g., LA, NaS, and Li-ion) owing to the separation of power and energy. They are also environmentally benign because the utilized iron and chromium species have low toxicity.

2.5 FCSs and battery technologies

A major challenge for public charging stations is reducing charging time. This can be addressed by increasing the rate of power transfer through energy storage units (e.g., batteries; Sbordonea, 2014). As discussed in the previous section, many types of batteries are available for an FCS. By improving the operational capabilities of the FCS, battery storage can contribute to system reliability and emergency preparedness with backup power, potentially lowering costs and reducing infrastructure investments (Akhil et al., 2015). In addition to supporting DC fast charging, battery systems are used to sell power back to the grid. As mentioned in Joos and Freige (2010), battery storage should satisfy the following performance criteria to maximize charging station efficiency:

(A) Dynamic device: Because the charging station operates for only 20 minutes (short duration), the storage devices must be able to charge and discharge in that period.

(B) High-power density: Because of the previous requirement, devices must also have high power density to deliver a large amount of power for a short period.

(C) High efficiency: The charging station must achieve maximum efficiency. This last criterion depends on the converters and storage devices, which are the main station components. Therefore, considering highly efficient energy storage and conversion is required.

(D) Environmentally friendly: The device must have no or negligible adverse effects on the environment.

A battery storage system used in conjunction with a FCS operates in the following modes (Aziz, 2016):

1. Battery discharge mode: The battery discharges its electricity in assisting the system. EV charging is performed using electricity from both the grid and the battery. This mode is applied in fast charging of multiple EVs, especially when electricity prices are high. The power balance equation for this mode is shown in Eq. 1.

$$P(\text{grid}) + P(\text{batt}) = P(\text{fc}) + P(\text{loss}) \tag{1}$$

where $P(\text{grid})$ is the electricity from the grid, $P(\text{batt})$ is electricity charged/discharged from battery, $P(\text{fc})$ is electricity for EV quick charging, and $P(\text{loss})$ is electricity loss.

2. Battery charging mode: When a surplus of electricity from the grid exists, the demand for charging is low and the price of electricity is reduced. The power balance function for this mode is shown in Eq. 2.

$$P(grid) - P(batt) = P(fc) + P(loss) \quad (2)$$

3. Battery idle mode: The battery can be in idle mode when the power capacity from the grid is sufficient to cover quick charging of EVs or the battery is empty owing to continuous charging of multiple EVs. The power balance function for this mode is shown in Eq. 3.

$$P(grid) = P(fc) + P(loss) \quad (3)$$

2.6 Microgrid

A microgrid is a small-scale power grid that can operate independently or in conjunction with the area's main electric grid (Rouse, 2015). Microgrids can be intended as backup power or to support the main power grid during periods of heavy demand. Microgrids incorporate renewable power using multiple energy sources like distributed generators, batteries, or solar panels (Microgrid Institute, 2014). A microgrid is a locally controlled system and can function both connected to the traditional grid or as an electrical island. According to Berkeley Lab (2015), there are two major types of microgrids: customer microgrids (wholly on one site, akin to a traditional utility customer) and milligrids (involving a legacy regulated grid segment). Military bases, hospitals, municipalities, data centers, and business parks are all developing microgrids. Microgrids tend to be owned by private or government entities; some utilities have also constructed microgrids.

The operation of microgrids offers distinct advantages to customers and utilities: improved energy efficiency, minimization of overall energy consumption, reduced environmental effects, supply reliability improvements, network operational benefits (e.g., loss reduction, congestion relief, voltage control, and security of supply), and cost-efficient electricity infrastructure replacement (Berkeley Lab, 2015). Microgrids may offer new revenue streams to utilities because they make the grid more efficient. However, costs exist for building new infrastructure, and new microgrids may adversely impact customer rates (U.S. Department of Energy, 2014). According to Stadler et. al. (2015), significant economic returns can be achieved by the deployment of microgrids in applications ranging from residential to commercial and large industrial.

2.7 Summary

Battery storage systems enable FCSs to meet power demand. For supporting a DC fast charger, battery systems with less than 100kW power that can run for at least 4 hours are required (depending on the load profiles of the charging station). Existing research suggests that Li-ion batteries currently provide the best safety, cost, and technical performance for small-sized power distribution applications, and LA and VFRB are also competitive in these areas. These three technologies are relatively mature and scalable, and operational and safety solutions have already been developed. They have the highest number of projects installed with less than 1 MW power. Furthermore, for the technologies, the number of installations is increasing, large availability of suppliers ensures that future installations are cost-competitive and that support remains available, and service and cycle life are competitive with other technologies.

Chapter 3

Construction of a FCS and battery storage

3.1 Installation process of a FCS

As an increasing number of consumers purchase PEVs, the demand for electrical charging stations will increase. Contractors will therefore receive more requests to install charging stations in both new construction and existing homes, retail outlets, corporate campuses, and parking decks. Electrical inspectors will also be challenged by this evolving technology as requests for approvals increase and the installation scope varies (Advanced Energy Co., 2011). Understanding the processes involved in the installation of a DC FCS are then vital.

Fig. 3.1 shows a flowchart (IDEF0 diagram) depicting the processes involved in the installation of a FCS. Tables 3.1 and 3.2 summarize the five predefined control categories and the five predefined mechanism categories for function modeling, respectively.

Table 3.1 Control categories in FCS installation

Identifier	Control (constraint)	Description
C1	Assessment	Engineering calculations, service upgrade assessment, site plan
C2	Approvals	Permit and estimate approval
C3	Regulations	Standards and requirements
C4	Efficiency	Adequate qualified resources

Table 3.2 Mechanism categories in FCS installation

Identifier	Mechanism (resource)	Description
M1	Space	Parking, facilities, and electric service availability at site
M2	Funding	Government/utility incentives
M3	Professionalism	Licensed contractor/expertise, skills, good judgement

Table 3.2 (cont'd)

M4	Time	Schedule
M5	Collaboration	Communication and coordination with third parties

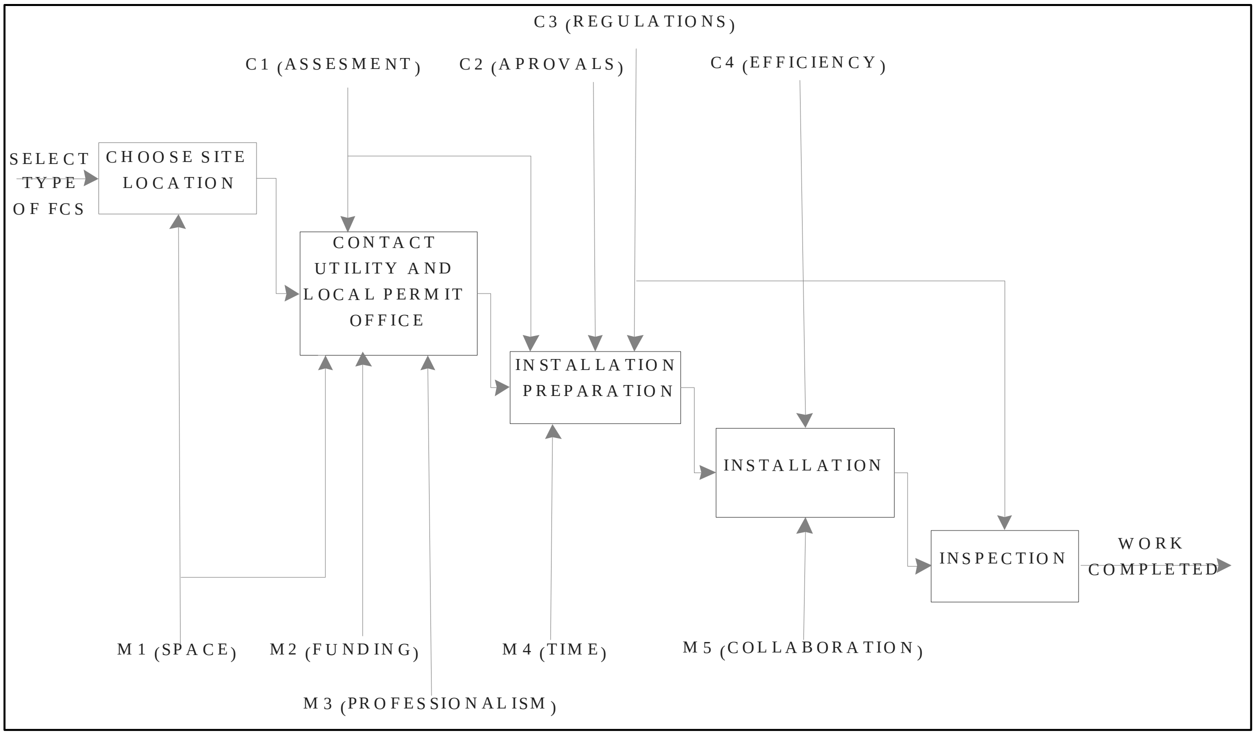


Figure 3.1 IDEF0 diagram of a FCS installation process

The following sections describe each stage of the installation process in detail, including the steps contractors should follow.

3.1.1 Site requirements

The site for an FCS must be safe, accessible, convenient, and reliable. The site should contain a type and mix of charging stations that maximize usefulness (Alternative Energy Systems Consulting, Dec 2015) and meet the following minimum requirements to satisfy the needs of the

EV client and infrastructure goals (Alternative Energy Systems Consulting, Dec 2015) & (Advanced Energy, 2013):

(A) Location: The host site should be within urban areas, preferably within a one-mile radius from a highway interchange. The location must be cleared and accessible during winter and not be used as a snow dump or hinder snow-clearing operations. It should be visible to encourage its use by EV drivers.

(B) Parking: It should have adequately lit, appropriate paved parking and reasonable ingress/egress points.

(C) New construction: From an electrical and accessibility standpoint, it is simpler (but not always preferable) to design a new DC FCS than retrofit an existing location.

(D) Facilities: Host sites should ideally have 24-hour access to well-maintained restrooms. Preferred sites should have internet connectivity capabilities to facilitate communications between the EV supply equipment (EVSE) and EV and serve as the medium for integrating the EVSE with utility smart-grid systems. Moreover, sites that offer products and ancillary services while charging, such as snacks, vending machines, fast food, shopping, and restaurants, are preferred.

(E) Safety: The site should have dusk-to-dawn area lighting and have a reasonable level of activity. The site must also have shelter for inclement weather.

(F) Electric power: Access to existing 480-V three-phase power nearby is preferable. The local grid must have adequate capacity to serve the site and all chargers.

An FCS usually requires a concrete base, and its installation is like that of street-side locations. In choosing a location for this type of station, the following factors must be considered (Hydro Quebec, 2015):

(A) Station configuration

(B) Locations of any underground lines and tanks

(C) Distance from the street (i.e., the charging cable must never extend over the sidewalk)

(D) Required excavation work

(E) Proximity of the distribution panel

(F) Planning of any underground conduits and excavation work

(G) Coordination with excavation consultants before starting work

(H) Contractor expertise (must have appropriate licenses)

(I) Possibility of installing a concrete base

Appendix A provides a general overview of the installation process in different phases and a contractor checklist for surveying FCSs (Advanced Energy Co., 2011).

3.1.2 Installation preparation

Following the initial site visit, the contractor should prepare for installation. Complete the following checklist (Advanced Energy Co., 2011):

(A) Submit price quote to customer and get approval. Ensure that total installation cost, including utility upgrades and all other work, is understood by the customer.

(B) Order equipment including selected charging station(s).

(C) If necessary, perform and stamp engineering calculations. Contact local permit department for questions regarding the need for load calculations.

(D) Complete site plan modification along with necessary diagrams (typically required for parking lots, decks, and on-street parking).

(E) Perform service upgrade and/or new service assessment if required.

(F) Fill out permit application along with site plan modification, load calculations, and any other information deemed necessary by the local permitting department.

(G) Ensure permit is approved.

(H) Schedule the plan (i.e., contact all stakeholder parties and schedule work).

(I) Hire additional contractors for boring, concrete, paving, or other surface restoration work.

(J) Utility work: utility markings, service upgrades, new service, and meter pull.

(K) Utility marking of existing power lines, gas lines, and other infrastructure should be conducted prior to installation. Utilize "Call Miss Dig" services.

3.1.3 Installation and inspection

The process remains similar despite that installation varies based on type of site and number of stations installed (Advanced Energy Co., 2011):

(A) Post permit at site in visible location.

(B) Conduct any excavations of materials required to run a conduit and/or wiring and install a charging station. Typical excavation actions include the removal of drywall, insulation, pavers, and concrete or pavement as well as hand digging, trenching, boring, and drilling.

(C) Run the conduit from the power source to the station location. For charging stations rated more than 60 amp, a separate disconnect must be installed (NEC 625.23) when running the conduit. Some customers may desire a separate disconnect for stations rated below 60 amp, and this disconnect should be visible from the charging station.

(D) Schedule an initial rough electrical inspection after the conduit has been run and prior to connecting equipment and running wires. If the installation does not pass inspection, the contractor should correct any items discussed by the inspector and schedule a second rough inspection prior to moving on to the next step.

(E) Pull the wires. Charging stations require two hot lines (a neutral and a ground), and as charging equipment is considered a continuous load, conductors should be sized to support 125 percent of the rated equipment load (NEC 625.21).

(F) Prepare the mounting surface according to the charging station manufacturer's instructions. Floor mounts typically require a concrete foundation that allow the conductors to enter through the base of the charging station and the appropriate installation of J-bolts should be based on the station base plate. For wall/pole/ceiling mounts, brackets may need to be installed to mount the charging equipment.

(G) Mount the charging station(s), and ensure that equipment is level and mounted in accordance with manufacturer instructions.

(H) Install any necessary protective bollard(s) and/or wheel stop(s).

(I) Install any required electrical panels or sub-panels.

(J) Perform utility work such as service upgrades, new service, and new meter installations. The utility may also pull a meter to allow for the charging station wires to be connected to a panel.

(K) Finish electrical wiring.

(L) Perform finishing work.

(M) Replace drywall.

(N) Bury conduit and conductors.

(O) Fill and compact as needed.

(P) Replace walking surfaces—concrete, asphalt, and pavers.

(Q) Perform final inspection. If required, the inspector should examine the wiring, connections, mounting and finish work, and ensure that the charging station is safe for operation in its given location.

(R) If possible, the contractor should verify that the charging station functions properly.

3.1.4 Responsibility matrix

Table 3.3 shows the stakeholders responsible for each process during FCS installation.

Table 3.3 Responsibility matrix of various stakeholders for FCS installations

Step	Action	Person responsible
1	Approve installation of charging station: (1) Workplace, retail, public lots/decks (2) On-street parking, residential owner (obtain permit and reserve parking space) (3) On-street parking, non-residential owner	(1) Parking spot owner (2) Residential owner (3) Right-of-way owner
2	Select charging level and number of charging stations	Owner
3	Select charging station(s)	Owner
4	Select parking space(s)	Owner
5	Select power source	Owner/utility
6	Estimate installation costs	Contractor
7	Create site plan and determine whether electrical upgrades are necessary	Contractor/utility
8	Approve/accept estimate	Owner/contractor
9	File permit application	Contractor
10	Complete electrical upgrade, if required: (1) Panel upgrade/new panel (2) Service upgrade/new service (3) New meter	Utility (1) Contractor (2) Utility (3) Utility
11	Restore power	Utility
12	Conduct installation	Contractor
13	Perform inspection	Inspector
14	Verify performance	Contractor

3.1.5 Applicable codes and standards

These general EV charging station (EVCS) installation standards relate to electrical code and workmanship requirements, equipment, determination of proper electrical load, physical installation, post-installation equipment use and maintenance, and communications (California Energy Commission, 2016). The National Electrical Contractors Association (NECA) publishes the National Electrical Installation Standards (NEIS) to define a minimum baseline of quality and workmanship for installing electrical products and systems. The NEIS code for EVCS is NECA 413-2012, Standard for Installing and Maintaining Electric Vehicle Supply Equipment. NECA 413 includes guidance on the EVSE, the installation process, ongoing maintenance, and communications. NECA 413 also recommends that all work should be performed in accordance with established requirements for electrical safety.

Society of automotive engineers and national electrical code standards

The Society of Automotive Engineers (SAE) has developed standards for energy transfer and a common cord set to ensure common standards for vehicle charging. These standards ensure that all PEVs have a common charging 'plug,' that is, that any PEV can plug into any charging station. The two main standards are SAE J1772 and SAE J2293, which reference other SAE, National Electrical Code (NEC), and Underwriters Laboratories (UL) standards or codes.

Table 3.4 SAE standards for charging stations

SAE standards for charging stations	
Standard	Description
J1772	Electrical and mechanical aspects of the cord set; references UL for safety and shock protection as well as the NEC for the cord and couple.
J2293	Standard for the EV energy transfer system. This encompasses the system for transferring energy from the charging station to the car.
J2293-1	Functionality requirements and system architecture
J2293-2	Communication requirements and network architecture

Table 3.5 NEC standards for charging stations

NEC standards for charging stations	
Standard	Description
NEC 110.11	Deteriorating Agents
NEC 110.28	Enclosure Types
NEC 110.26	Electrical Equipment Spacing
NEC 110.26 (A)(2)	Width of Working Space
NEC 110.27(B)	Guarding of Live Parts – Prevent Physical Damage
NEC 210.70(A)(2)	Lighting Outlets Required – Dwelling Units – Additional Locations
NEC 300.4	Protection [of conductors] Against Physical Damage
NEC 334.15	Exposed Work [requirements for nonmetallic-sheathed cable]
NEC 334.30	Securing and supporting nonmetallic-sheathed cable
NEC 625.1–625.5	General (Scope, Definitions, Other Articles, Voltage, Listed/Labeled)
NEC 625.9 (A–F)	Wiring Methods (EV Coupler)
NEC 625.13–625.19	Equipment Construction
NEC 625.21–625.26	Control and Protection
NEC 626.28–625.30	EV Supply Equipment Locations

3.1.6 Signage

Although many EV users locate EVCS locations through their smart phones or onboard navigation systems, clear roadside signage for EVSEs is critical (Vermont Energy Investment Co., 2014). In the United States, the Federal Highway Administration developed a pictogram that represents a charging station (see Figure 3.2) used in public parking areas equipped with charging stations. In addition, supplemental plaques denoting the level of charging below the main sign may also be added to inform drivers of the limitations.

Figure 3.2 Signage for EV charging stations

3.2 FCS costs

EVSE installation costs vary widely depending on site characteristics and the quantity and type of EVSE being installed. Like any product, price is influenced by the degree of competition amongst EVSE vendors and the ability of vendors to achieve economies of scale in service delivery. As EVSEs become more prevalent, equipment prices and installation costs decrease (particularly for Level 3 charging equipment) (Vermont Energy Investment Co., 2014).

Although past EVSE installations provide a wide range of information on costs for future installations, cost estimates for a specific site can only be determined by contacting the utility, EVSE manufacturers, and EVSE installers who can conduct a site assessment.

The following installation costs exist for an FCS (Hydro Quebec, 2015), (Vermont Energy Investment Co., 2014):

(A) Purchase price of the charging station and associated equipment

(B) Power connection to the electric grid, including purchase and installation of electrical equipment (e.g., conduits, conductors, transformers, protective devices, switching equipment, cabinet, and grounding)

(C) Civil engineering work (e.g., mounting, excavation, and concrete bases)

(D) Charging station installation

(E) Protective devices (e.g., bollards and wheel stops)

(F) Signage, parking lot lines, and stripes

(G) Lighting

Different sources provide varying estimates for DC fast charger (DCFC) installation costs. A DC FCS can have multiple DCFC. According to a study by American Council for an Energy-Efficient Economy titled "Plug-in EV Challenges and Opportunities," installation costs for a DCFC range from \$20,000 to \$50,000. Installation cost estimates obtained from experienced installers such as Green Power Technologies and Peck Electric indicate that the equipment cost varies from \$15,000 to \$60,000 and the installation cost varies from \$10,000 to \$25,000. Thus, total costs are between \$25,000 and \$85,000, where the lower cost range is for sites that used existing electrical services. DCFCs proposed in remote areas may require additional costs if the site lacks access to three-phase power: the cost of introducing three-phase power to a new location is costly (approximately \$15,000 to \$30,000 per mile) or more, depending on the utility company performing the work and the number of customers served. Permit costs are not a significant factor impacting commercial installation costs (Alexander, 2014). The DC FCS installation costs presented in Fig. 3.3 are based on single-port products available in 2014 and 2015.

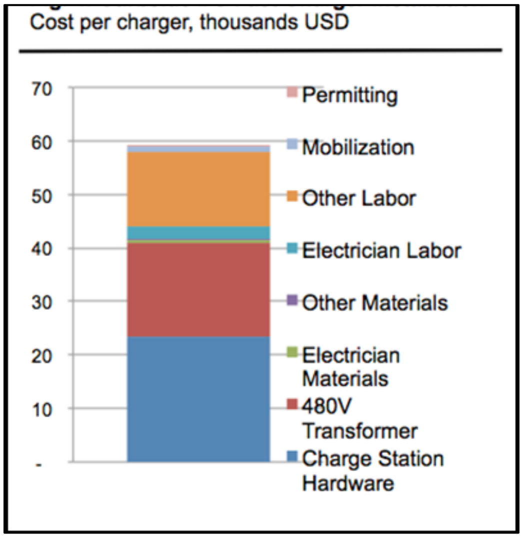


Figure 3.3 Costs of DC fast charger installation

Table 3.6 presents two charging station configuration options, as recommended by Alternative Energy Systems Consulting (AESC).

Table 3.6 Charging station configurations

Equipment	Option 1 quantity	Option 2 quantity
Level 2 charger (single port)	1	0
Level 2 charger (dual port)	0	1
Dual-protocol DCFC	1	2

Tables 3.7 and 3.8 break down the costs for these two DCFC installation options. The costs used to determine the limits for Options 1 and 2 represent the maximum expected costs of installation and equipment for each option, but specific site conditions may result in significant deviations from estimated costs. Price ranges were determined using a combination of interviews with industry experts (Alternative Energy Systems Consulting, Dec 2015). The dual-protocol DCFC is configured with both a CHAdeMO and SAE Combo (CCS) connector; however, because only one protocol can be used at a time, it effectively becomes a single-port unit. A Level 2 charger is

desirable because it significantly increases the functionality of the charging station with little added cost and serves as a backup in case all DCFCs are in use. This option also allows the station to serve local drivers.

Table 3.7 Costs for option 1

Costs for Option 1			
Description	Units	Typical cost per unit	Total cost
Site work (e.g., demolition, concrete, mounting, signs)	1	$10,000	$10,000
General electrical work (e.g., wire and conduit)	1	$3,000	$3,000
New 300kVA transformer	1	$32,500	$32,500
Extend utility service	1	$17,500	$17,500
Level 2 charger (single port)	1	$7,500	$7,500
Dual-protocol DCFC	1	$35,000	$35,000
Subtotal			$98,000
10% contingency			$10,550
Total			$108,550

Table 3.8 Costs for option 2

Costs for Option 2			
Description	Units	Typical cost per unit	Total cost
Site work (e.g., demolition, concrete, mounting, signs)	1	$15,000	$15,000
General electrical work (e.g., wire and conduit)	1	$3,000	$3,000
New 500kVA transformer	1	$40,000	$40,000
Extend utility service	1	$17,500	$17,500
Level 2 charger (dual port)	1	$10,000	$10,000
Dual-protocol DCFC	2	$35,000	$70,000
Subtotal			$155,500
10% contingency			$15,550
Total			$171,050

Based on the costs for each activity/item specified in these tables, more DCFC installation configurations can be created depending on whether an additional Level 2 charger, an electrical upgrade (new transformer), or extended utility service are required. Table 3.9 lists total costs for such configurations.

Table 3.9 Costs of a DCFC under different configurations

Step	Cost of a DCFC under different configurations					
	Dual-protocol DCFC	Level 2 charger (single port)	Level 2 charger (dual port)	Electrical upgrade	Extend utility service	Total cost
1	Yes	No	No	No	No	$58,550
2	Yes	No	No	No	Yes	$76,050
3	Yes	No	No	Yes	No	$91,050
4	Yes	No	No	Yes	Yes	$108,550
5	Yes	Yes	No	Yes	Yes	$116,050
6	Yes	No	Yes	Yes	Yes	$171,050

3.3 Battery storage installation process

The introduction of new storage equipment solutions has led to the emergence of grid-connected battery storage installation. Fig. 3.4 shows a flowchart (IDEF0 diagram) depicting the processes involved in installation of a battery storage unit. Tables 3.10 and 3.11 summarize the five predefined control categories and the four predefined mechanism categories for function modeling, respectively.

Table 3.10 Control categories in battery system installation

Identifier	Control (constraint)	Description
C1	Assessment	Site visit and evaluation
C2	Approvals	Building permission and permission to connect to local grid
C3	Regulations	Standards and requirements
C4	Time	Delivery at customer site and installation schedule

Table 3.11 Mechanism categories in battery system installation

Identifier	Mechanism (resource)	Description
M1	Space	Environment, temperature, foundation, electric power
M2	Professionalism	Licensed contractor
M3	Collaboration	Communication with other parties
M4	Materials	Construction of foundation/concrete plate and resources

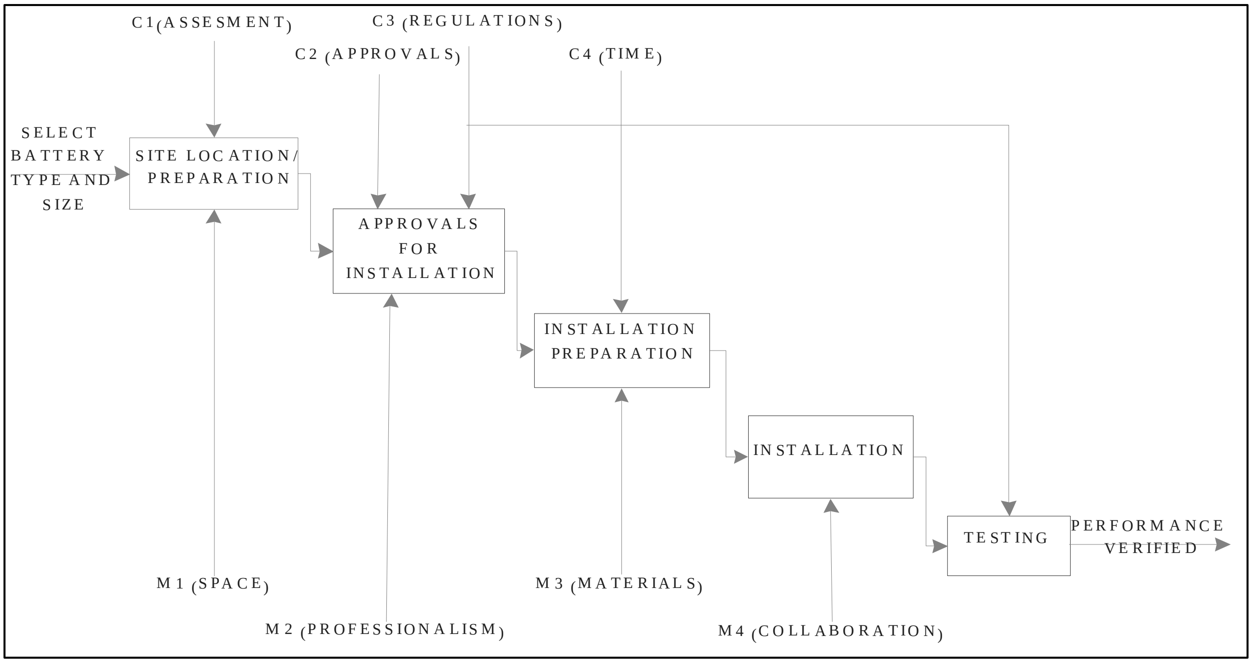


Figure 3.4 IDEF0 diagram of battery storage installation process

Appendix B lists different phases and actions in each phase of a battery storage project. The following step-by-step process for installing a battery storage unit at any given site is as follows:

1. Location/site preparation requirements:

When planning the battery system space requirements, consider the following issues (Enersys, 2016), (Clean Energy Council, 2016):

(A) Space—Maintain proper spacing between cells/batteries to provide thermal management and ensure proper fit of hardware connections. Proper accessibility to the installation area must be provided.

(B) Environment—Must be a clean, cool, and dry place.

(C) Temperature—Installing the unit where ambient temperature is within operating range is recommended, as higher temperatures reduce operating life and lower temperatures reduce battery performance.

(D) Ventilation—Adequate ventilation must be provided.

(E) Codes—Building codes and fire codes may require a spill-containment system for battery installations.

(F) Foundation—The foundation must support the weight of the battery as well as any auxiliary equipment. Foundation documents and execution planning for a standard soil are usually delivered in advance to the installation, and the specific thickness of the concrete plate must be defined with respect to the properties of the installation area.

2. Electrical power connection

3. Communication interfaces

4. Grounding and lighting protection: A proper grounding connection compatible with local standards must be provided at the installation site. Inspection for electrical code compliance must be performed through a locally certified and approved electrician.

5. Installation approval: All necessary approvals, including building permission and permission to connect to the local grid, should be obtained prior to installation.

6. Commissioning process: The commissioning process covers three main phases (Sandia National Laboratories, 2016):

I Pre-installation measures

- (A) Building and construction permission
- (B) Permission for electrical connection
- (C) Definition of contact people for IT systems integration, electrical installation, and facility management
- (D) Installation timeframe approval
- (E) Construction of foundation, concrete plating, and electrical connection points
- (F) Foundation specifications approval
- (G) Delivery at customer site

II Installation measures

- (A) Unload with a crane
- (B) Place the energy unit at final position (on concrete plate)
- (C) Maintain electrical ground connection
- (D) Receive approval for ground connection
- (E) Place the power unit
- (F) Connect the battery to the grid
- (G) Connect the communication devices
- (H) Maintain fluid and electrical connections
- (I) Conduct a safety test

III Power-up

- (A) Conduct a system test
- (B) Switch system on
- (C) Charge to 100% charge level

(D) Discharge to 0% charge level

(E) Charge to 30% charge level

Project timeline: Smaller storage systems (in the 1 MW–5 MW range) have been commissioned in less than 2 years from initial concept to commission (Akhil et al., 2015). Storage systems in the 50kW–150kW, which is the optimal range for an FCS, may be installed in the field and brought online within months after reaching the project site.

Applicable codes and standards: The increased interest in battery storage solutions has led various code- and standard-making bodies to expand their regulations and align local municipal building and electrical codes to the National Electric Code (Centorbi, 2017). Typically, storage systems are governed by the National Electrical Safety Code. A sampling of relevant codes and standards for a utility-based, advanced LA battery project is shown in Table 3.12:

Table 3.12 Applicable codes and standard bodies for battery projects

ANSI	American National Standards Institute
IEEE	Institute of Electrical and Electronics Engineers
NEC	National Electrical Code
NEMA	National Electrical Manufacturers Association
NESC®	National Electrical Safety Code®
NFPA	National Fire Protection Association
OSHA	Occupational Safety and Health Administration
UL	Underwriters Laboratories

Project developers should be aware of all applicable national and local codes, local interpretations of codes, and code overlaps or gray areas where codes conflict or do not exist.

3.4 Battery storage costs

Storage system costs involve two components, power and energy. The power cost component is the cost of the power conditioning system and its auxiliaries that determine the kW or MW capability of the system and can be described in $/kW, whereas the energy component is the cost of the battery. For a given system, the total cost is the sum of these components. We focus on only the energy component in this study. This total cost is specific to system size and is (mostly) not linearly scalable.

Table 3.13 Cost comparison of various battery technologies

Battery Storage Technology	Power Cost ($/KW)	Energy Cost ($/KWh)
Lithium-ion (all)	$1,800–$4,100	$800–$2,500
Sodium-sulfur	$3,200–$4,000	$400–$900
Lead-acid	$2,000–$4,600	$500–$1,700
Vanadium-redox	$3,000–$3,300	$500–$1,500
Sodium-nickel-chloride	$2,900–$4,000	$700–$1,200
Zinc-bromine	$1,670–$2,015	$300–$1,600
Zinc-air	$1,440–$1,700	$300–$600
Iron-chromium	$1,200–$1,600	$200–$600

3.4.1 Various cost metrics

For battery storage, considering costs to install (in $/kW), present value of lifecycle costs (LCC; in $/kW and $/kWh), and levelized cost of energy (in $/MWh) is also critical. The values of these costs are taken from storage system cost details for distribution and transmission in the DOE/EPRI Electricity Storage Handbook. The cost to install includes all equipment, delivery, installation, and interconnection costs, but does not include land costs, permitting, and project planning costs. The present value of LCC includes costs to install and all ongoing fixed and variable operating costs over the useful life of the project. The levelized cost of energy includes LCC and rate of return based on financing assumptions. This metric is often used to compare the cost to deliver energy among a variety of technologies and regions (DOE-EPRI 2013 *Energy Storage Handbook*). Table 3.14 details storage system costs for transmission and distribution.

Table 3.14 Storage system cost details

Battery storage technology	System size (MW)	System storage (Hr)	Installed cost ($/kW)	Installed cost ($/kWh)	Present value of lifecycle Costs ($/kW)	Present value of lifecycle costs ($kWh)	Levelized cost of energy ($/MWh)	Levelized cost of capacity ($/kW-yr)
Lithium-ion	1–10	1–6	1,400–6,000	1,000–2,100	2,000–13,000	2,200–4,000	700–1,300	250–1,500
Sodium-sulfur	1–100	6–7	3,100–3,700	500–600	5,500–7,000	500–1,000	250–300	650–720
Lead-acid	1–100	3–4	2,500–5,800	500–2,500	4,500–11,000	500–4,000	270–1,300	500–1,250
Vanadium redox	4–10	3.5–5	3,300–4,000	800–1,100	6,000–7,500	1,500–2,000	400–600	680–800
Sodium-nickel-chloride	1–2	4–5	2,900–5,600	700–1,200	5,000–10,000	1,200–2,500	350–650	550–1,200
Zinc-bromine	1–100	2–5	1,600–3,000	300–1,600	3,000–6,000	500–3,000	120–850	300–680
Zinc-air	1–3	6–6.5	2,000–2,200	200–300	3,500–4,000	500–1,000	180–220	400–450
Iron-chromium	1–70	4–5	1,500–1,800	300–500	2,800–3,500	1,000–1,300	200–280	320–400

The following energy storage system costs are critical to understanding the economics of energy storage. Appendix C provides a list of nomenclature and formulae for each cost category.

1. Total capital cost (TCC)—Also known as total plant cost, TCC evaluates all costs that should be covered for the purchase, installation, and delivery of an EES unit, including costs of PCS, energy storage-related costs, and balance-of-power (BOP) costs (Zakeri, 2015).

2. BOP cost—BOP costs include costs for project engineering, grid connection interfaces, and integration facilities (e.g. transformers), construction management (including cost of land and accessibility), and other services and assets required that are not included in the scope of PCS and storage-related costs (Zakeri, 2015).

3. LCC—LCC encompasses fixed and variable operation and maintenance (O&M) expenses as well as replacement, disposal and recycling costs, and TCC (Zakeri, 2015).

4. Levelized cost of energy (LCOE)—This represents the revenue for delivered energy required to cover all fixed and variable LCCs and provides the target rate of return based on financing assumptions and ownership types (Akhil et al., 2015).

3.4.2 Vendor costs

For a pilot battery project for Consumers Energy, Michigan State University surveyed various vendors via questionnaire. The responses received from the vendors for their battery product offering costs are shown in Table 3.15 (Thomas et al., 2016a, 2016b):

Table 3.15 Summary of battery costs provided by vendors

Vendors	Price Range ($/kWh)
ABB	600–1,000
NEC	480–790
S&C	758–860
Gildemeister	675–775
Doosan Gridtech	800–1,000
Greensmith	700–750

This cost includes only the purchase price of the battery system; that is, installation, site development, and project management costs are considered separately depending on the size of the system, site conditions, and requirements. Project estimates are more detailed and based on site-specific conditions and use cases. Site-specific requirements such as shipping, labor, engineering studies, interconnection, and permitting should be added to the cost of the battery system to obtain total project cost.

3.5 Summary

The construction processes of FCSs and battery storage are similar. The construction cost of an FCS typically lies in the \$58,000–\$171,000 range depending on whether the FCS requires an additional Level 2 charger, electric upgrades, or extended utility service. Smaller battery storage units in the 50kW to 150kW range may be appropriate for supporting an FCS, but battery storage of this magnitude might not be cost-effective unless it is connected to a microgrid of FCSs.

The actual costs of a storage system depend on many factors, and the assumptions and means for calculating some of the values are subjective and continue to be debated even among subject experts. Costs of energy storage systems depend not only on the type of technology but also on the planned operation and hours of storage required. Calculating the present LCC value allows for an equal-value comparison of the benefits. Given that there are many performance dimensions for a battery storage technology, a direct cost comparison is typically not appropriate. A more useful approach would be to identify the applications that a utility needs to serve and then identify the appropriate battery storage technology for that application. Then, cost for each candidate battery technology can be estimated based on use over its lifetime, which varies by application.

Moreover, as battery storage costs depend on several parameters, identifying and establishing parameters such as battery size, type, and hours of use is critical. In this study, DES is used to calculate costs associated with battery storage units appropriate for supporting a network of FCSs during peak hours.

Chapter 4

A FCS network with battery storage to meet energy demand: DES modeling

4.1 Introduction and objective

There often exists a gap between energy supplied by the electric grid and expected demand for an FCS during peak hours (Negarestani, 2016). EV users may have to wait and charge for longer as they receive less energy from the charging station even when the charging station is capable of supplying energy up to its maximum rated value. Of great interest to charging station operators and electric utilities is how FCSs with reduced energy supply use stored energy from a battery to access electrical energy that helps bridge the gap. Thus, analyzing how a condensed network of FCSs maintains required energy using supply from multiple battery storage units is of interest.

In this chapter, a model of FCSs with varying supply and demand gaps was qualitatively built based on a network of 15 FCSs located in Southeast Michigan. The model evaluates the optimal configuration of battery units required to meet the network energy gap by simulating network structures and comparing the results. The model delivers insights into how battery characteristics such as size, battery type, number of battery units, and exchange range radius address this gap. The model aims to lower the cost of supplied energy for the entire network while fully supplying energy demanded by all FCSs using the supplemental battery units.

4.2 Model description and assumptions

DES is the process of codifying the behavior of a complex system as an ordered sequence of well-defined events. Nance (1993) described DES as a mathematical and logical model of a physical system that has changes at precise points in simulated time. In this study, Model #1 was implemented as a DES (i.e., in Model #1, the number of battery units consecutively marks a change of state in the system), whereas Model #2 was implemented as an optimization problem using a Monte Carlo simulation. Because events in a DES are bootstrapped, the simulation designer must decide when the simulation ends (e.g., when a statistical measure reaches a particular value; Albrecht, 2010). The simulations of Model 1 in this study stop when the energy gap of the entire system reaches zero. The models were implemented in Python 2.7.13, and Python-generated functions are used to model the active components. A Monte Carlo package known as scikit-monaco was used to lognormally distribute the cost range inputs in Model #2. In contrast to a normal distribution that can take both positive and negative values, a lognormal distribution is commonly used for distribution of financial assets (e.g., prices), which cannot be negative (Zucchi, 2014). Figure 4.1 provides a conceptualization of the function of Model #2.

4.2.1 Assumptions

1. All FCSs are connected to the electric grid as part of the distribution network, which supplies limited energy.

2. The demand for each FCS is considered constant during peak hours, which is equal to the power rating (maximum capacity) of that FCS.

3. The gap in supply and demand exists only during peak hours (i.e., for 4 hours). During this 4-hour period, this gap is addressed by battery units charging from the grid at a low level of power at off-peak hours or when the battery is not in use. This assumption is based on the study by ChargePoint (2016), that is, the peak hours of DCFCs are between 1 and 5 PM. These peaks arise because drivers who started long trips early in the day start to deplete their batteries, people need

to charge rapidly while running errands around town, or because of those deciding to charge on their way home from work.

4. The cost ($) of energy supply depends on the following:

(A) Network costs, that is, construction of a new overhead distribution line may be required so energy from a battery can be supplied to other FCSs. A utility would not build this unless there is a positive business case, but the relatively low level of EV market penetration means that this is unlikely.

(B) Installation costs of the battery by battery type.

(C) Construction cost of the battery, including land cost, permitting, and project development cost.

5. A battery storage unit with surplus energy can provide energy to a nearby FCS if it is inside the exchange range specified in the model. In this study, the exchange range is the radial distance outward from the battery storage unit. In an energy exchange, the battery first provides a full supply of energy to fulfill the energy gap of the FCS it is positioned at. Then, if any energy remains, it supports other FCSs within the exchange range. During the exchange, if a battery unit can choose between two other FCSs that are both in need of energy, it prefers the one closer to it. Figure 4.1 demonstrates the decision rules governing the exchange of energy in Models #1 and #2.

6. A microgrid is proposed within an established distribution system. Here, an FCS network is considered a microgrid. Each FCS draws power from the distribution network, and batteries are charged during off-peak hours to supply energy during peak hours. An FCS with excess capacity can sell power to the utility at on-peak rates or receive a credit that other FCSs within the microgrid can use. However, it might not make financial sense to construct a separate transmission system. The test microgrid falls within the service territory of DTE (utility serving Southeast Michigan), implying that the FCSs are already connected and can exchange energy. Without the utility already

connecting these FCSs, a microgrid would prove costly; therefore, keeping a microgrid within the service area is recommended.

4.2.2 DES diagram

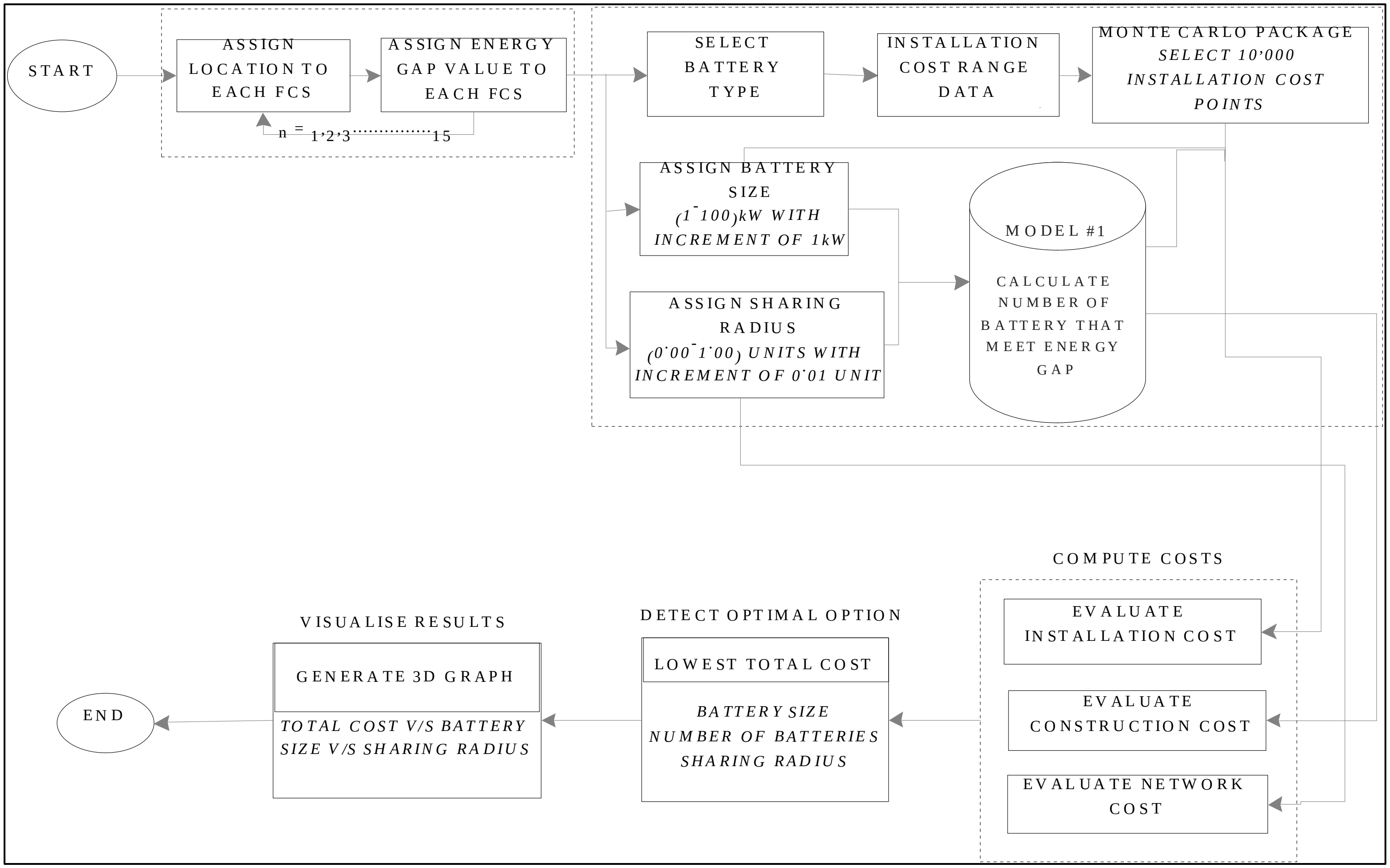


Figure 4.1 Conceptual diagram of model #2

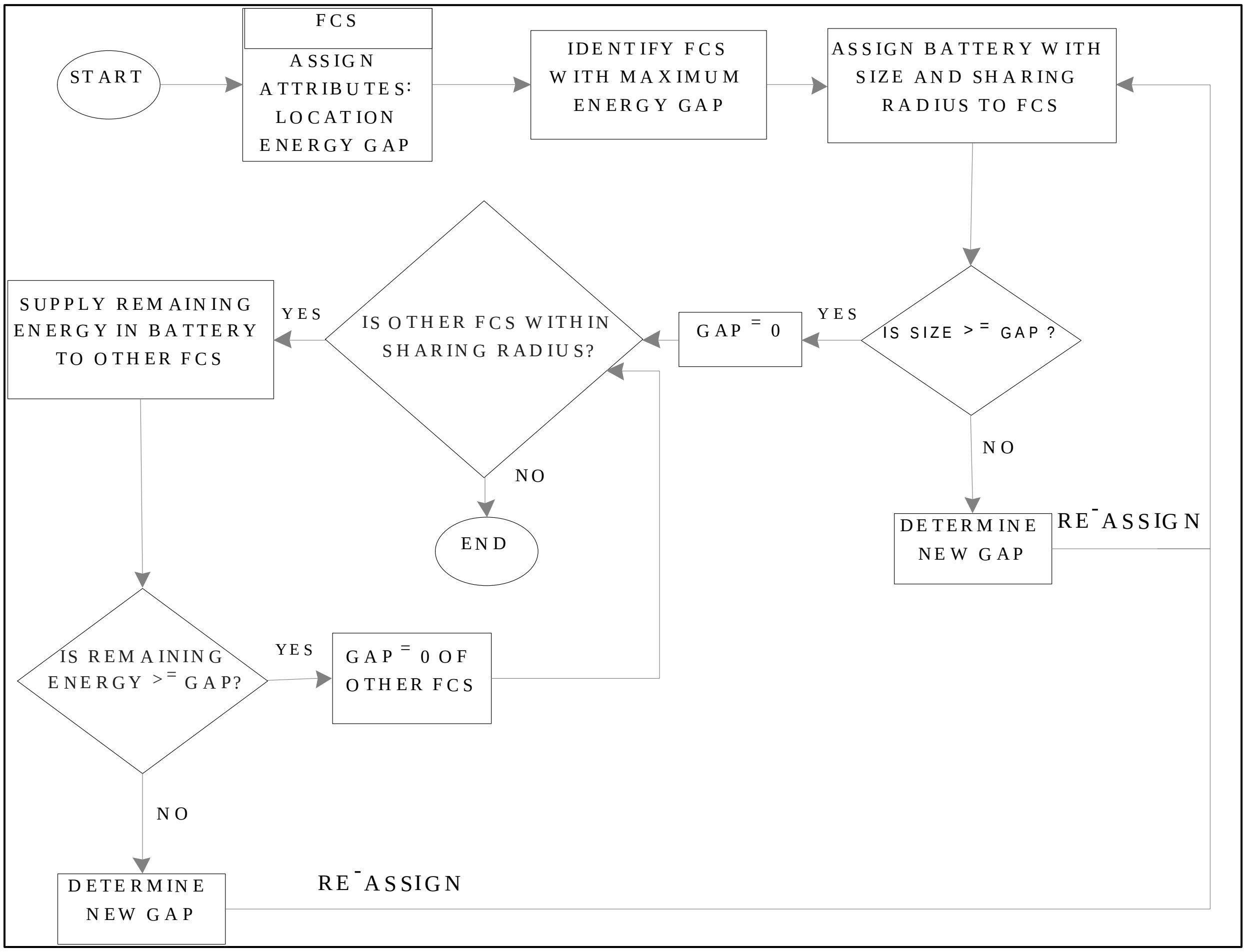


Figure 4.2 Energy exchange decision rule within the microgrid in model #1

4.2.3 Study area

Each FCS has two attributes, its location and a fixed demand–supply energy gap. The coordinates (i.e., the latitude and longitude values) are known for all 15 FCSs in Southeast Michigan. For the demand–supply gap, it is assumed that every FCS has a constant demand equal to the maximum rated power of that FCS. The supply range for each FCS is obtained from comments (online) by EV owners using those FCSs (PlugShare, 2017). The energy gap is calculated by taking the difference in demand and minimum supply for the FCSs. The following table summarizes the characteristics of the FCS network in Southeast Michigan on which the model is based.

Table 4.1 Information on 15 FCSs used in simulation

Station #	Station Name & City	Outlets	EV network	EV connector types	Latitude	Longitude	Demand	Supply	Gap
1	Dunkin Donuts – Sterling Heights	1	eVgo Network	Chademo & J1772combo	42.58	-83.03	44	24–35	20
2	Dunkin Donuts – Ferndale	1	eVgo Network	Chademo & J1772combo	42.45	-83.13	44	35	9
3	Dunkin Donuts – Dearborn Heights	1	eVgo Network	Chademo & J1772combo	42.27	-83.27	44	37	7
4	Dunkin Donuts – Woodhaven	1	eVgo Network	Chademo & J1772combo	42.14	-83.22	44	33	11
5	Nissan Technical Center – Farmington Hills	1	ChargePoint Network	Chademo	42.49	-83.42	50	27–41	23
6	USA 2 Go – Novi	1	eVgo Network	Chademo & J1772combo	42.49	-83.51	44	28–37	16
7	Dunkin Donuts – Plymouth	1	eVgo Network	Chademo & J1772combo	42.36	-83.43	44	30–38	14
8	AAA – Canton	1	eVgo Network	Chademo & J1772combo	42.32	-83.48	44	28–31	16
9	DD – Belleville	1	eVgo Network	Chademo & J1772combo	42.22	-83.48	44	31–36	13
10	Tim Hortons – Howell	1	eVgo Network	Chademo & J1772combo	42.62	-83.87	44	33–40	11
11	USA 2 Go – Howell	1	eVgo Network	Chademo & J1772combo	42.58	-83.88	44	25	19
12	AAA – Brighton	1	eVgo Network	Chademo & J1772combo	42.54	-83.78	44	26–36	18

Table 4.1 (cont'd)

13	NISSAN – Ann Arbor	1	Charge Point Network	Chademo	42.28	-83.80	50	26–41	24
14	Meijer, Tesla – Ann Arbor	8	Tesla	Tesla	42.23	-83.76	120	70–93	50
15	Shell – Ann Arbor	1	eVgo Network	Chademo & J1772combo	42.24	-83.73	44	34–36.5	10

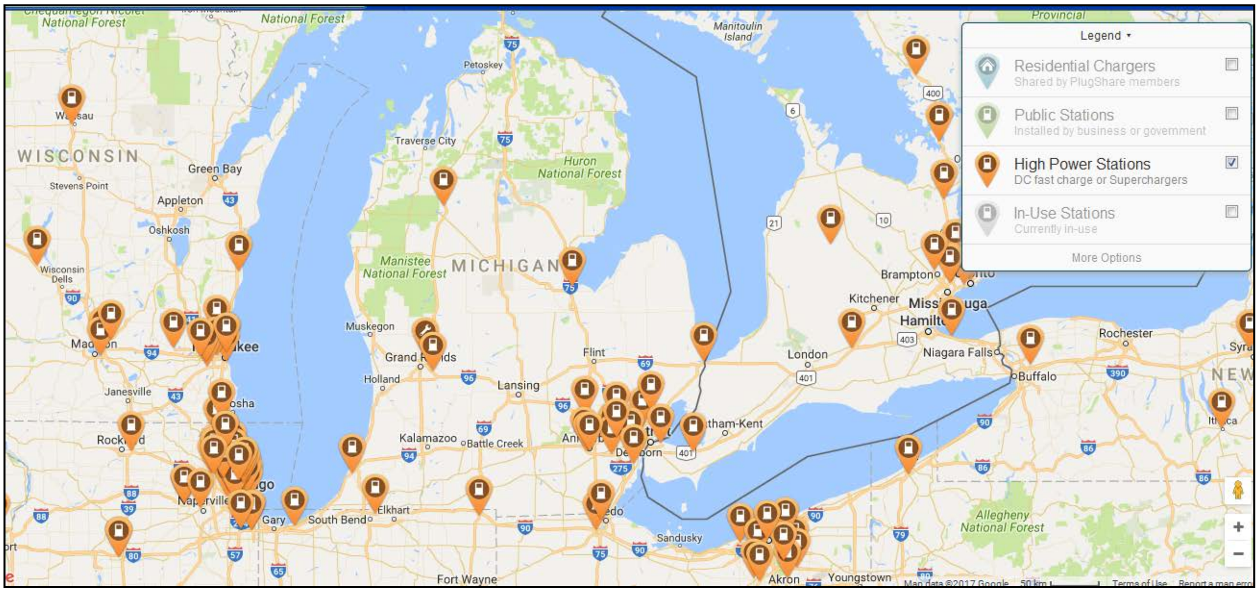


Figure 4.3 Map of all DCFCs in Michigan

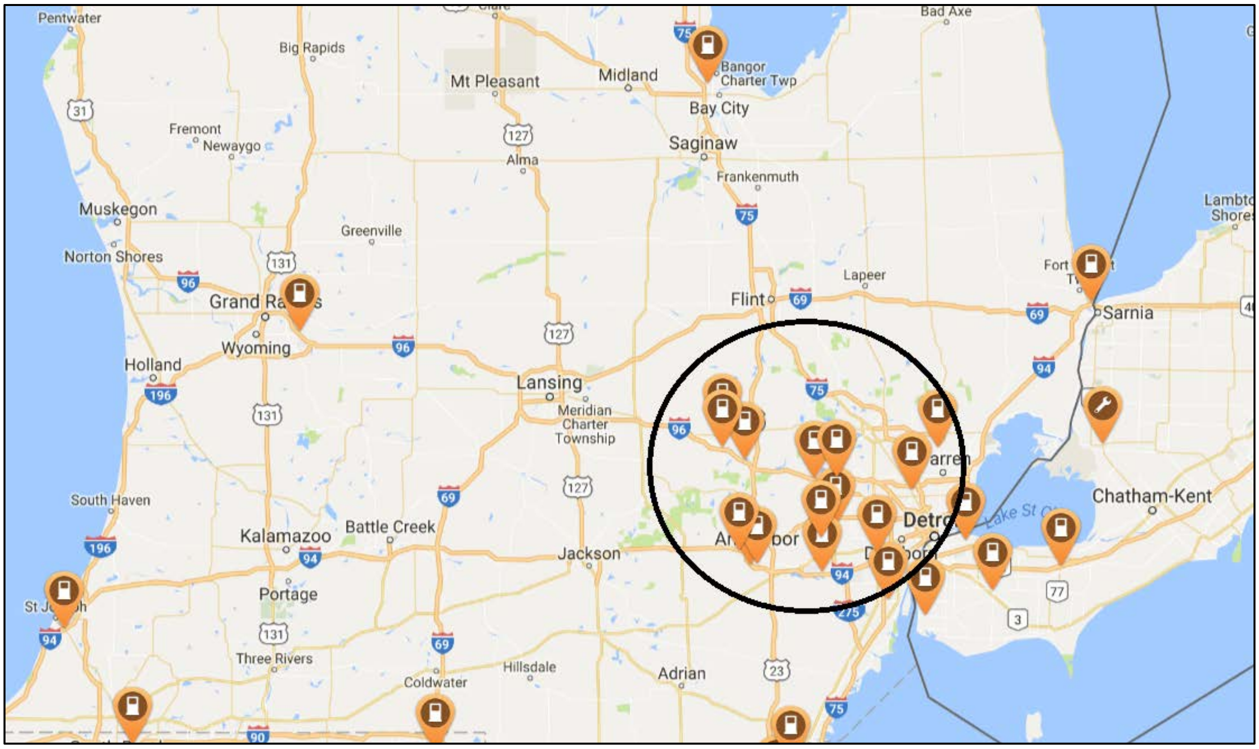


Figure 4.4 Map of 15 FCSs used in simulation

4.2.4 Functioning of model #1

First, respective coordinates and energy gaps are assigned to all 15 FCSs. The model requests battery size and exchange range as user inputs. After providing the inputs, the specified battery units are introduced to each FCS to reduce the energy gap until the total energy gap of all charging stations is reduced to zero. A battery that is assigned to the FCSs and closes the energy gap checks whether other FCSs exist within the exchange range specified. To exchange energy, the battery first supplies its energy to the FCS it is positioned at. If the battery is then left with surplus power, it supplies the remaining energy to meet the energy gap of the FCS nearest to it within the exchange range. The next battery is that positioned at the FCS with the second-highest energy gap, and so on. This model then outputs the number of batteries required for a given battery size and exchange range. Appendix D provides the code for this model, and Fig. 4.6 shows a screenshot of the Python interface. For example, when battery units of size 30kW and exchange range of 0.2 units are input into the system, the following depicts the functioning of the model as output with each incremental battery unit until the energy gap is fully addressed:

Enter battery supply unit value: 30 kW

Enter exchange range: 0.2 units

1. At ID: 14, Gap = 50. New Gap = 20. Total batteries used: 1.
2. At ID: 13, Gap = 24. New Gap = 0. Exchange from ID: 13 to ID: 14, Energy units = 6 with new Gap at Station 14 = 14. Total batteries used: 2.
3. At ID: 5, Gap = 23. New Gap = 0. Exchange from ID: 5 to ID: 6, Energy units = 7 with new Gap at Station 6 = 9. Total Number of Battery Consumed: 3.
4. At ID: 1, Gap = 20. New Gap = 0. Exchange from ID: 1 to ID: 2, Energy units = 9 with new Gap at Station 2 = 0. Total batteries used: 4
5. At ID: 11, Gap = 19. New Gap = 0. Exchange from ID: 11 to ID: 10, Energy units = 11 with new Gap at Station 10 = 0. Total batteries used: 5
6. At ID: 12, Gap = 18. New Gap = 0. Total batteries used: 6
7. At ID: 8, Gap = 16. New Gap = 0. Exchange from ID: 8 to ID: 7, Energy units = 14 with new Gap at Station 7 = 0. Total Number batteries used: 7
8. At ID: 14, Gap = 14. New Gap = 0. Exchange from ID: 14 to ID: 15, Energy units = 10 with new Gap at Station 15 = 0. Total batteries used: 8
9. At ID: 9, Gap = 13. New Gap = 0. Total batteries used: 9
10. At ID: 4, Gap = 11. New Gap = 0. Exchange from ID: 4 to ID: 3, Energy units = 7 with new Gap at Station 3 = 0. Total batteries used: 10
11. At ID: 6, Gap = 9. New Gap = 0. Total batteries used: 11

Total surplus energy remaining in batteries = 69

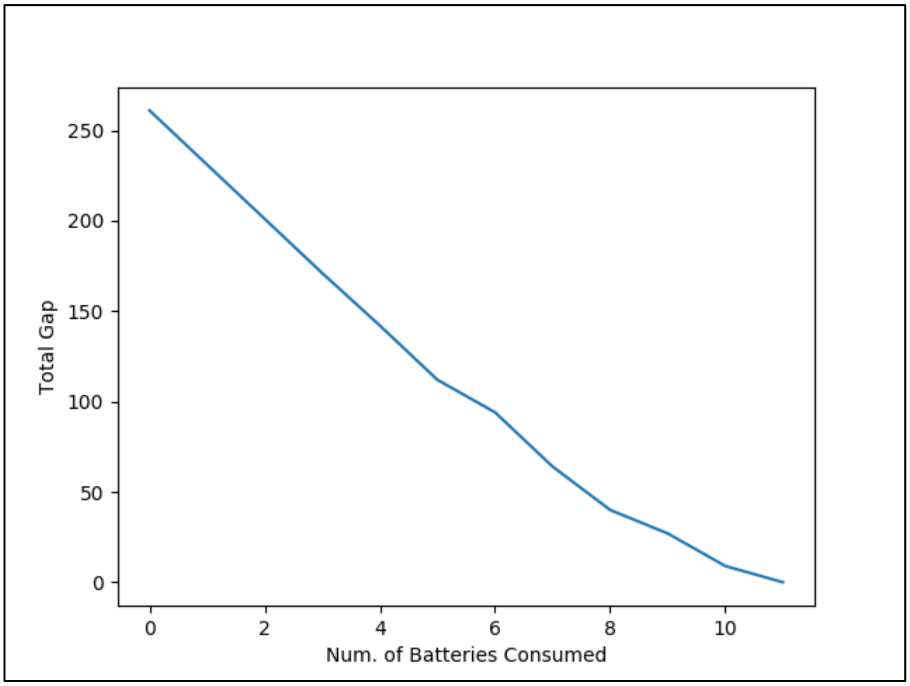
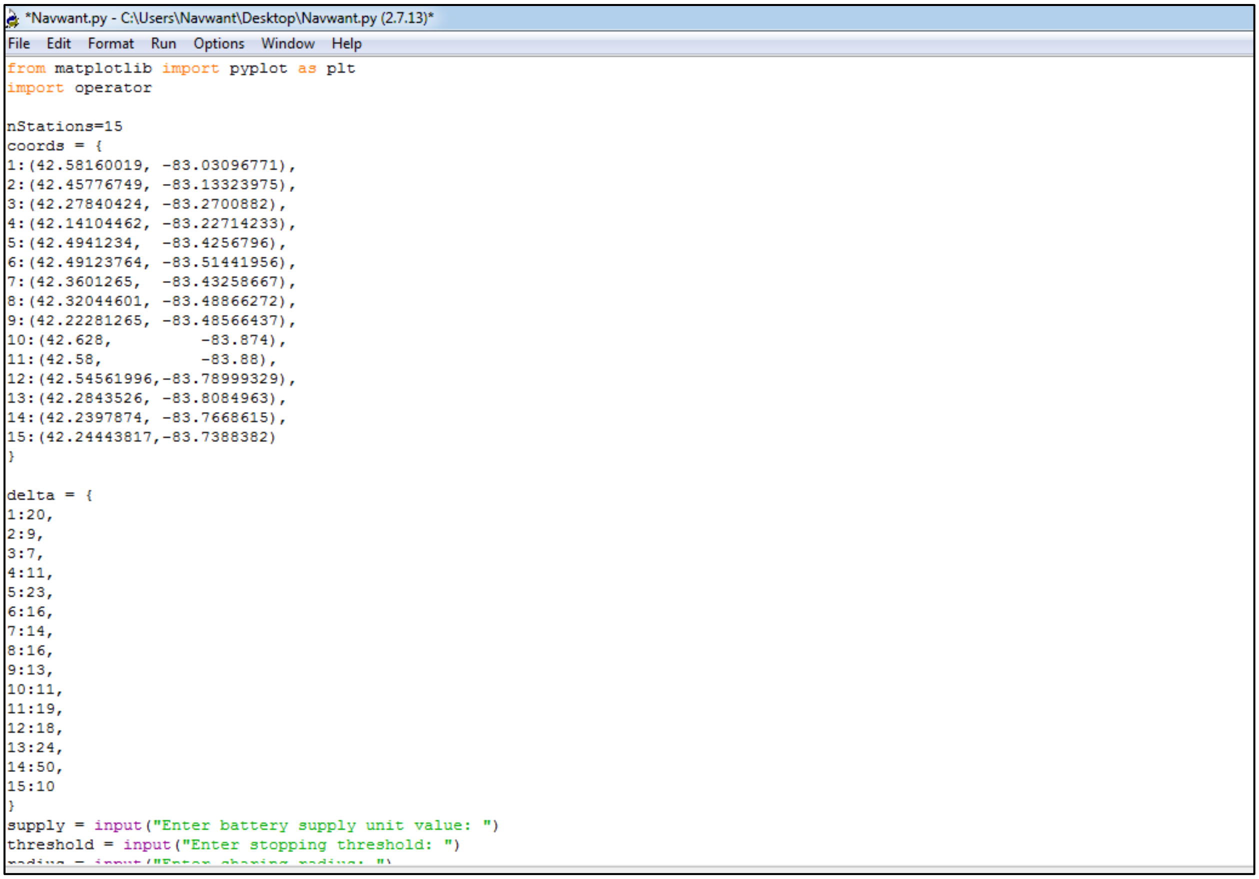


Figure 4.5 Graph of total gap vs. number of batteries for given inputs

Hence, for a battery size of 30kW with a share radius of 0.2 units, 11 batteries are required to reduce the system gap to zero.

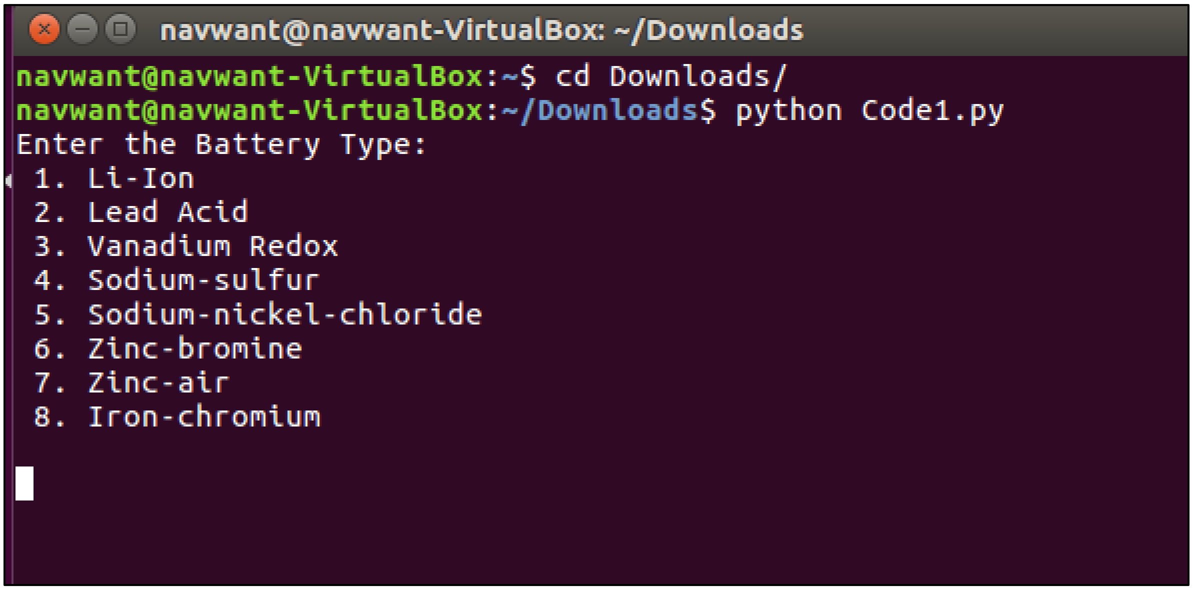


```python
from matplotlib import pyplot as plt
import operator

nStations=15
coords = {
1:(42.58160019, -83.03096771),
2:(42.45776749, -83.13323975),
3:(42.27840424, -83.2700882),
4:(42.14104462, -83.22714233),
5:(42.4941234,  -83.4256796),
6:(42.49123764, -83.51441956),
7:(42.3601265,  -83.43258667),
8:(42.32044601, -83.48866272),
9:(42.22281265, -83.48566437),
10:(42.628,         -83.874),
11:(42.58,          -83.88),
12:(42.54561996,-83.78999329),
13:(42.2843526, -83.8084963),
14:(42.2397874, -83.7668615),
15:(42.24443817,-83.7388382)
}

delta = {
1:20,
2:9,
3:7,
4:11,
5:23,
6:16,
7:14,
8:16,
9:13,
10:11,
11:19,
12:18,
13:24,
14:50,
15:10
}
supply = input("Enter battery supply unit value: ")
threshold = input("Enter stopping threshold: ")
```

Figure 4.6 Screenshot of python interface showing the code for model #1

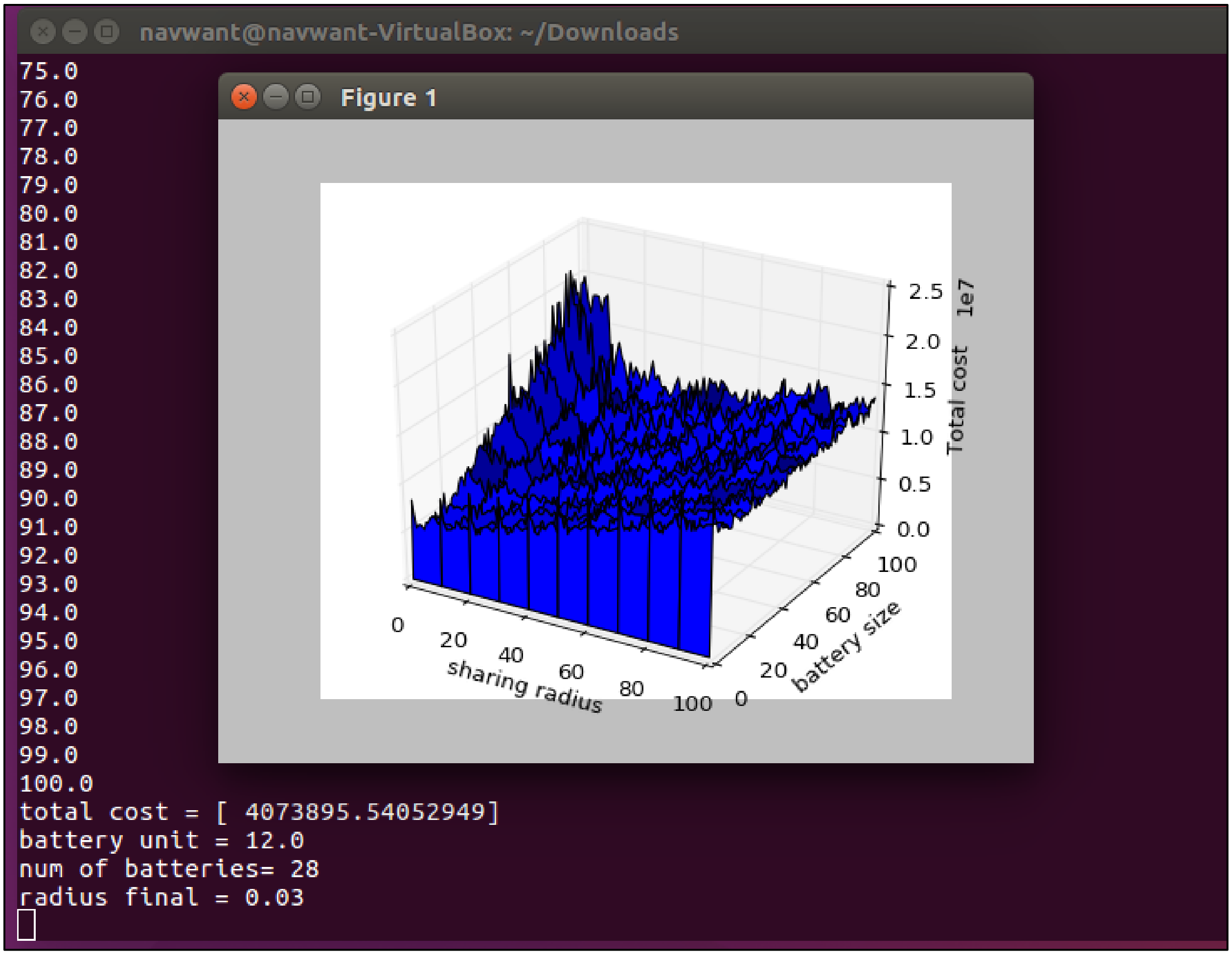
4.2.5 Functioning of model #2

This model is a revised version of the previous model. It additionally considers installation and construction costs of the battery systems (Table 4.3) as well as the cost of setting up a new distribution line (network cost) to enable the exchange of energy from batteries. Table 4.2 shows the inputs used in this model, which was implemented in Python using the scikit-monaco library for Monte Carlo integrations. The installation cost range of various battery types is shown in Table 3.14, and construction and network costs are fixed for all battery types. The model asks the user to input the battery type. Based on the battery type selected, the installation cost range of that battery is chosen and converted into a lognormal distribution. Next, the model calculates total costs and selects 10,000 total cost values from the lognormal distribution. The model varies battery size from 1kW to 100kW in increments of 1kW and share radius from 0.00 to 1 in increments of 0.01 units. This generates 100x100x10,000 input points. For all input points, the model calculates the number of batteries required, battery size, and exchange range that result in the lowest energy supply cost. The model is run twice for each battery type, first considering network costs and second without network costs. In the first case (i.e., considering network costs), new distribution lines are constructed within the existing microgrid. In the second case (i.e., no network costs), all batteries and FCSs are connected to the microgrid within the existing distribution system. Appendix D provides the code for this model. Figures 4.7 and 4.8 show the input interface and the running model, respectively.



```
navwant@navwant-VirtualBox:~$ cd Downloads/
navwant@navwant-VirtualBox:~/Downloads$ python Code1.py
Enter the Battery Type:
 1. Li-Ion
 2. Lead Acid
 3. Vanadium Redox
 4. Sodium-sulfur
 5. Sodium-nickel-chloride
 6. Zinc-bromine
 7. Zinc-air
 8. Iron-chromium
```

Figure 4.7 Screenshot of input interface for model #2



```
75.0
76.0
77.0
78.0
79.0
80.0
81.0
82.0
83.0
84.0
85.0
86.0
87.0
88.0
89.0
90.0
91.0
92.0
93.0
94.0
95.0
96.0
97.0
98.0
99.0
100.0
total cost = [ 4073895.54052949]
battery unit = 12.0
num of batteries= 28
radius final = 0.03
```

Figure 4.8 Screenshot of model #2 running with computing status

Table 4.2 Inputs used in model

Input Category	Inputs	Input values
Battery	Battery type cost	Table 4.3
	Battery size	(1–100) kW
FCS	Location	(x, y) coordinates
	Demand gap	constant (kW)
Network	Exchange range	(0.00–1) unit distance
	New distribution line cost	$ 8,325,000 per unit distance

Table 4.3 Battery costs used in model

Battery type	Installation cost ($/kWh) (range)	Construction cost ($) (fixed)
Lithium-ion	1,000–2,100	20,000 per installation
Lead-acid	500–2,500	20,000 per installation
Vanadium redox	800–1,100	20,000 per installation
Sodium-sulfur	500–600	20,000 per installation
Sodium-nickel-chloride	700–1,200	20,000 per installation
Zinc-bromine	300–1,600	20,000 per installation
Zinc-air	200–300	20,000 per installation
Iron-chromium	300–500	20,000 per installation

Table 4.4 provides the breakdown of construction-related costs for site preparation, project management, and general conditions for building of a 20'x20' concrete pad for battery installation. This table does not include costs related to the battery storage system itself.

Table 4.4 Construction cost for battery installation

Cost type	**Quantity**	**Unit**	**Cost ($)**
Building permit			2,500
Survey			
Professional surveyor	1	lump sum	2,000
Engineering testing			
Soil test			1,500
Sitework			
Clearing and grubbing (for an approx. area of 400 sqft)	400	sqft	250
Excavation and compaction	400	sqft	500
Grading	400	sqft	100
Site layout			400
Concrete pad (20' x 20')			
Formwork			200
Reinforcement			300
Labor (1 foreman, 1 finisher, 1 carpenter)			1,800
Concrete	7	cy	840
Rental equipment (compactor, spreader, finisher)			800
Curing			0
Project management costs			
Project engineer (for 5 days)	1	lump sum	1,800

Table 4.4 (cont'd)

Temp. fencing			1,000
Temp. power supply			1,500
Temp. water supply			500
Temp. toilets			1,000
Dumpster			400
Safety and first aid			
Safety signs			200
Fire protection			1,000
First aid supplies			500
		Total cost ($)	19,090

The total cost of energy supply considered in the model is as follows:

1. Installation cost: The installation costs were taken from Table 3.14 and are in kW/h. The battery system is assumed to run for a 4-hour duration.

   The total cost of installation = (Installation cost x battery size x 4 x number of units) (4)

2. Construction cost: A cost of $20,000 for the installation of each battery unit is assumed irrespective of the battery size. Although the installation cost varies based on the size of the battery, battery size is below 100kW; thus, installation costs are consistent. This estimated value is detailed in Table 4.4.

   Total construction cost = ($20,000 x number of units) (5)

3. Network cost: According to McCarthy (2011), building a new overhead distribution line costs an average of $166,500 per mile. In the model, 1 mile is equivalent to 0.02 units of distance, bringing network costs to $8,325,000 per unit distance if no local grid/distribution exists for the network and it is not located in an urban area.

   Network cost = ($8,325,000 x exchange range) (6)

Total cost of energy supply = Installation cost + Construction cost + Network cost (7)

4.3 Results

Table 4.5 shows the results for the model considering network costs, and Table 4.6 indicates the results without considering network costs. Table 4.7 shows a comparison table indicating the difference in results between the two cases.

Table 4.5 Model results for each battery type considering network costs

Battery type	**Total cost ($)**	**Battery size (kW)**	**Exchange range (units)**	**Number of batteries**
Lithium-ion	5,295,019	7	0.00	45
Lead-acid	4,569,688	10	0.00	33
Vanadium redox	3,740,124	10	0.00	33
Sodium-sulfur	2,504,760	12	0.00	29
Sodium-nickel-chloride	3,655,281	11	0.00	31
Zinc-bromine	3,114,688	13	0.00	27
Zinc-air	1,380,862	20	0.00	20
Iron-chromium	1,880,297	14	0.00	26

Table 4.6 Model results for each battery type without network costs

Battery type	**Total cost ($)**	**Battery size (kW)**	**Exchange range (units)**	**Number of batteries**
Lithium-ion	4,218,274	22	0.81	13
Lead-acid	3,548,833	29	0.67	10
Vanadium redox	2,889,329	29	0.36	10
Sodium-sulfur	1,786,008	29	0.36	10
Sodium-nickel-chloride	2,784,694	29	0.73	10
Zinc-bromine	2,323,296	29	0.95	10
Zinc-air	877,810	53	0.98	6
Iron-chromium	1,295,707	29	0.5	10

Table 4.7 Difference in results for each battery type with and without network costs

Battery type	Total cost ($)		Battery size (kW)		Number of batteries	
	Diff.	**% Diff.**	**Diff.**	**% Diff.**	**Diff.**	**% Diff.**
Lithium-ion	-1,076,745	-20.34	15	0.68	-32	-0.71
Lead-acid	-1,020,855	-22.34	19	0.66	-23	-0.70
Vanadium redox	-850,795	-22.75	19	0.66	-23	-0.70
Sodium sulfur	-718,752	-28.70	17	0.59	-19	-0.66
Sodium-nickel-chloride	-870,587	-23.82	18	0.62	-21	-0.68
Zinc-bromine	-791,392	-25.41	16	0.55	-17	-0.63
Zinc-air	-503,052	-36.43	33	0.62	-14	-0.70
Iron-chromium	-584,590	-31.09	15	0.52	-16	-0.62

The following total cost vs. battery size vs. exchange range graphs are obtained for each battery type. Figure 4.9 shows this comparison considering network costs, and Figure 4.10 does so without considering network costs.

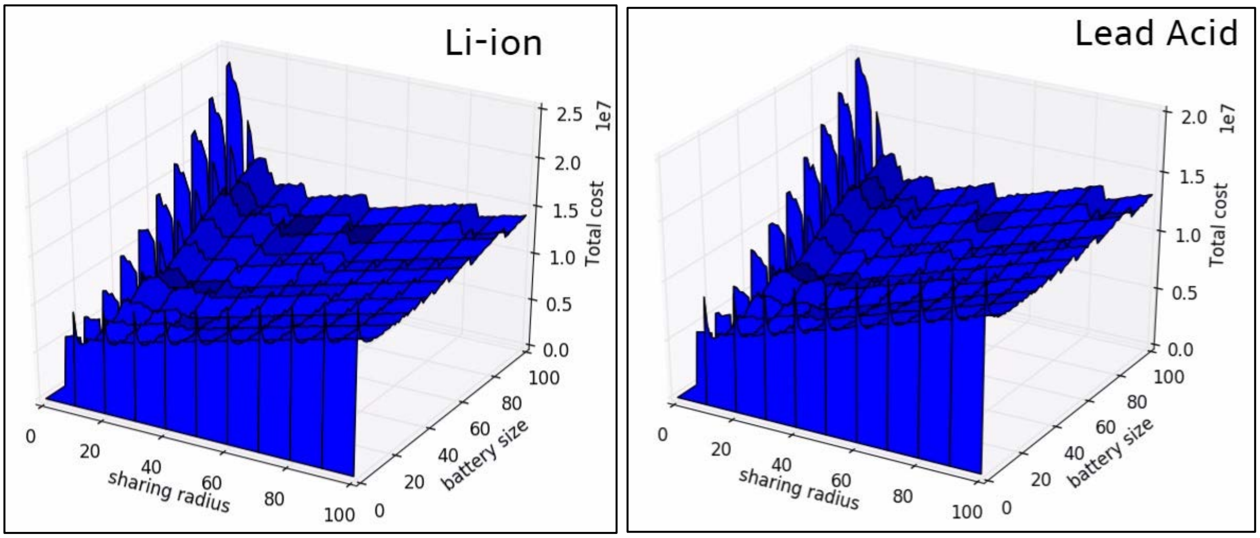
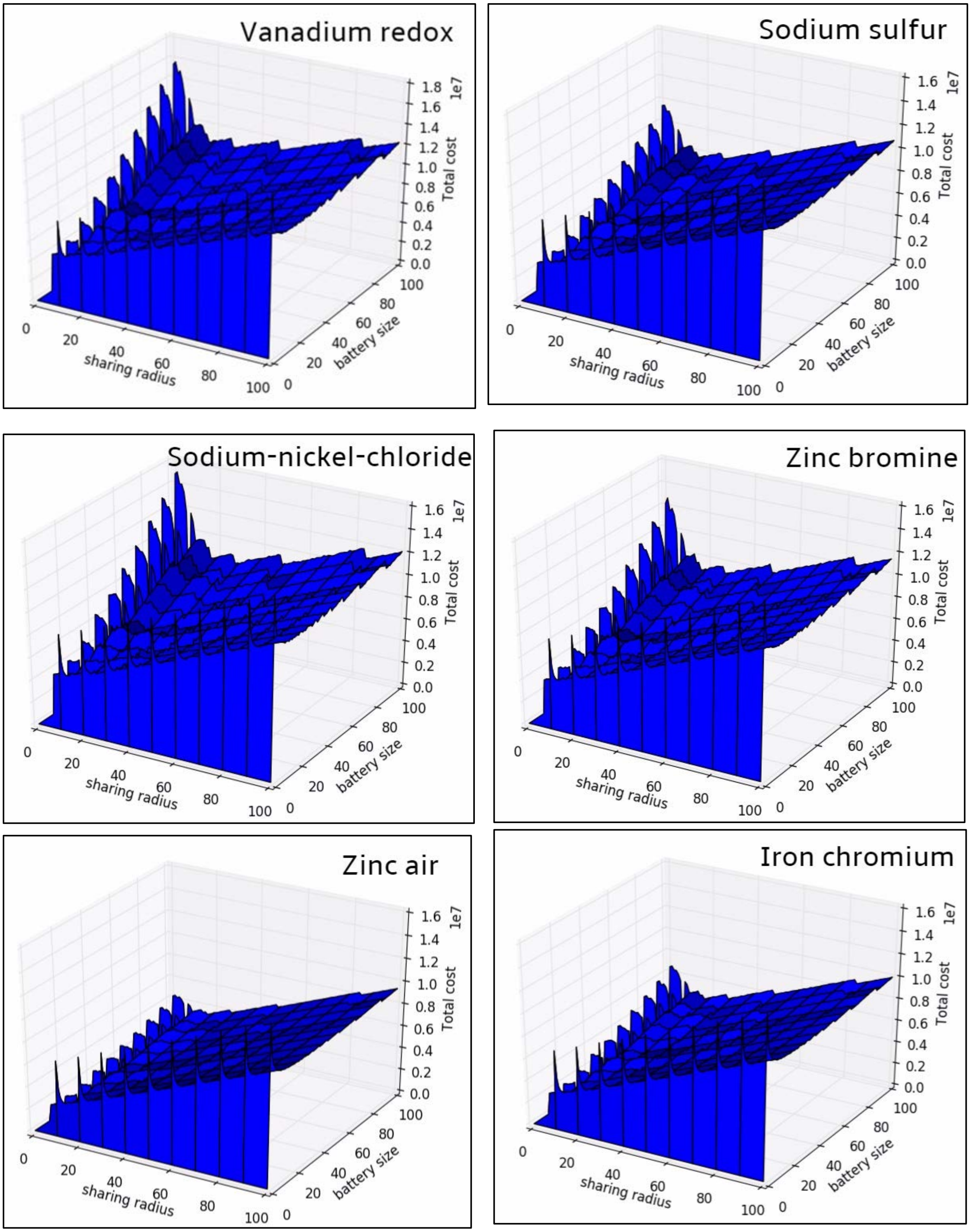


Figure 4.9 3D graphs for battery types considering network costs

Figure 4.9 (cont’d)



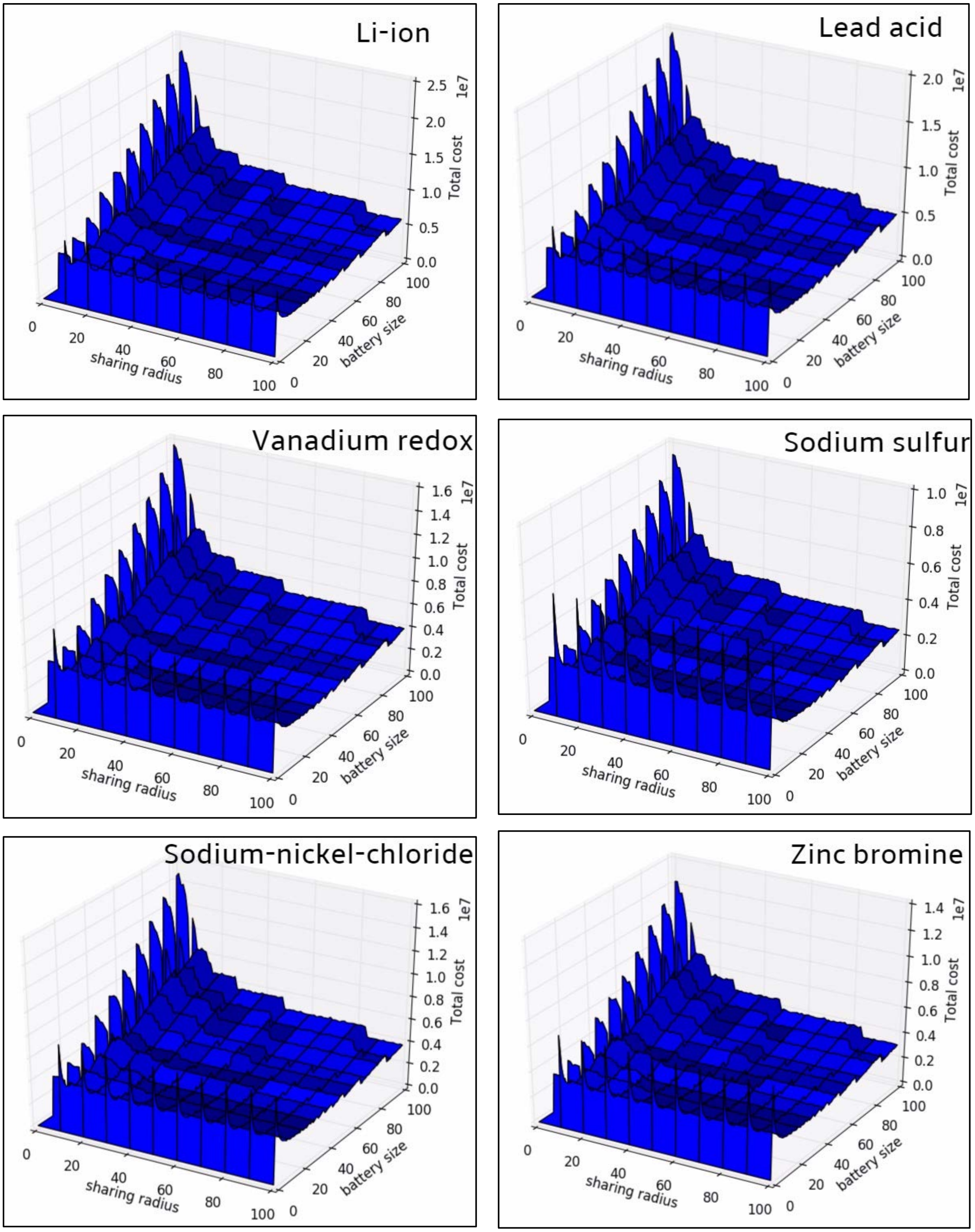
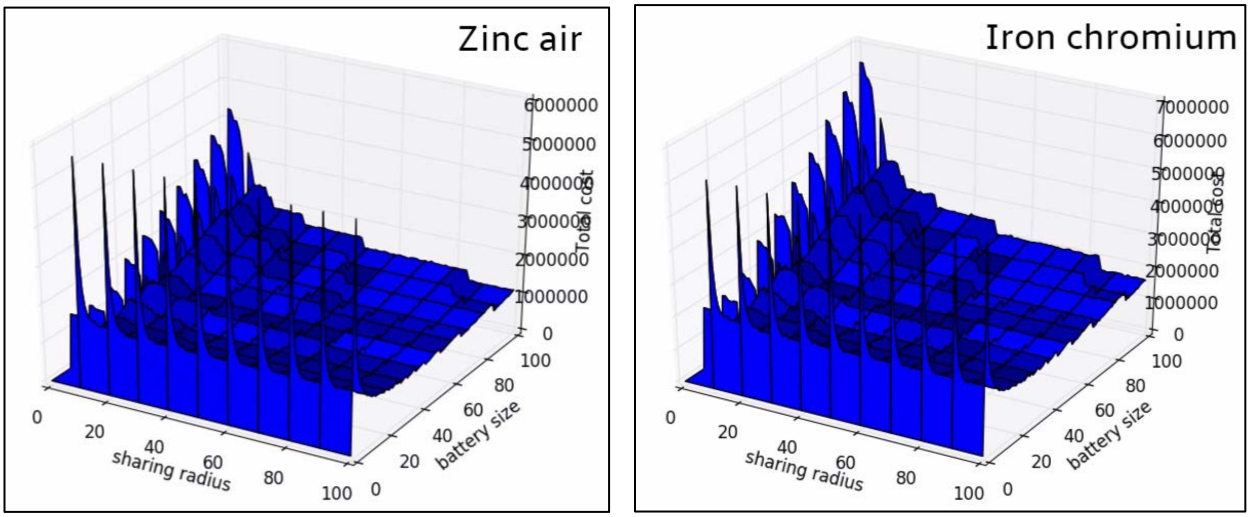


Figure 4.10 3D graphs for battery types without considering network costs

Figure 4.10 (cont'd)



1. **Considering network costs**: Li-ion batteries have the highest cost, whereas zinc-air batteries have the lowest cost. This is because li-ion batteries are the most expensive to install and zinc-air batteries are the least expensive. For all battery types, the exchange range for the lowest total cost is 0.00 units, indicating that no exchange of battery energy occurs. This is because the construction cost of the utility network is much higher than that of battery storage. In this case, total cost is dependent only on construction and installation costs. The battery size varies from 7–20 kW: Li-ion is the smallest (7 kW) and zinc-air is the largest (20 kW). Similarly, the number of batteries used vary from 20–45: the most being li-ion (45 batteries) and the least zinc-air (20 batteries). This indicates that to operate effectively, each of the 15 FCSs requires at least one battery. Total construction cost is dependent on the number of batteries, and total installation cost is dependent on battery size, battery type, and number of batteries. Therefore, to achieve the lowest cost required to meet the energy gap of all charging stations using high-cost batteries such as li-ion, smaller batteries are used in higher quantities. For low-cost

batteries (e.g., zinc-air batteries), larger batteries are used in lower quantities to achieve the same results.

2. **Without considering network costs**: When the exchange of energy occurs without network costs, the highest total costs are for li-ion batteries and the lowest total costs are for zinc-air batteries, as in the previous case. For all battery types, the observed exchange range is less than 0.1 units (i.e., 5 miles). This indicates that to achieve less total costs, energy exchange is viable only within a 5-mile radius. Most batteries in this model choose a 29 Kw battery, which is smaller than expected given that the exchange of energy takes place without network costs. However, zinc-air has a large battery (53 Kw), a high exchange range (0.98 units), and a low number of batteries (6). This indicates that as the installation costs decrease for a specific battery type, its battery size increases, the exchange of energy increases, and fewer batteries are required to meet the energy gap at the lowest total cost. The number of batteries used remains consistent at 10 batteries except for li-ion (13) and zinc-air (6). This indicates that among the 15 FCSs, at least two-thirds would require a battery.

3. **Comparison table**: The pattern of each battery type remains consistent whether network costs are considered.

4.4 Summary

This chapter describes the study area, functioning, assumptions, and results of a DES model. Battery units are introduced to address the supply and demand energy gap of a network of FCSs in Southeast Michigan with the goal of achieving a zero gap in stored energy. Here, FCSs within a battery's exchange range can receive that battery's remaining energy; in this manner, the energy gap of the entire FCS network can be met by fewer batteries and better battery utilization. The gap in energy and the locations of the FCSs are known, and the model identifies the battery size and exchange range that results in lowest total cost for each battery type.

When the model is run for each battery type considering network costs, no exchange of energy from the battery takes place for any battery type. For smaller battery sizes, more than one battery is required for each FCS to meet the network energy gap. When the model is run without considering network costs, exchange of energy takes place for all battery types, and less (and larger) batteries are required. These results indicate that a condensed network of FCSs that is energy deficient from the grid can benefit from battery units that supply stored energy during peak hours and recharged during off-peak hours. Such a model can be applied to any network to determine the battery size, number of units, and exchange range that results in the lowest-cost investment to achieve an energy gap of zero. Based on the total cost, the best battery type for the given network can be chosen. These findings may be useful for FCS operators, who can contract with players in the battery space and identify the size and number of batteries most suitable for their network at the lowest cost.

Chapter 5

Conclusion

5.1 Findings

This study found that battery storage can be used in coordination with FCSs to support the energy demands of a FCS during peak hours. Batteries act as buffer storage for energy: excess capacity is sold during on-peak hours and charging occurs during non-peak hours. Li-ion batteries (followed by LA and VRFB) are chiefly recommended for these projects as they are the most appropriate for charging-station applications. These batteries show the best safety, cost, and technical performance for small-sized power distribution applications and are relatively mature, scalable, and have existing operational and safety solutions. This recommendation was made based on the literature review and comparative analysis of various battery technologies but does not consider the results from Chapter 4.

The construction processes of FCSs and of battery storage are similar. The construction cost of a FCS typically varies from $58,000–$171,000 depending on whether the FCS requires an additional Level 2 charger, an electric upgrade, or extended utility service. Smaller battery storage (i.e., 50kW to 150Kw) may be appropriate for supporting an FCS, but battery storage of that magnitude may not be cost-effective unless connected to an FCS microgrid. The costs of energy storage depend on many factors such as the type of technology, battery size, hours of operation, and vendors. Identifying the application and battery storage parameters to establish costs is critical. Here, as a case study, a DES model is used to calculate the cost and characteristics of battery storage for a FCS network in Southeast Michigan.

The DES model results indicate that less exchange of energy from battery units occurs for the FCS network even when no network costs exist. At least two-thirds of the FCSs require a battery, indicating that every FCS may need a battery to support itself. When network costs are considered, each of the 15 FCSs requires at least two batteries to meet the energy demand at lowest total cost, and no exchange of energy takes place. Li-ion batteries exhibit the highest cost, whereas zinc-air batteries cost the least. Owing to the high cost of setting up a new distribution line, a highly condensed discrete microgrids of FCSs would benefit more from exchange of energy between battery units to neighboring FCSs.

5.2 Contribution

This study provides information on EV charging, particularly fast charging, and the role of battery technology to support its power supply. From the literature review, a general understanding of types of EVs, charging types, and charging standards is obtained that is useful in the subsequent chapters of this study. Through a comparative analysis of performance attributes of present battery types, the most-suitable potential battery technologies to be used in coordination with a FCS are recommended. The following chapter reviews the entire FCS and battery storage system installation process. It provides insights into the responsibilities, considerations, measures, and standards owners and contractors must adhere to for successful installations of such systems. Cost values for various configurations of fast chargers are estimated. Then, battery system costs are provided in addition to the relation to battery size and type most useful to stakeholders. In the final chapter, an FCS model is created and the simulation study helps identify the battery size and exchange range that meets the required energy supply and minimum cost of supplied energy for the entire system. The simulation can be extended to any condensed network of FCSs to evaluate battery storage characteristics most fit for the network that address the gap in energy demanded.

5.3 Limitations

The study limitations include data constraints, scope, and assumptions. In this study, cost values for charging stations and batteries used were based on literature sources and information provided by vendors. These values may not exactly match prevailing industry standards, but they offer possible pre-construction phase estimates. Once the scope and requirements of such projects are defined, more precise cost values over different installation phases can be easily obtained from charging station network operators/suppliers as well as battery manufacturers/vendors. This study also does not consider technical aspects of using batteries along with FCSs. The simulation model is based on many assumptions. It would be more useful to have realistic values of energy supply and demand as well as the costs of exchanging energy through batteries for a FCS network.

5.4 Future work

Future work can conduct a detailed cost comparison of FCSs between network operators or suppliers. A more feasible approach would be to conduct a site visit of a battery powered FCS installation and note the associated costs. The simulation model should be applied to a condensed network of fast chargers, where energy exchange from battery storage may be more feasible and economical. An LCC analysis can also be performed for battery and FCS to evaluate the operational costs.

APPENDICES

Appendix A. Construction process of a charging station

The following information provides a general overview of the installation process, and is broken down into three phases:

Phase 1: Pre-work – contractor (Checklist)

Site information

Address: An address must be available in order to obtain a permit in most areas. If an address does not exist for the parking area, the building address for the supporting parking site may be used in many areas. In some cases where a dedicated meter is installed, a new address may need to be applied for. The local permitting entity should be contacted for questions regarding addressing.

Does Customer have ownership of the site in which charging station(s) will be installed? Yes/No

If NO - Does the customer have necessary approval to install charging station(s) at site? Yes/No

If YES - The customer should have authorization form available upon site visit and/or be willing to sign forms claiming permission to install charging station(s) at the site.

If NO - The customer will need to obtain approval from site owner.

Intended use

In order to ensure proper technology selection and charging station placement, it is important to understand the intended use of the charging station(s). The intended use should be one or more of the following:

○Personal ○Fleet ○Employee ○Customer ○Visitor

Customer decisions

The customer will make a number of decisions regarding the installation. All decisions should be reviewed to ensure requirements will be met and to avoid potential problems. Remaining decisions should be finalized following the initial on-site portion of this process.

Charging Station Make ___________________________

Model ____

From this information, the contractor can determine important information regarding the charging station including the following:

Mounting Type: ○Bollard ○Wall-Mount ○Pole-Mount ○Ceiling-Mount

Vehicle charging

Number of Vehicle Charging Connectors per Charging Station ______________

Communications Requirements: ○Ethernet ○Cellular ○Wi-Fi ○Other____________

Physical Dimensions: Height___________ Width____________ Depth_____________

Base Dimensions (for bollard units) ___________ Cord Length______________

Number of charging stations to be installed: _____________ It is important to understand whether this number refers to number of stations or the number of cord sets (which references the number of vehicles that can be served simultaneously).

Have specific parking spaces been selected? ○Yes ○No

Has a power source been selected? ○Yes ○No

If Yes – Does the customer have ownership of the power source? ○Yes ○No

If Yes - The customer must provide proof of approval and/ or be willing to sign documentation claiming necessary approval.

If No - Does the customer have approval to use the power source? ○Yes ○No

Approval must be gained prior to installation.

If No - The contractor will need to aid in this decision during the on-site portion of this process.

Phase 2: Pre-work – customer

After gathering initial information from the customer, it is important to suggest actions the customer can take in order to save time during the installation process.

Contact utility

The customer should contact their local utility to inform them vehicle charging infrastructure will be installed at the site. The customer should ask their utility the following questions: Are there any incentives or different rate structures that may save the customer cost in installation or ongoing electricity cost? What is the size of the electrical service to the site? The utility may be able to provide knowledge as to the likelihood of needing a service upgrade based on the existing service and the intended number of charging stations. If there has been a determined need for a service upgrade or a new meter, an appointment should be made with a utility planner to visit the site. When possible, this should be coordinated with the contractor.

Contact local permit office

Different jurisdictions may have slightly different requirements or processes regarding the permitting, installation and inspection of charging stations. The contractor should contact the permitting office with jurisdiction over the installation site to identify specific requirements. Requirements of interest are listed below.

Concealment - While uncommon, certain municipalities may require charging stations are concealed with a hedge, fence or other object.

Engineering calculations - Municipalities may require load calculations to be performed and/or stamped by a licensed engineer. This can vary based on the location and number of charging stations to be installed. If engineering calculations are required, the contractor should coordinate the assessment time with the visit of a utility planner (if deemed necessary), the initial contractor visit and the customer's schedule. If these cannot be coordinated, each visit should be encouraged to happen as quickly as possible and all information should be reported to the contractor.

Phase 3: On-site evaluation

Once the necessary information is gathered and appointments are coordinated, the contractor will visit the site. The first site visit will answer any additional questions and resolve any decisions yet to be made. The charging station selected will influence the site selection and vice versa. If the customer has selected both the charging station and the site in advance, it will be important to check the National Electrical Code is adhered to and potential problems are avoided.

Whether a charging station has already been selected or still needs to be selected, contractors should ensure the charging station meets the following guidelines:

Surveying fast charging stations

Contractors are encouraged to use the following checklists for surveying charging station locations. Select appropriate parking spaces based on the following criteria:

- Visibility: Locations more visible to drivers and pedestrians, are less likely to be vandalized.
- Proximity to building entrance: Particularly important in locations where vehicle charging is viewed as an incentive, such as retail locations and places of work.
- Proximity to power source: Selecting spaces close to an existing transformer or panel with sufficient electrical capacity will save cost.

- Avoidance of existing infrastructure and landscaping: Installing charging stations close to existing infrastructure or trees can cause damage which may result in higher costs, potential hazards and other undesirable outcomes.
- Length of parking spaces: If there is a difference in length of parking spaces in a parking deck, longer parking spaces will allow for greater room to fit a charging station while maintaining usability and limiting the risk of vehicle impact. It is important the installation of a charging station does not shorten parking spaces to below minimum local zoning requirements.
- Width of parking spaces: Wider parking spaces decrease the risk of a cord set being damaged if it lies to the side of PEV, connected or otherwise. Additionally, wider spaces provided space for proper operation of the charging station and plugging the PEV in should the charge port be located in the side of the vehicle.
- Lighting: A well-lit parking space may reduce the risk of tripping and damage to the charging station from vehicle impact or vandalism. Additionally, it may aid in the operation of the charging station, including plugging the vehicle in.

Survey the charging station at the particular parking space(s)

- Consider available space on floors, walls and ceiling.
- If a charging station mounting type has been selected, eliminate types of location that do not match (i.e.: ceiling-mount units may not work on walls). Ensure installation does not conflict with vehicle’s ability to park within the space and to adequately use the charging station and plug in the vehicle.
- If a charging station has been selected or a particular model is desired note the number of cord sets per charging station. The charging station should be placed to provide direct access to each parking space without a cord being draped across another space and without blocking walking paths.

Ensure remaining locations best meet guidelines for a parking lot as follows:

- Lighting

Requirement: Lighting in parking lots is typically governed by local zoning codes. Review local codes to ensure compliance.

Recommendation: Ensure lighting is functional and discuss the addition of a separate lighting circuit if lighting levels are determined to be insufficient. Lighting levels are recommended to be two foot candles or higher.

- Connector height

Requirement: Connector will be mounted at a height between 24″ and 48″ from the ground (NEC 625.29).

Recommendation: Connector should be mounted at a height between 36″ and 48″ from the ground.

- Enclosure height

Requirement: None

Recommendation: For wall/pole-mount stations, the enclosure should be installed at a height above 36″. Greater heights are typically recommended, provided the connector can be mounted below 48″.

- Space around enclosure

Requirements: Sufficient space will exist around electrical equipment for safe operation and maintenance (NEC 110.26). A space 30″ wide or the width of the charging station, whichever is greater, should be maintained to a depth of 3′ from the front of the enclosure without physical obstruction, at a height of 6′ 6″.

- Tripping hazard mitigation

Requirement: None

Recommendation: Charging stations should be placed as to minimize the intersection of cords with typical walking paths. Stations mounted at greater heights and equipped with cord management technologies may further reduce this risk.

- Physical damage prevention

Requirement: Equipment operating above 50 volts will be protected against accidental physical damage (NEC 110.27).

Recommendation: When possible, placement of the charging station out of the line of vehicle travel is advised. Protective bollards can offer significant protection where there is sufficient space. Wheel stops may be beneficial in areas where bollards are not feasible.

Appendix B. Phases and actions for a battery storage project

Actions in different phases of a battery storage project:

1. Planning and analysis phase

This phase includes four areas of investigation:

- Battery system analysis - A detailed analysis of each battery technology based on considerations of feasibility, cost, power capacity, environmental and safety concerns should be carried out. Determining use cases is the next step in the process and identifying the battery storage technology most appropriate for that application.
- Circuit analysis - Circuits that would benefit from battery storage systems should be identified, located, and tested.
- Financial analysis - Costs of battery scale (dollars per kW/kWh), converting existing transformers to battery storage, life cycle costs, site development and construction, and potential return on investment, all these costs should be analyzed.
- Vendor analysis – Identification of battery manufacturers, integrators and suppliers to have an idea of the product offerings, typical cost, system features etc.

2. Contracting phase

The contracting phase consists of four general actions, creating a short list of vendors for battery technologies, application, and systems; determining the type of contract; developing a project solicitation; and reviewing proposals and awarding the contract.

3. Construction and testing phase

Once the previous steps are completed, including the circuit analysis and selection of contractors, the project would commence with the procurement of financing, site analysis and engineering, and obtaining the necessary building permits. Significant interaction with local communities would include public information dissemination, permit application including assessments of environmental impacts, noise, and land use compatibility; public hearings; and so on before site preparation and construction would begin. Pre-operation testing would follow installation of the battery system.

Appendix C. Cost calculations for battery storage

Calculations for cost of battery storage

Nomenclature

C_{BOP}	Cost of balance of plant (\$/kW)
C_{cap}	Total capital costs per unit of power rating (\$/kW)
$C_{cap;a}$	Annualized value of total capital costs(\$/kW-yr)
C_{DR}	Disposal and recycling costs (\$/kW)
$C_{DR,a}$	Annualized disposal and recycling costs(\$/kW-yr)
$C_{FOM,a}$	Fixed operational and maintenance costs(\$/kW-yr)
$C_{LCC,a}$	Annualized life cycle costs(\$/kW-yr)
$C_{O\&M,a}$	Annualized operational and maintenance costs(\$/kW-yr)
C_{PCS}	Cost of power conversion system (\$/kW)
C_R	Replacement costs (\$/kWh)
$C_{R,a}$	Annualized replacement costs(\$/kW-yr)
C_{stor}	Cost of storage section (€/kWh)
C_{VOM}	Variable operational and maintenance costs (€/kWh)
E_{in}	Input energy in one cycle (kWh)
E_{out}	Output energy in one cycle (kWh)
h	Discharge time(hr)
i	Interest rate (_)
n	Number of discharge cycles per year
r	Number of replacements
t	Replacement period(yr)
T	Lifetime (yr)
η_{sys}	Overall efficiency of storage system(%) = $\frac{E_{out}}{E_{in}}$ (kWh/kWh) (8)

Total capital cost (TCC) calculation

TCC can be calculated per unit of output power rating, presented as (C_{cap}) in the following equation. While C_{PCS}, C_{BOP}, and C_{stor} represent unitary costs of PCS, BOP, and storage compartment ($/kWh), respectively, 'h' is the charging/discharging time. (Behnam Zakeri, Electrical energy storage systems: A comparative life cycle cost analysis, 2015)

$$C_{cap} = C_{PCS} + C_{BOP} + C_{stor} \times h (\$/\text{kW}) \qquad (9)$$

C_{cap} can be interchangeably presented per unit of power rating or storage capacity ($/kWh). Cost per kWh per cycle offers a better indicator for the cost evaluation of EES systems, as it also accounts for the lifecycle numbers of EES (Chen H, 2009).

Life cycle cost (LCC) calculation

LCC is an important indicator to evaluate and compare different EES systems. LCC can be presented in levelized annual costs ($/kW yr), which is the yearly payment that the operator should maintain for all services of EES, including repayment of the loan and upfront of the capital costs. LCC calculations can be performed, first, by annualizing TCC (C_{cap}), presented by ($C_{cap,a}$) in Eq. (3). Based on the present value of money the capital recovery factor (CRF) is calculated by applying Eq. (4), subject to the interest rate (i) during the lifetime (T). (Behnam Zakeri, Electrical energy storage systems: A comparative life cycle cost analysis, 2015)

$$C_{cap,a} = TCC \times CRF \quad (\$/\text{kW} - \text{yr}) \qquad (10)$$

$$CRF = \frac{i(1+i)^T}{(1+i)^T - 1} \qquad (11)$$

Total annual O&M costs ($C_{O\&M,a}$) can be expressed by adding annualized costs of fixed O&M ($C_{FOM,a}$), and variable O&M (C_{VOM}) multiplied by yearly operating hours, as presented in Eq. (5).

$$C_{O\&M,a} = C_{FOM,a} + C_{VOM} \times n \times h \ \ (\$/\text{kW-yr}) \qquad (12)$$

To accommodate the replacement costs for replaceable EES systems, e.g. batteries, the future cost of replacement (C_R) in $/kWh and replacement period (t) in years should be known. Annualized replacement costs ($C_{R,a}$) can be calculated by using Eq. (6), given the number of replacements (r) during the application lifetime.

$$C_{R,a} = CRF \times \sum_{k=1}^{r} (1+i)^{-kt} \times \frac{C_R \times h}{n_{sys}} \ \ (\$/\text{kW-yr}) \qquad (13)$$

Disposal and recycling costs (C_{DR}) are other cost items that are usually neglected in the LCC analysis of EES in the literature. Annualized disposal and recycling costs ($C_{DR,a}$) can be calculated by applying interest rate(i) and lifetime of the plant(T), as explained in Eq. (7).

$$C_{DR,a} = C_{DR} \times \frac{i}{(1+i)^T - 1} \quad (\$/kW\text{-}yr) \qquad (14)$$

The annualized LCC costs (ALCC) of EES systems, presented by $C_{LCC,a}$ in Eq. (8), is determined by stacking the previously discussed cost items.

$$C_{LCC,a} = C_{cap,a} + C_{O\&M,a} + C_{R,a} + C_{DR,a} \quad (\$/kW\text{-}yr) \qquad (15)$$

Levelized cost of energy (LCOE) calculation

The levelized cost of electricity (LCOE) delivered by EES systems can be then calculated by applying Eq. (9), knowing the annual operating hours of the system in question. (Zakeri, 2015)

$$LCOE = \frac{ALCC}{yearly\ operating\ hours} = \frac{C_{LCC,a}}{n \times h} \quad (\$/kWh) \qquad (16)$$

Levelized cost of storage (LCOS) calculation

If the cost of charging electricity would be deducted from the LCOE delivered by EES, the net levelized cost of storage (LCOS) itself can be realized (Eq. (10)). (Zakeri, 2015)

$$LCOS = LCOE - \frac{Price\ of\ charging\ power}{Overall\ Efficiency} \quad (\$/kWh) \qquad (17)$$

Appendix D. DES modeling codes

Code for model #1

```
from matplotlib import pyplot as plt
import operator

nStations=15
coords = {
1:(42.58160019,     -83.03096771),
2:(42.45776749,     -83.13323975),
3:(42.27840424,     -83.2700882),
4:(42.14104462,     -83.22714233),
5:(42.4941234, -83.4256796),
6:(42.49123764,     -83.51441956),
7:(42.3601265, -83.43258667),
8:(42.32044601,     -83.48866272),
9:(42.22281265,     -83.48566437),
10:(42.628,      -83.874),
11:(42.58,       -83.88),
12:(42.54561996,-83.78999329),
13:(42.2843526,     -83.8084963),
14:(42.2397874, -83.7668615),
15:(42.24443817,-83.7388382)
}

delta = {
1:20,
2:9,
3:7,
4:11,
5:23,
6:16,
7:14,
8:16,
9:13,
10:11,
11:19,
12:18,
13:24,
14:50,
15:10
}

supply = input("Enter battery supply unit value: ")
```

```
threshold = input("Enter stopping threshold: ")
radius = input("Enter exchange range: ")

count=1
maxDelta=0

deltaLevels = []

wastage=0

while(1):
     sorted_delta = sorted(delta.items(),
key=operator.itemgetter(1), reverse=True)
     deltaLevels.append(sum(delta.values()))
     unit=sorted_delta[0]
     stationID = unit[0]

     print "ID: " + str(stationID) + ", Gap = " +
str(delta[stationID])

     demand = delta[stationID]
     if(demand>threshold):
          print "Battery Consumed : " + str(count)

          extraSupply=0
          if(supply>demand):
               delta[stationID] = 0
               extraSupply = supply-demand
          else:
               delta[stationID] = demand-supply

          print "ID: " + str(stationID) + ", New Gap = " +
str(delta[stationID])

          if(extraSupply>0):
               locA = coords[stationID];
               distFromLocA={}
               for n,p in coords.iteritems():
                    locB = p;
                    dist = pow(pow((locA[0]-
locB[0]),2)+pow((locA[1]-locB[1]),2),0.5)

                    distFromLocA[n]=dist

               sorted_dist = sorted(distFromLocA.items(),
key=operator.itemgetter(1))
```

```
               for n,dist in sorted_dist:
                    if n!=stationID and delta[n]>0 and
extraSupply>0 and dist<=radius :
                         demand = delta[n]
                         if(extraSupply>demand):
                              delta[n] = 0
                              extraSupply = extraSupply - demand
                              print "Exchange from " +
str(stationID) + " to " + str(n) + " amount = " + str(demand) +
" still remaining: " + str(extraSupply)

                         else:
                              delta[n]= demand-extraSupply
                              print "Exchange from " +
str(stationID) + " to " + str(n) + " all amount = " +
str(extraSupply) + " with updated Gap at Station " + str(n) + "
= " + str(delta[n])
                              extraSupply=0

               if(extraSupply>0):
                    wastage=wastage+extraSupply

          count=count+1
     else:
          break

print "Total Surplus Energy Remaining in Batteries = " +
str(wastage)

x = range(len(deltaLevels))
plt.plot(x,deltaLevels)
plt.ylabel('Total Gap')
plt.xlabel('Num. of Batteries Consumed')
plt.show()
```

Code for model #2

```
import math
import numpy
from matplotlib import pyplot as plt
import operator
from mpl_toolkits.mplot3d import Axes3D
from skmonaco import mcquad
from skmonaco import mcimport
from numpy.random import normal,lognormal
```

```
print 'Enter the Battery Type:'
print ' 1. Li-Ion\n 2. Lead Acid\n 3. Vanadium Redox\n 4.
Sodium-sulfur\n 5. Sodium-nickel-chloride\n 6. Zinc-bromine\n 7.
Zinc-air\n 8. Iron-chromium\n'
opt = input()
if(opt==1):
     xl=[1000.]
     xu=[2100.]
elif(opt==2):
     xl=[500.]
     xu=[2500.]
elif(opt==3):
     xl=[800.]
     xu=[1100.]
elif(opt==4):
     xl=[500.]
     xu=[600.]
elif(opt==5):
     xl=[700.]
     xu=[1200.]
elif(opt==6):
     xl=[300.]
     xu=[1600.]
elif(opt==7):
     xl=[200.]
     xu=[300.]
elif(opt==8):
     xl=[300.]
     xu=[500.]


mean= (xl[0]+xu[0])/2
print mean

threshold = 0

costArray=numpy.zeros((101,101))

totalcost = 10000000000000

for supply in numpy.linspace(1, 100, 100):
     print supply
    for radius in numpy.linspace(0.00, 1, 101):

        nStations=15
        coords = {
```

```
        1:(42.58160019,  -83.03096771),
        2:(42.45776749,  -83.13323975),
        3:(42.27840424,  -83.2700882),
        4:(42.14104462,  -83.22714233),
        5:(42.4941234,   -83.4256796),
        6:(42.49123764,  -83.51441956),
        7:(42.3601265,   -83.43258667),
        8:(42.32044601,  -83.48866272),
        9:(42.22281265,  -83.48566437),
        10:(42.628,   -83.874),
        11:(42.58,    -83.88),
        12:(42.54561996,-83.78999329),
        13:(42.2843526,  -83.8084963),
        14:(42.2397874, -83.7668615),
        15:(42.24443817,-83.7388382)
        }

        delta = {
        1:20,
        2:9,
        3:7,
        4:11,
        5:23,
        6:16,
        7:14,
        8:16,
        9:13,
        10:11,
        11:19,
        12:18,
        13:24,
        14:50,
        15:10
        }

        count=1
        maxDelta=0

        deltaLevels = []

        wastage=0

        while(1):
            sorted_delta = sorted(delta.items(), 
key=operator.itemgetter(1), reverse=True)
            deltaLevels.append(sum(delta.values()))
            unit=sorted_delta[0]
```

```
            stationID = unit[0]

            demand = delta[stationID]
            if(demand>threshold):

                extraSupply=0
                if(supply>demand):
                    delta[stationID] = 0
                    extraSupply = supply-demand
                else:
                    delta[stationID] = demand-supply

                if(extraSupply>0):
                    locA = coords[stationID];
                    distFromLocA={}
                    for n,p in coords.iteritems():
                        locB = p;
                        dist = pow(pow((locA[0]-
locB[0]),2)+pow((locA[1]-locB[1]),2),0.5)

                        distFromLocA[n]=dist

                    sorted_dist = sorted(distFromLocA.items(),
key=operator.itemgetter(1))

                    for n,dist in sorted_dist:
                        if n!=stationID and delta[n]>0 and
extraSupply>0 and dist<=radius :
                            demand = delta[n]
                            if(extraSupply>demand):
                                delta[n] = 0
                                extraSupply = extraSupply -
demand

                    if(extraSupply>0):
                        wastage=wastage+extraSupply

                count=count+1
            else:
                break

        c = lambda supplycost: (0 * radius) +
(((supplycost*mean)+xl[0]) * supply * count * 4) + (20000 *
count)
        cost,error =
mcimport(c,npoints=100,distribution=lognormal)
```

```
        costArray[int(supply)][int(radius*100)]=cost

        if(cost<totalcost):
            totalcost = cost
            batteryUnit = supply
            batteryCount = count
            radiusFinal = radius
            print 'total cost = ' + str(totalcost)
            print 'battery unit = ' + str(batteryUnit)
            print 'battery cost range ' + str(xl[0]) + ' to ' +
str(xu[0])
            print 'num of batteries= ' + str(batteryCount)
            print 'radius final = ' + str(radiusFinal)
            print "Total Wastage = " + str(wastage)
            print ""

print 'total cost = ' + str(totalcost)
print 'battery unit = ' + str(batteryUnit)
print 'num of batteries= ' + str(batteryCount)
print 'radius final = ' + str(radiusFinal)

nx, ny = 101,101
x = range(nx)
y = range(ny)
hf = plt.figure()
ha = hf.add_subplot(111,projection='3d')
X,Y = numpy.meshgrid(x,y)
ha.plot_surface(X,Y,costArray)
ha.set_xlabel("exchange range")
ha.set_ylabel("battery size")
ha.set_zlabel("Total cost")
plt.show()
```

BIBLIOGRAPHY

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Akhil, A., et al. (2015). DOE/EPRI Electricity Storage Handbook in Collaboration with NRECA. Sandia National Laboratories.

Advanced Energy. (2013). Installation of EV Supply Equipment (EVSE). Advanced Energy.

Advanced Energy Co. (2011). Charging Station Installation Handbook. Advanced Energy.

Agenbroad, J., & Holland, B. (2014, April). Pulling Back the Veil on EV Charging Station Costs. Retrieved November 2016, from Rocky Mountains Institute: http://blog.rmi.org/blog_2014_04_29_pulling_back_the_veil_on_ev_charging_station_costs

Albrecht, M. (2010). Introduction to Discrete Event Simulation.

Alexander, M. (2014). EV Supply Equipment Installed Cost Analysis. Palo Alto: EPRI.

Alternative Energy Systems Consulting, (Dec 2015). Considerations for Corridor Direct Current Fast Charging Infrastructure in California. California Energy Commission.

Association, E. D. (2016). Electric Drive Sales. Retrieved from http://electricdrive.org/index.php?ht=d/sp/i/20952/pid/20952

Aziz, M., T. O. (2016). Battery-assisted charging system for simultaneous charging of EVs. Elsevier, 82-90.

Bashiri, M., N.B. (2016). Optimized plan of charging stations for management of demands: An emerging need of hybrid electric vehicle. Future Technologies Conference (FTC). IEEE.

Bayram, I., G.M., M.D., F.G. (2013). Electric Power Allocation in a Network of Fast Charging Stations. IEEE Journal on Selected Areas in Communications, 1235-1246.

Bradbury, K., L. P. (2014). Economic viability of energy storage systems based on price arbitrage potential in real-time U.S. electricity markets. Applied Energy, 512-519.

California Energy Commission. (2016). EV Charging Station Installation Best Practices. Center for Sustainable Energy.

Canis, B. (2011). Battery Manufacturing for Hybrid and EVs Policy Issues. Tech. Rep. CRS Report for Congress.

Caro, J. J. (2005). Pharmacoeconomic Analyses using Discrete Event Simulation. Pharmacoeconomics.

Carnegie, R., D.G. (2013). Utility Scale Energy Storage Systems: Benefits, Applications and Technologies. State Utility Forecasting Group.

Centorbi, H. (2017, May 20). Webinar: Best practices for installing battery storage systems. Retrieved from Solar Power World: http://www.solarpowerworldonline.com/2015/05/webinar-best-practices-in-the-installation-of-battery-storage-system/

Chen, C. (2009). Progress in electrical energy: A critical review. Progress in Natural Science, 291-312.

Clean Energy Council. (2016). Grid Connected Battery Systems with Energy Storage. Accredited Installer.

Corporation, E. (2016). Types of EVs. Retrieved October 2016, from Entergy: entergy.com/our_community/environment/ev_types

Corporation, P. (2016). Monte Carlo Simulation. Retrieved December 2016, from Palisade: http://www.palisade.com/risk/monte_carlo_simulation.asp

DeForest, N., J. F. (2009). Impact of Widespread EV Adoption on the Electrical Utility Business-Threats & Opportunities. Berkley: University of California.

DiOrio, N., A. D. (2015). Economic Analysis Case Studies of Battery Energy Storage with SAM. Denver: National Renewable Energy Laboratory (NREL).

Deng, J., J. S. (2016). Application of a hybrid energy storage system in the fast charging station of EVs. IET Generation, Transmission & Distribution, 1092-1097

Ding, H., Z. H. (2015). Value of the energy storage system in an electric bus fast charging station. Applied Energy, 630-639.

Detwiler, P. (2014, March 13). Building out the EV Charging Infrastructure. Retrieved from Forbes Energy: http://www.forbes.com/sites/peterdetwiler/2014/03/13/building-out-the-electric-vehicle-charging-infrastructure-greenlots-advocates-for-open-standards/#4d2289d93f7a

Energy, C. (2015). About EVs Types & Comparison. Retrieved November 2016, from Refuel Colorado: www.refuelcolorado.com/ev/about

Enersys. (2016). Battery Safety, Storage, Installation, Operation and Maintenance Manual. Enersys.

Evans, L., G. G. (2013). The role of storage in a competitive electricity market and the effects of climate change. Energy Economics, 405-418.

Flores, R. (2016). Electricity costs for an EV fueling station with Level 3 charging. Applied Energy, 813-830.

Gartner, J. (2012, June 05). Energy Storage is Key to Reducing the Cost of Fast Charging. Retrieved from Plug-In Cars: http://www.plugincars.com/energy-storage-key-reducing-cost-fast-charging-121913.html

Ghamami, M., (2016). Planning charging infrastructure for plug-in EVs in city centers. International Journal of Sustainable Transportation, 343-353.

Herron, D. (2014). DC Fast Charging Standards. Retrieved from Green Transportation: https://greentransportation.info/ev-charging/range-confidence/chap8-tech/ev-dc-fast-charging-standards-chademo-ccs-sae-combo-tesla-supercharger-etc.html

Hydro Quebec. (2015). EV Charging Stations- Technical Installation Guide. International Electrotechnical Commission.

Institute for Energy Research. (2013). Retrieved from http://www.instituteforenergyresearch.org/2011/03/10/ obama-administration-pushes-electric-vehicles

International Electrotechnical Commission. (2011). Electrical Energy Storage: white paper.

Joos, G., M. F. (2010). Design and Simulation of a Fast Charging Station. IEEE.

John, J. S. (2015, July 21). How EV Chargers and Energy Storage Can Make Good Grid Partners. Retrieved February 04, 2017, from Greentech media: https://www.greentechmedia.com/articles/read/how-ev-chargers-and-energy-storage-can-make-good-grid-partners

Li, S., K. B. (2014). Energy Management and Control of EV Charging Station. Electric Power Components and Systems, 42:3-4, 339-347.

Lin, S., Z. H. (2010). Impact of plug-in hybrid EVs on distribution systems. Power System Technology(POWERCON), (pp. 1-5).

Macal, C., M. J. (2008). AGENT-BASED MODELING AND SIMULATION: ABMS EXAMPLES. Winter Simulation Conference (pp. 101-112). Argonne, IL: Argonne National Laboratory.

Momtazpour, M., P. B. (2014). Charging and storage infrastructure design for EVs. ACM Trans. Intell. Syst. Technol, 42-69.

McCarthy, K. (2011, October 03). OLR Research Report. Retrieved from Undergrounding Electric Lines: https://www.cga.ct.gov/2011/rpt/2011-R-0338.htm

McDonald, Z. (2016, February 04). A Simple Guide to DC Fast Charging. Retrieved January 20, 2017, from Fleetcarma: http://www.fleetcarma.com/dc-fast-charging-guide/

Morrow, K. (2008). Plugin hybrid EV charging. U.S. Department of Energy.

Negarestani, S., M. F., F. G. (2016). Optimal Sizing of Storage System in a Fast Charging Station for Plug-in Hybrid EVs. IEEE TRANSACTIONS ON TRANSPORTATION ELECTRIFICATION, 443-453.

Nie, Y., M. G. (2013). A corridor-centric approach to planning electric vehicle. Transportation Research, 172-190.

Office of the Press Secretary. (2009). Retrieved Sept 2016, from President Obama Announces $2.4 Billion in Funding: http://www.whitehouse.gov/the-press-office/presidentobama-announces-24-billion-funding-support-next-generation-electric-vehic

Oswal M., P. J. (2010). A comparative study of Lithium Ion Batteries. University of Southern California.

PlugShare. (2017, February). EV Charging Station Map. Retrieved from www.plugshare.com

Puget Sound Energy. (2015). Appendix L: Electric Energy Storage.

Rogge, M., S. W. (2015). Fast Charging Battery Buses for the Electrification of Urban Public Transport—A Feasibility Study Focusing on Charging Infrastructure and Energy Storage Requirements. Energies, 4587-4606.

Sandia National Laboratories. (2016). Energy Storage Procurement Guidance Documents for Municipalities. Clean Energy Group.

Saxton, T. (2013, May 30). EV Charging Infrastructure Priorities. Retrieved November 2016, from Plug In America: https://pluginamerica.org/electric-vehicle-charging-infrastructure-priorities/

Sbordonea, D., I. B. (2014). EV fast charging stations and energy storage technologies: A real implementation in the smart micro grid paradigm. Electric Power Systems Research, 96-108

Schneider, K., G.M. (2008). Impact assessment of plug-in hybrid vehicles on pacific northwest distribution systems. Power and Energy Society General Meeting- Conversion and Delivery of Electrical Energy in the 21st Century (pp. 1-6). IEEE.

Schroeder, T. (2012). The economics of fast charging infrastructure for EVs. Energy Policy, 136-144.

Smith, M., J. C. (2015). Costs Associated With Non-Residential EVSupply Equipment. U.S. Dept of Energy Vehicle Technologies.

Tesla. (2017). Superchargers. Retrieved from Tesla: https://www.tesla.com/supercharger

Thomas, M., J.M., T.Y., A.B., N.T. ((2016a and 2016b)). Research and Testing of Utility-Scale Battery Storage Technologies and Applications in Support of Power Generation and Distribution. Phase I/II Reports. Michigan State University School of Planning, Design, and Construction and Department of Electrical Engineering and Computer Sciences.

U.S. Department of Energy. (2016, June). Global Energy Storage Database. Retrieved from DOE: www.energystorageexchange.org

United States Environmental Protection Agency. (n.d.). Retrieved from http://www.epa.gov/oms/climate/basicinfo.htm

Vermont Energy Investment Co. (2014). EV Charging Station Guidebook. Winooski: Chittenden County RPC.

Zakeri, B., S. S. (2014). Electrical energy storage systems: A comparative life cycle cost analysis. Renewable and Sustainable Energy, 569-596.

Zhao, D., A. P. (2016). Decision-Making Chains in Electrical Safety for Construction Workers. Journal of Construction Engineering and Management, 142 (1),1-11.

Zhu, D., W. Y. (2013). Maximizing return on investment of a grid-connected hybrid electrical energy storage system. Asia and South Pacific Design Automation Conference.

Zucchi, K. (2014, October 20). Lognormal and Normal Distribution. Retrieved from Investopedia: http://www.investopedia.com/articles/investing/102014/lognormal-and-normal-distribution.asp