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Techno Economical Analysis of Solid Oxide Iron-Air Redox Battery for Power Generation and Energy Storage

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TECHNO ECONOMICAL ANALYSIS OF SOLID OXIDE IRON–AIR REDOX BATTERY FOR POWER GENERATION AND ENERGY STORAGE

By

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DEDICATION

I dedicate my thesis work to my family. A special feeling of gratitude to my husband, Mohammad Faisal Haider, for his words of encouragement and support during graduate life. This work is also dedicated to my daughter and parents for their endless love.

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ABSTRACT

The largest source of greenhouse gas emissions in the United States is from burning fossil fuels for electricity, heat, and transportation. Due to increasing environmental constraints associated with greenhouse gas emissions and uncertainty in the supply of fossil fuels, power systems of the future will become more reliable on renewable power source. To overcome the intermittency issue of renewable power, a promising cost effective electricity-storage systems is vital. The U.S. Department of Energy (DOE) has established detailed cost targets for energy storage system. One of the targets is capital cost which should be under $150/kWh for new technology. Another target is levelized cost of electricity (LCOE) which is defined as the net cost to install energy storage system over its expected lifetime energy output. The DOE target for energy storage systems is a levelized cost of 10 ¢$kWh^{-1}cycle^{-1}$. For this reason, it is very important to evaluate the techno economic feasibility of energy storage systems for different application. The aim of this thesis is to analysis the techno-economic viability of new technology Solid oxide iron-air redox battery for stationary application.

Attention in the development of new battery technology for grid storage is growing, and considerable investments have been made into the research and development of new battery technology over the past few decades. But, implementation of new technology into the grid has been impeded by various cost and performance issues. The purpose of this study is to develop a design and techno economic model for a 5 kW/50 kWh Solid oxide iron-air redox battery (SOFeARB) storage system with a nominal cell voltage of 0.83V

and current density 100mA/cm^2. Rechargeable solid oxide Iron air redox battery (SOFeARB) system consists of regenerative solid oxide fuel cell (RSOFC), energy storage system (ESU), balance of plant (BOP), power conditioning system (PCS) and thermal storage tank. Expected system cost calculated $232/kwh to $309/kwh for different production volume (100, 1,000, 10,000, and 50,000 systems per year). Using the estimated capital cost, an economic analysis was performed to determine the LCOE for the system. The levelized cost for highest production volume of the delivered electricity is estimated 27.5¢kWh^{-1}cycle^{-1}. The major components of a SOFeARB that affect LCOE are also identified. The LCOE are also calculated for a range of different parameter values. Key findings include a high sensitivity of system levelized cost of electricity to power density, life time of storage and discharging time. The result of the sensitivity analysis can be used to make the SOFeARB system more emulous in future. Finally, we compared SOFeARB with other mature battery storage technologies to find out the position of SOFeARB in energy storage market.

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LIST OF ABBREVIATIONS

BOP ..... Balance of Plant

CAES ..... Compressed Air Energy Storage

DOE ..... Department of Energy

EES ..... Electrical Functioning Unit

ESU ..... Energy Storage Unit

ERB ..... Electrochemical Rechargeable Batteries

FHS ..... Flywheel Energy Storage

GDC ..... Gd- Doped CeO_2

GPM ..... Gallon per minutes

LCOE ..... levelized cost of electricity

LIB ..... Lithium-Ion Battery

LSCF ..... Sr- and Fe- doped $LaCoO_3$

PCS ..... Power Conversion System

PHS ..... Pumped Hydropower System

RFB ..... Redox Flow Battery

RSOFC ..... Regenerative Solid Oxide Fuel Cell

SES ..... Supercapacitors Energy Storage

SMES .....Superconducting Magnetic Energy Storage

SOFeARB .....Solid Oxide Fe-air Redox Battery

SOMARB ..... Solid Oxide Metal-air Redox Battery

SOFC.....Solid Oxide Fuel Cell

TES ..... Thermal Energy Storage

CHAPTER 1
INTRODUCTION

The sunlight falling on the United States in one day contains more than twice the energy we consume in an entire year. In contrast, the largest source of greenhouse gas emissions from human activities in the United States is from burning fossil fuels for electricity, heat, and transportation [1]. In addition, about 81% of all U.S. greenhouse gases are carbon dioxide emissions from energy-related sources [2]. Due to increasing environmental constraints associated with greenhouse gas emissions and uncertainty in the supply of fossil fuels, power systems of the future will become more reliant on renewable power. Increasing demands for energy help to create the growing market for fuel cells and different type of energy storage systems. There are a variety of potential energy storage options for the electric sector, each with unique operational, performance, and cycling and durability characteristics. The following sections of this chapter begin with a brief description of various grid energy storage technology, the performance and cost characteristics of different storage system discusses in the following section. The chapter concludes with a description of the thesis objective.

1.1 GRID ENERGY STORAGE TECHNOLOGY

There are several categories of energy storage system (EES). Figure 1.1 provides worldwide comparative estimates of total current installed storage capacity for energy storage system [3]. The most common type of technology are pumped hydropower system (PHS), compressed air energy storage (CAES), electrochemical batteries and fuel cells,

flywheels, capacitors, superconducting magnetic energy storage system(SMES) and thermal energy storage system(TES). Different kinds of EES are describe below.

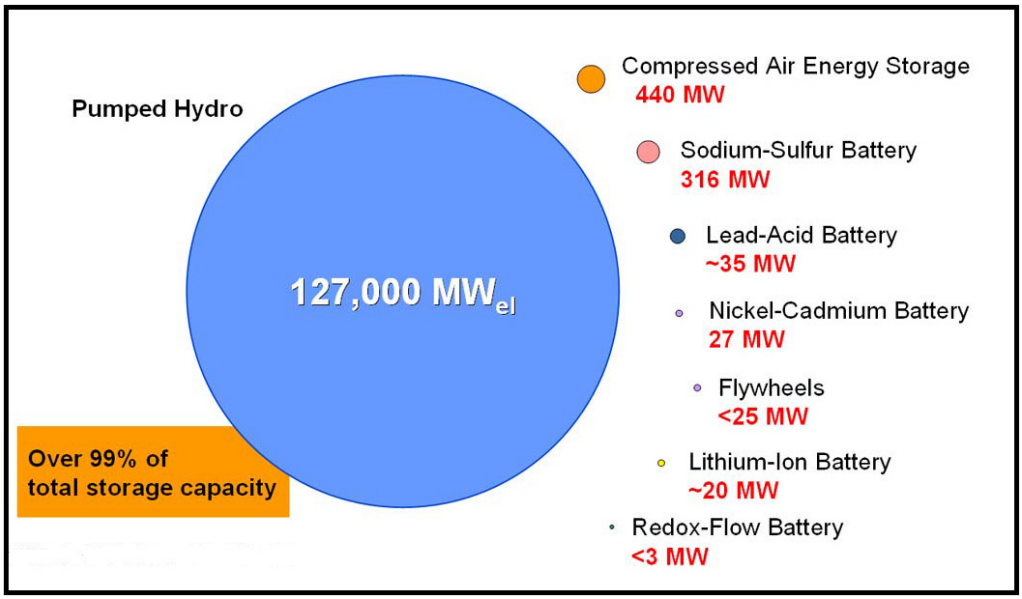

Figure 1.1 Worldwide installed storage capacity for electrical energy

1.1.1 Pumped hydropower system (PHS)

In pumping hydro storage (Figure 1.2), a body of water at a relatively high elevation represents a potential or stored energy. During peak hours the water in the upper reservoir is led through a pipe downhill into a hydroelectric generator and stored in the lower reservoir. Along off-peak periods the water is pumped back up to recharge the upper reservoir and the power plant acts like a load in power system [4], [5]. United States alone own approximately 40 PHES stations with a total capacity of ~20GW. Worldwide, there are hundreds of PHES stations operating with a total capacities of 127GW [6]. PHS can provide energy-balancing, stability, storage capacity and ancillary grid service such as network frequency control and reserves [7]. PHS facilities provide very large capacities of electricity, with low operation and maintenance cost, and high reliability. The levelized

storage cost for electricity using PHS is usually much lower than other electricity storage technologies [8].

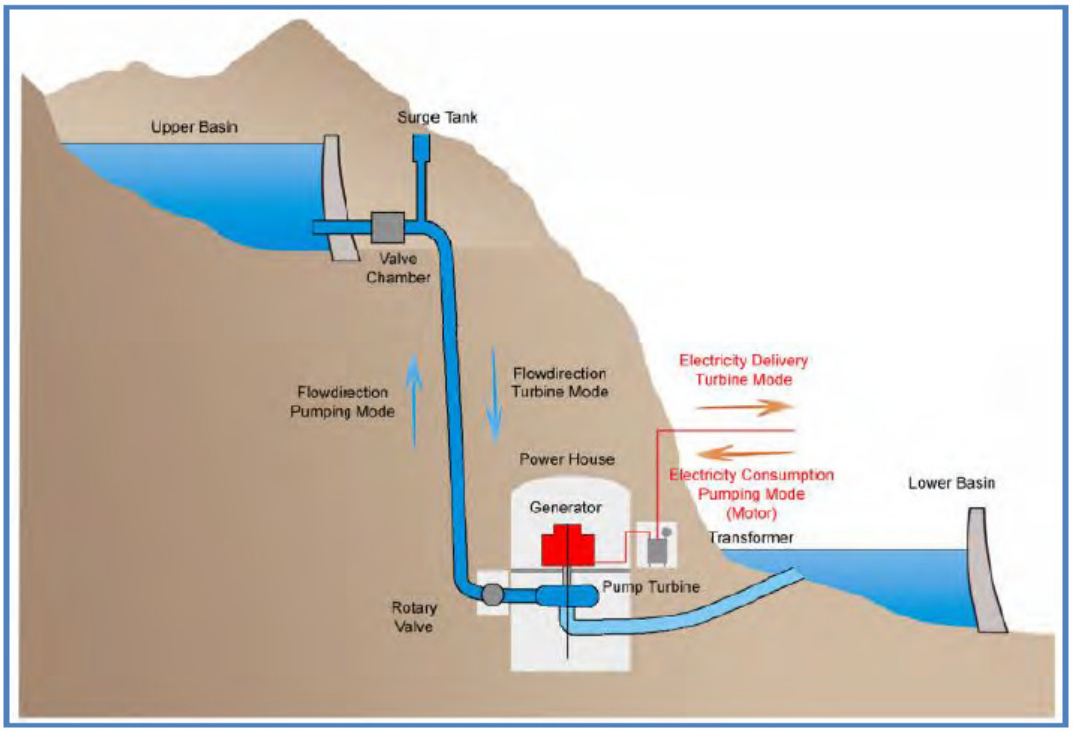

Figure 1.2 pumping hydro storage [9]

1.1.2 Compressed air energy storage (CAES)

This method (Figure 1.3) consist to use off-peak power to pressurize air into an underground reservoir (salt cavern, abandoned hard rock mine or aquifer) which is then released during peak daytime hours to power a turbine/generator for power production. CAES is the only other commercially available technology (besides pumped-hydro) able to provide the very-large system energy storage deliverability (above 100 MW in single unit sizes) to use for commodity storage or other large-scale setting [10]. It has a long storage period, low capital costs but relatively low efficiency in comparison with other

energy storage technologies. CAES can be used for peak shaving, load leveling, energy management, renewable energy and standby power [11].

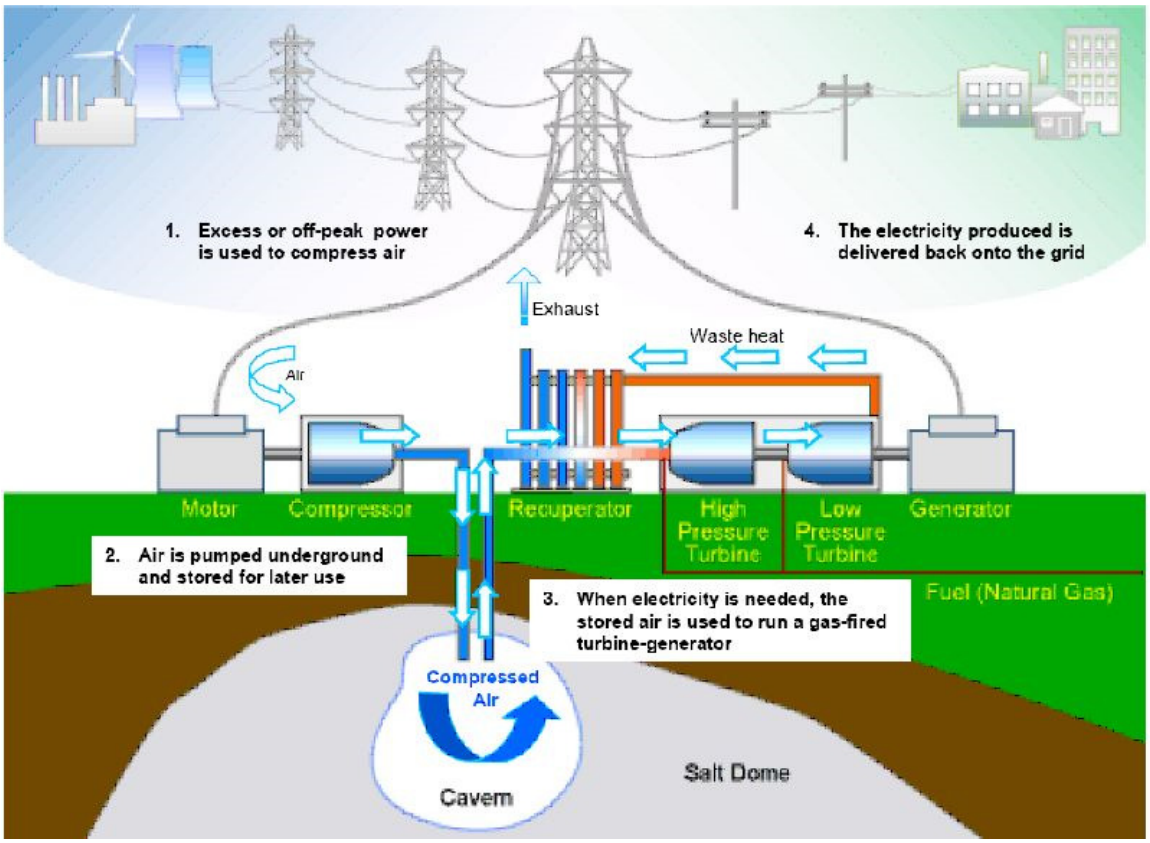

Figure 1.3 Compressed air energy storage [11].

1.1.3 Flywheel energy storage (FES)

The operating principle of a flywheel energy storage system (FESS) (Figure 1.4) is that electrical energy is converted to kinetic energy and stored in the flywheel, and the kinetic energy can be converted back to electrical energy when required later. The energy that can be stored in flywheel is proportional to the moment of inertia times the square of angular velocity of rotating disc. Flywheel energy accumulators are comprised of a massive or composite flywheel coupled with a motor-generator and special brackets (often magnetic), set inside a housing at very low pressure to reduce self-discharge losses [11]. FESS are

well-suited to serve several applications like power quality and reliability, longer term backup, area regulation and frequency response [7].

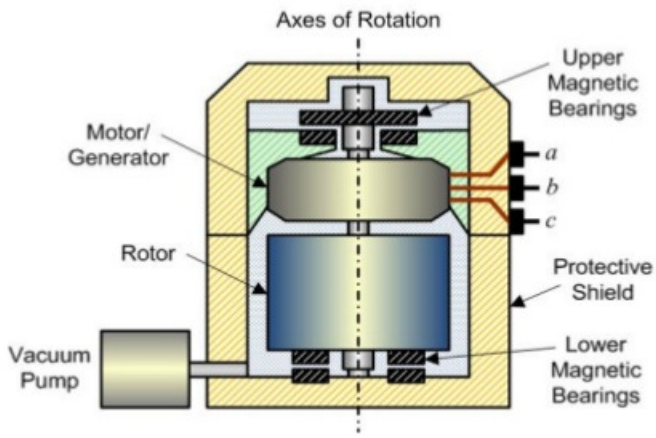

Figure 1.4 Flywheel Energy storage system [12]

1.1.4 Supercapacitors energy storage (SES)

The term supercapacitor is usually used to describe an energy storage device based on the charge storage in the electrical double layer (EDL) of a high-surface area carbon in aqueous electrolytes. In general, supercapacitors have referred to capacitors with two high-surface area carbon electrodes for the anode and cathode. This arrangement where both electrodes have the same configuration will be referred to as a symmetric capacitor [14]. The supercapacitor allows a much powerful power and energy density. Supercapacitors are used in applications requiring many rapid charge/discharge cycles rather than long term compact energy storage.

1.1.5 Electrochemical rechargeable batteries (ERB)

Batteries are self-contained units that store chemical energy and, on demand, convert it directly into electrical energy to power a variety of applications. Batteries are divided into

two general classes: primary batteries that are discharged once and discarded; secondary, rechargeable batteries that can be discharged and then restored to their original condition by reversing the current flow through the cell [14]. Among all, electrochemical rechargeable batteries are the most promising technology for stationary applications. A number of electrochemical rechargeable batteries have already developed but very few of them are compatible with grid applications in terms of performance, cost, reliability and appearance. Figure 1.5 demonstrated four factors which are very important to success in the battery market.

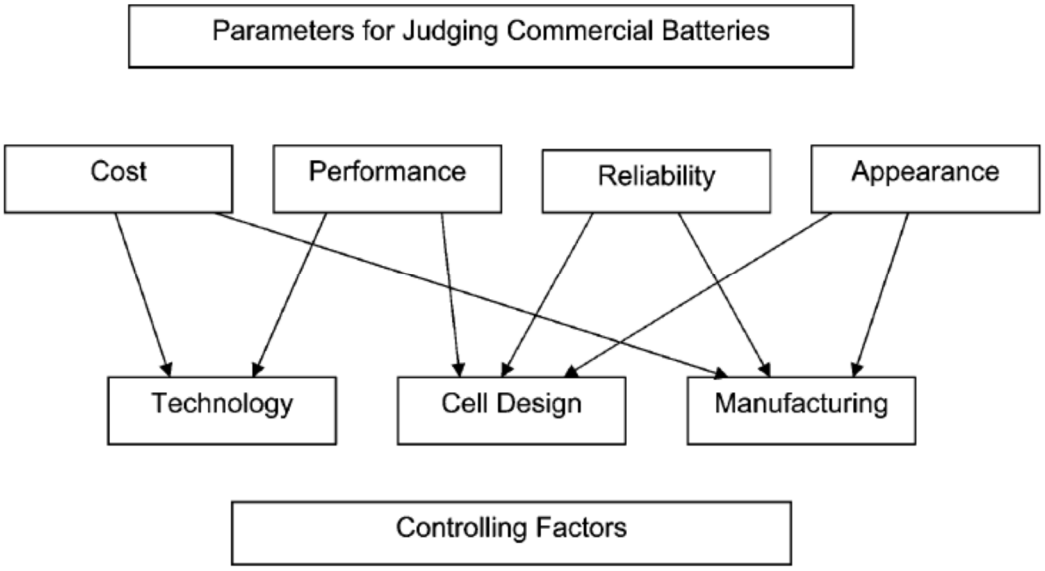

Figure 1.5 How batteries are judged by users and the factors that control these criteria [14]

The most common rechargeable batteries on the market today are lead-acid, alkaline batteries, metal hydrides, redox flow batteries, lithium ion and sodium-sulfur batteries. Lead–acid batteries, invented in 1859 by French physicist Gaston Planté, are the oldest type of rechargeable battery. Despite having a very low energy-to-weight ratio and a low energy-to-volume ratio, their ability to supply high surge currents means that the cells maintain a relatively large power to-weight ratio. These features, along with their low

cost, make them attractive for use in motor vehicles to provide the high current required by automobile starter motors. The first generation rechargeable alkaline technology was developed by Battery Technologies Inc. in Canada and licensed to Pure Energy, EnviroCell, Rayovac, and Grandcell. Rechargeable alkaline batteries have the ability to carry their charge for years, unlike most NiCd and NiMH batteries which self-discharge in 90 days .If produced properly, rechargeable alkaline batteries can have a charge/recharge efficiency of as much as 99.9% and be an environmentally friendly form of energy storage. The nickel–iron battery (NiFe battery) is a storage battery having a nickel (III) oxide-hydroxide cathode and an iron anode, with an electrolyte of potassium hydroxide. The active materials are held in nickel-plated steel tubes or perforated pockets. It is a very robust battery, which is tolerant of abuse, (overcharge, over discharge, and short-circuiting) and can have very long life even if so treated. It is often used in backup situations where it can be continuously charged and can last for more than 20 years. Due to its low specific energy, poor charge retention, and its high cost of manufacture, other types of rechargeable batteries have displaced the nickel–iron battery in most applications. They are currently gaining popularity for off-the-grid applications where daily charging makes them an appropriate technology. A lithium-ion battery (LIB) is a family of rechargeable battery types in which lithium ions move from the negative electrode to the positive electrode during discharge, and back when charging. Chemistry, performance, cost, and safety characteristics vary across LIB types. Unlike lithium primary batteries (which are disposable), lithium-ion electrochemical cells use an intercalated lithium compound as the electrode material instead of metallic lithium. Lithium-ion batteries are common in

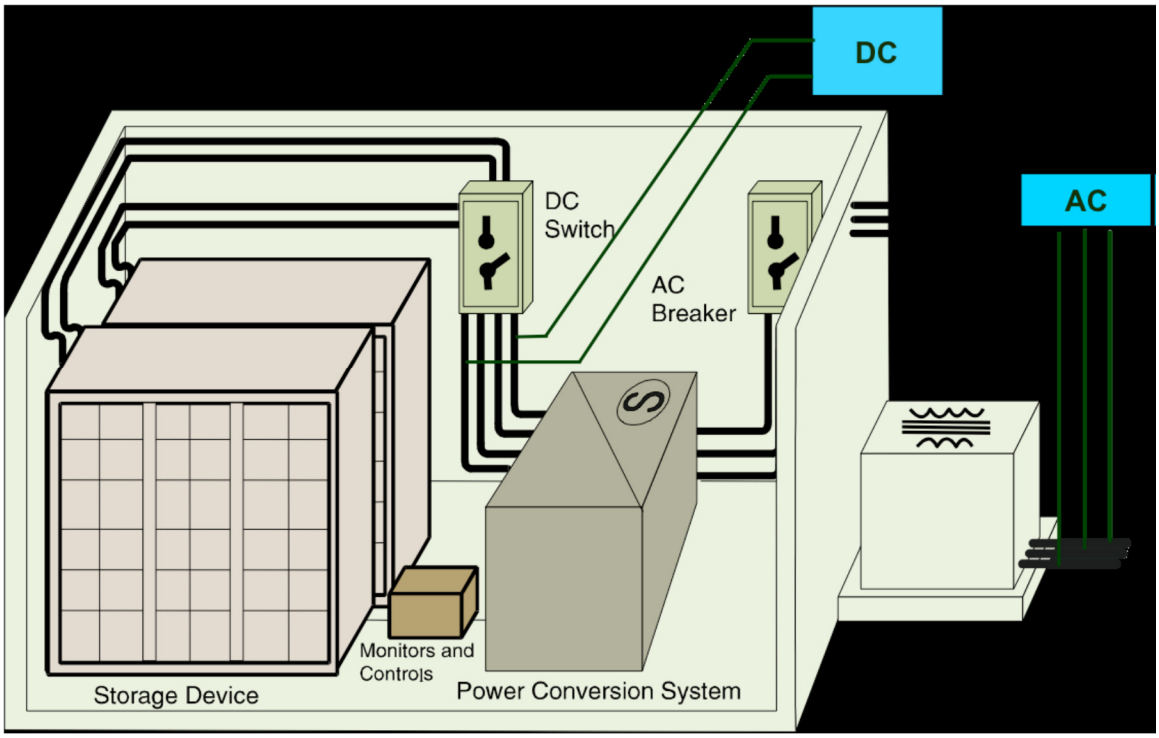

Figure 1.6 Schematic of a Battery Energy Storage System (source: Sandia National Laboratories)

Consumer electronics. They are one of the most popular types of rechargeable battery for portable electronics, with one of the best energy densities, no memory effect, and a slow loss of charge when not in use. Beyond consumer electronics, LIBs are also growing in popularity for military, electric vehicle, and aerospace applications. Research is yielding a stream of improvements to traditional LIB technology, focusing on energy density, durability, cost, and intrinsic safety [14]. Among electrochemical systems, redox flow batteries (RFBs) represent one of the most recent technologies and a highly promising choice for stationary energy storage. They are electrochemical energy conversion devices, which exploit redox processes of species in solution in fluid form, stored in external tanks and introduced into the RFB when needed. In this sense a RFB is similar to a polymer electrolyte membrane fuel cell (PEMFC) and indeed it is a sort of FC. The most appealing features of this technology are: scalability and flexibility, independent sizing of power and

energy, high round-trip efficiency, high DOD, long durability, fast responsiveness, and reduced environmental impact [16] . Another type of battery named metal–air battery that uses metal as an anode and air as a cathode. Although metal-air batteries are very attractive in principle as portable electrical sources in view of their light weight and high energy density, there are still many difficulties like thermal management in developing practical batteries of this type [18].

1.1.6 Superconducting magnetic coil (SMES)

Superconducting Magnetic Energy Storage (SMES) is a novel technology that stores electricity from the grid within the magnetic field of a coil comprised of superconducting wire with near-zero loss of energy. SMES is a grid-enabling device that stores and discharges large quantities of power almost instantaneously. A typical SMES consists of two parts – cryogenically cooled superconducting coil and power conditioning system – which are motionless and result in higher reliability than many other power storage devices. Ideally, once the superconducting coil is charged, the current will not decay and the magnetic energy can be stored indefinitely. The main application of SMES is to improve power quality for critical loads, provides carryover energy during momentary voltage sags and power outages and improves load leveling between renewable energy sources and the transmission and distribution network [20].

1.1.7 Thermal storage systems

The thermal energy storage (TES) can be defined as the temporary storage of thermal energy at high or low temperatures. There are three basic methods for storing thermal energy. First method called sensible heat storage is based on heating a liquid or a solid

without changing phase. Hot water, organic liquids, molten salts, liquid metals, metals, minerals, ceramics are the examples of sensible heat storage medium. Another method called latent heat storage which involve heating a material, which undergoes a phase change e.g. nitrids, clorides, hydroxides, carbonates, flourides, entectics, hydroxides. Last method which use heat to produce a certain physicochemical reaction and then storing the product heat e.g. CaO/H_2O, MgO/H_2O, $FeCl_2/NH_3$, CH_4/ H_2O, $NaOH/H_2O$ [21].

1.2 GRID ENERGY STORAGE APPLICATION

Electricity storage has a remarkable benefit for promoting renewable-technology into the electrical grid, as installation of electric storage systems will improve the intermittency issue of renewable energy. According to report published by Sandia National laboratories on July 2013, there are 18 services and applications in five groups for energy storage on the grid. The five groups are:

i. **Bulk Energy Services**- includes energy time-shift and peak capacity application.

ii. **Ancillary Service-** includes regulation, spinning, non-spinning, and supplemental reserves, voltage support, black start, Load Following/Ramping Support for Renewables and Frequency Response application.

iii. **Transmission Infrastructure Services-**includes Transmission Upgrade Deferral and Transmission Congestion Relief, Transmission Stability Damping and Sub-synchronous Resonance Damping application.

iv. **Distribution Infrastructure Services**-includes Distribution Upgrade Deferral and Voltage Support,

v. **Customer Energy Management Services**-includes Power Quality, Power Reliability, Retail Energy Time-Shift and Demand Charge Management.

Different Application required different power and discharge duration. Table 1 summarizes these requirement [21].

Table 1.1 Application of grid-scale energy storage with power, discharge duration and minimum cycle/year requirements

Application	Power Range	Discharge duration	minimum cycle/year
Electric energy time-shift	1 – 500 MW	<1 hour	250+
Electric supply capacity	1 – 500 MW	2-6 hour	1-100
Regulation	10-40 MW	0.25-1 hour	250-10000
Spinning, Non-Spinning, and Supplemental Reserves	10-100 MW	0.25-1 hour	20-50
Voltage Support	1 – 10 mega volt-ampere reactive (MVAR)	not applicable	not applicable
Black Start	5 – 50 MW	0.25-1 hour	10-20
Load Following/Ramping Support for Renewables	1 – 100 MW	0.25-1 hour	not applicable
Transmission Upgrade Deferral	10 – 100 MW	2-8 hour	10-50
Transmission Congestion Relief	1 – 100 MW	1-4 hour	50 - 100
Transmission Stability Damping & Sub-synchronous Resonance Damping	10 – 100 MW	5 seconds – 2 hours	20-100
Distribution Upgrade Deferral and Voltage Support	500 kW – 10 MW	1-4 hour	50 - 100
Power Quality	100 kW – 10 MW	10 seconds – 15 minutes	10-200
Retail Energy Time-Shift	1 kW – 1 MW	1 – 6 hours	50-250
Demand Charge Management	50 kW – 10 MW	1-4 hour	50-500

1.3 STORAGE PERFORMANCE AND COST COMPARISON

It has already discussed that each application requires special technical consideration. So there is no single energy storage system that fits for all application. Each energy storage technology varies in terms of power rating and discharge duration. These are key indicators of what applications a storage medium might be able to fulfill. For example, a low-power

& longer discharge time might be appropriate for on-site auxiliary or supplementary power, whereas a high-power & shorter discharge time might be more appropriate for grid-scale power quality regulation. Figure 1.7 shows the relationship between power capacity and discharge time of various energy storage technologies [21]. As shown in the graph compressed air energy storage (CAES) and pumped hydro are capable of discharge times in tens of hours, with correspondingly high sizes that reach 1000 MW. In contrast to the capabilities of these two technologies, various electrochemical batteries and flywheels are positioned around lower power and shorter discharge times.

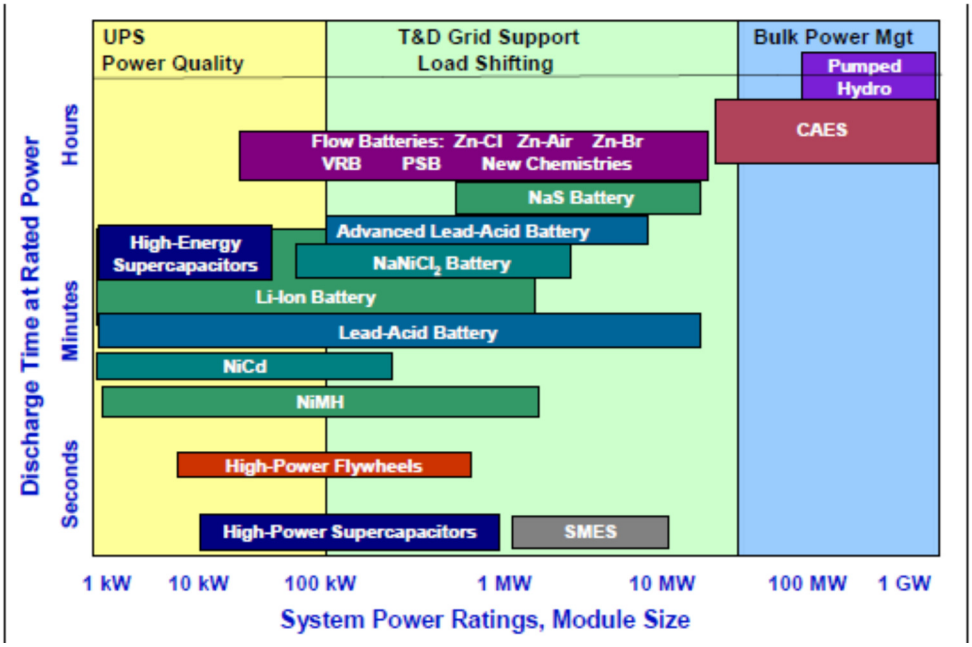

Figure 1.7 Positioning of Energy Storage Technologies

The cost of energy storage system is an important factor need to consider for customers. Figure 1.8 shows different storage technologies according to their capital costs per unit power ($/KW) and capital cost per unit energy ($/KWh), respectively. Apart from performance characteristics, capital and operating costs also determine whether a technology is viable for a given applications. For example, though a product might be

suited technically for a given application, the cost of the product might not justify its application. Ultimately, the answer to which storage device is best for a given application depends on its technical capabilities as well as the financial viability of the product, based on product costs and application revenues[23].

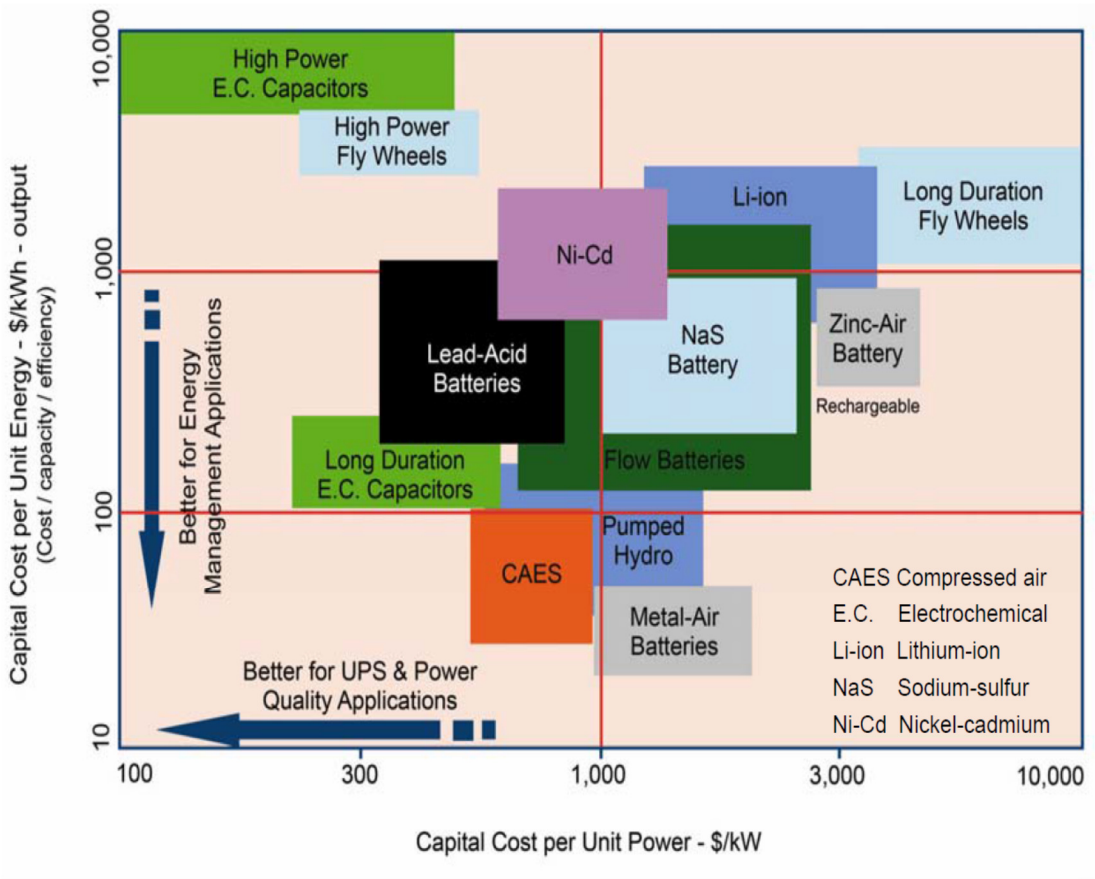

Figure 1.8 Capital Cost per unit power ($/KW) and per unit energy ($/KWh) [23]

1.4 THESIS OBJECTIVE

It is safe to say that all energy storage technologies need to satisfy some goals before penetrating in the market. Achievement of these goals requires attention to the factors such as life-cycle cost and performance (round-trip efficiency, energy density, cycle life, capacity fade, etc.). The U.S. Department of Energy (DOE) has established detailed cost

and performance targets for energy storage system. One of the targets is capital cost which should be under $150/kWh [24]. Another target is levelized cost of electricity (LCOE) which is often cited as a convenient summary measure of the overall competiveness of different generating technologies. It represents the per-kilowatt hour cost of building and operating a generating plant over an estimated financial life and duty cycle [24]. LCOE need to be under 10 ¢/kWh/cycle [24].

New rechargeable solid oxide metal air redox battery (SOMARBs) combines a regenerative solid oxide fuel cell (RSOFC) and hydrogen chemical-looping component. RSOFC is a device that can operate efficiently in both fuel cell and electrolysis operating modes and the hydrogen chemical-looping component functions as an energy storage unit (ESU), performing electrical-chemical energy conversion in situ via a H2/H2O-mediated metal/metal oxide redox reaction. Figure 1.9 shows the feature of our battery. It is a true rechargeable energy storage system which can store electricity inside the battery. In addition, it can function as a fuel cell to make electricity if fuel is supplied from external source.

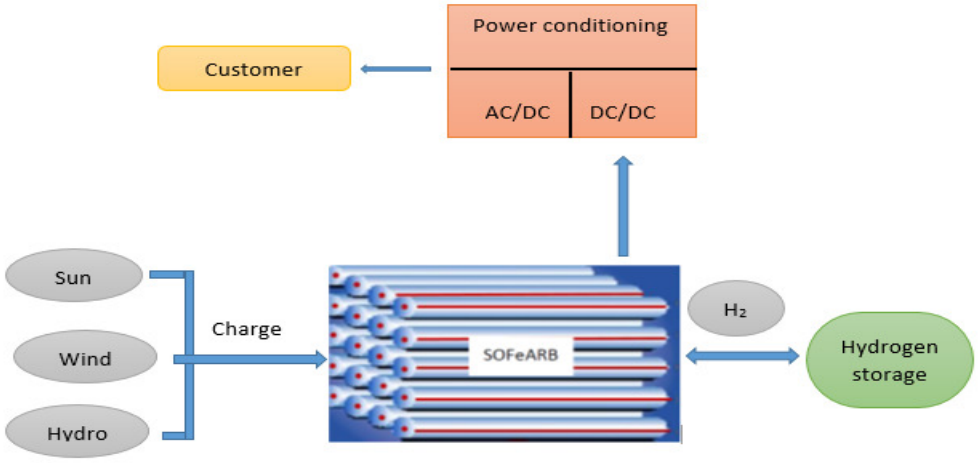

Figure 1.9 SOFeARB storage system

The objectives of this thesis are to develop a solid oxide iron air Redox battery (SOFeARB) system life cycle cost model using estimated performance characteristics. Sensitivity analysis is performed and the key characteristics of energy storage systems is identified that have the largest impact on economy. Sensitivity analysis technique is focused on how different values of the system components impact on the system's economics. The result of the sensitivity analysis can be used in near future to make the SOFeARB system more emulous

1.5 THESIS OUTLINES

This thesis is divided into five chapters. Chapter 1 provides a brief description of energy storage system, application of energy storage system, cost and performance of different energy storage system, finally the objectives of this research. Chapter 2 and Chapter 3 presents the step by step development procedure of Solid Oxide Metal Air Redox battery and literature reviews on current cost and economic models of different storage systems. Chapter 4 describes the battery cost estimation methodology and economic analysis. Chapter 5 discusses the results from the analysis. Finally Chapter 6 summarizes the main conclusions of this thesis.

CHAPTER 2
SOLID OXIDE METAL AIR REDOX BATTERY DEVELOPMENT

Development of SOMARB began in 2011 at the University of South Carolina in USA with patent being issued. Comprehensive reports on performance of solid oxide Fe–air redox battery has already been published [26]-[34]. Extensive work has been done to improve the current densities and power densities of the SOMARB cells and further improvements are expected in near future. A number of features of the new SOMARB are discernible from other batteries for large-scale stationary energy storage. In SOMARB the power and energy unit are separated from each other, so they can be designed independently. It is sustainable and environmental friendly due to use redox couple energy storage materials.

This novel Solid Oxide Metal Air redox flow battery consists of a RSOFC as the electrical functioning unit and a metal/metal oxide (Me/MeO_x) redox couple as the energy storage medium (ESU). RSOFC can operates as a solid oxide fuel cell or a solid oxide electrolyzer mode. Figure 2.1 shows schematically the working principle of the SOMARB. During the discharge cycle, Me (metal) is oxidized by H_2O to form MeO_x [26]

$$Me + xH_2O = MeO_X + xH_2 \tag{2.1}$$

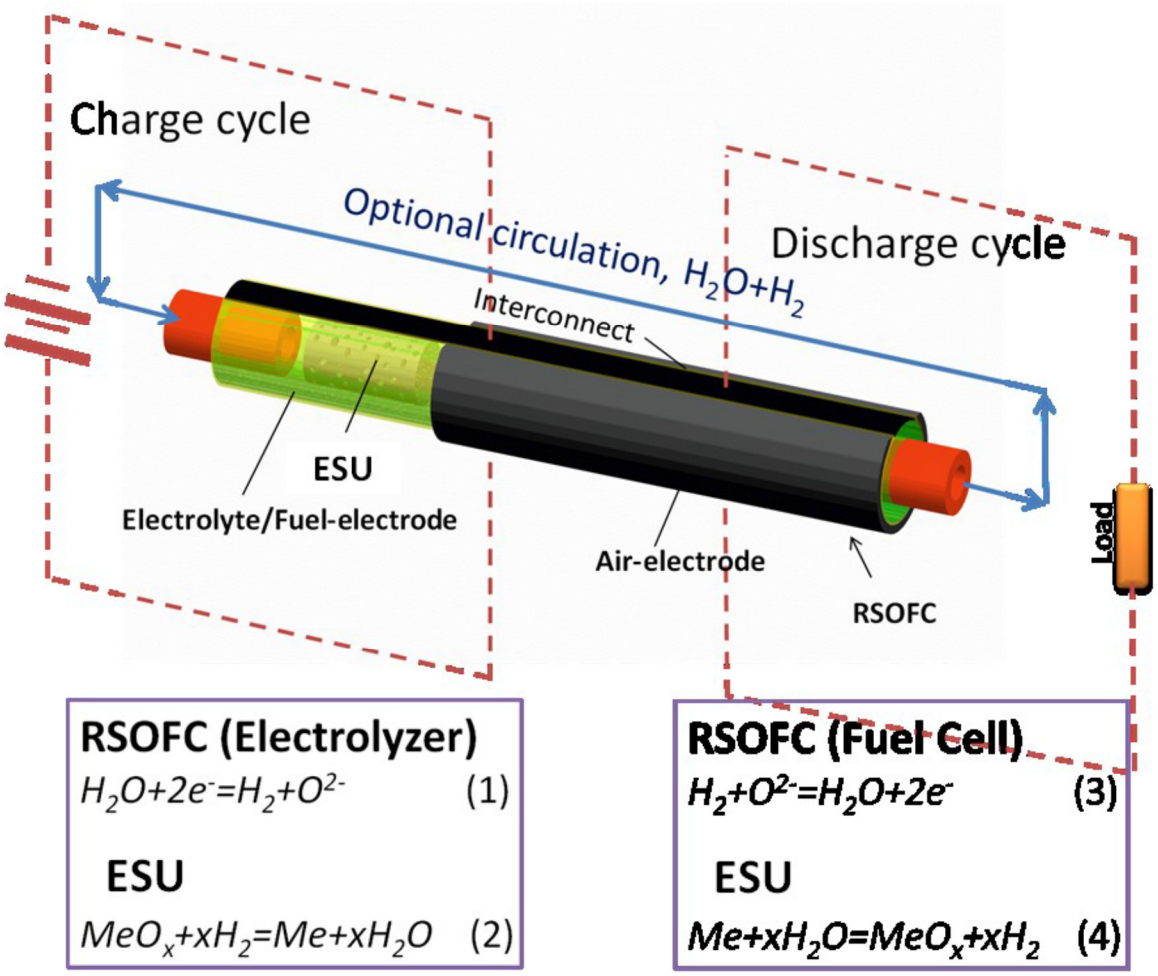

Figure 2.1 Working principle of the new metal-air battery based on an anode-supported tubular RSOFC [26].

Then generated H_2 is electrochemically oxidized at the anode, producing electricity and steam via the following electrochemical reactions.

$$H_2 + O^{2-} = H_2O + 2e^- \tag{2.2}$$

When all the Me phase is oxidized, the discharge cycle is stopped and the battery needs to be recharged. During the charge cycle, by H_2 that is generated by splitting H_2O in RSOFC, and the produced H_2O proceeds towards RSOFC for continued electrochemical splitting. During the charge cycle, the H_2O produced during discharge cycle is

electrochemically decomposed to produce H_2 at the cathode of the SOEC unit operating under the electrolysis mode.

$$H_2O + 2e^- = H_2 + O^{2-} \tag{2.3}$$

The generated H_2 then reduced MeO_x into Me.

$$MeO_x + xH_2 = Me + xH_2O \tag{2.4}$$

During the discharge and charge cycles, the reactions at the air-electrode are:

$$\tfrac{1}{2}O_2 + 2e^- \underset{charge}{\overset{discharge}{\rightleftharpoons}} O^{2-} \tag{2.5}$$

The overall chemical reaction of the SOARFB then becomes (By combining equations 2.1-2.5)

$$Me + \frac{x}{2}O_2 \underset{charge}{\overset{discharge}{\rightleftharpoons}} MeO_x \tag{2.6}$$

2.1 MATERIAL SYNTHESIS AND BATTERY ASSEMBLY IN THE LABORATORY

In this section, we provide a brief fabrication procedure of SOMARB. Several types of ESU and RSOFC materials were used in lab during fabrication of this battery.

2.1.1 Material Synthesis

2.1.1.1 The ESU redox couples

So far, different types of ESU material were fabricated and used in lab to produce SOMARB [26].

i. **Co-precipitated and pelletized Baseline Fe-based ESU:** To prepare Fe/FeO_x redox couple, the Fe_2O_3 was mixed with ZrO_2 by a co-precipitation method in a molar ratio

of Fe_2O_3:ZrO_2=85:15. The ZrO_2 is use to mitigate the coarsening of Fe-particles during redox cycles without interfering with the redox reaction occurring in the system. The nano sized Fe_2O_3 and ZrO_2 mixture powders were prepared by co-precipitating 0.1 M of aqueous solution containing $Fe(NO_3)_3 \cdot 9H_2O$ (Alfa Aeasar, 98.0-101.0%) and $ZrO(NO_3)_2 \cdot xH_2O$ (Alfa Aeasar, 99.9%) with $(NH_4)_2CO_3$. The molar ratio of $(NH_4)_2CO_3$ and Combined Fe and Zr cations was 2.5:1.

ii. **CeO_2-modified Fe-based ESU:** To prepare this type of ESU, CeO_2 nanoparticles were dispersed into the aforementioned Fe_2O_3/ZrO_2 granules by solution infiltration technique. A 2.0 M aqueous solution of $Ce(NO_3)_3 \cdot 6H_2O$ mixed with a dispersant Triton-X100 (3 wt%) was impregnated into the porous Fe_2O_3/ZrO_2under a vacuum condition for 8 times. For each impregnation, there was a 100°C-drying and 500°C-calcination step. The final CeO2 nanoparticles dispersed Fe_2O_3/ZrO_2 was obtained by firing the mixture at 600°C in air for 1 h.

iii. **ZrO_2-supported Fe-based ESU:** This type of ESU was used to investigate the effect of surface area of active metals on the redox kinetics. To get fine particles of Fe, an aqueous solution of $Fe(NO_3)_3$ was infiltrated into a commercial porous ZrO_2 catalyst support (Alfa Aesar, surface area: 51g/m^2) using a modified one-step infiltration procedure. Specifically, a 2 M $Fe(NO_3)_3$ aqueous solution was first mixed with Triton-X100 (3 wt%) in DI water, into which the porous ZrO_2 pellets were immersed. During the soaking, the solution was gradually heated to 80°C while the air trapped in the porous ZrO_2 pellets was driven out of the solution, allowing the maximum loading of Fe into the pores of ZrO_2.

iv. **Carbothermic reaction derived Fe-based ESU:** The Fe-based ESU was also synthesized by conventional carbothermic reaction as described as follows. To distinguish this ESU with the baseline ESU, the new ESU was termed Fe/C-ESU, and the corresponding battery is termed solid oxide Fe/C-air redox battery (SOFeCARB). The starting materials for the reaction are the co-precipitated Fe_2O_3-ZrO_2powder and carbon black (Fisher Scientific). The two powders were first intimately mixed in an atomic ratio of Fe:C=1:4.2, followed by ball milling in alcohol. The excess stoichiometry of C was intentional to ensure a full reduction of Fe_2O_3 to Fe. The mixed/milled powders were then dried, and pressed into pellets. The pellets were then reacted at 1000°C for 10h in a flowing N_2 at 100sccm.

v. **W-based ESU:** The functional redox precursor WO_3 in the W-based ESU was from a commercial source (Fisher Chemicals). The commercial WO_3 was first ball-milled into fine particles, followed by mixing with a microcrystalline cellulose pore-former (type NT-013, FMC Corp.) in a volume ratio of 1:1. Rectangular bars were then pressed from the powders and sintered at 1100°C for 2h. All heat treatments were conducted in open air. The sintered bars were broken into granules in 9-16 mm^2 by 2 mm.

vi. **Mo-based ESU:** The functional redox precursor MoO_3 in the Mo-based ESU was taken from commercial Molybdenum Trioxide (MP Biomedicals, LLC). The MoO_3 was first ball-milled into fine particles, followed by mixing with V-006A (Heraeus) to form a paste. The paste was then screen-printed on to a Ni-foil support, and calcined in open air at 650°C for 2h.

2.1.1.2 RSOFC functional materials

The following types of RSOFC materials are used in lab [26].

i. **Commercial anode-supported tubular RSOFC:** A commercially available anode-supported tubular RSOFC was used in a tubular SOFeARB. The tubular anode Ni-YSZ/YSZ (CoorsTek) has a 10 mm in OD, 1.25 mm in wall thickness and 40 mm in length. The resultant effective cell surface area is 4.78 cm^2. A cross-sectional view of the anode/electrolyte microstructure after reduction is shown in Figure 2.2 (a), where an approximately 25 μm-thick YSZ electrolyte on the anode is shown with a reasonably good porosity and pore size. A composite cathode ink consisting of GDC and LSCF (from LSCFGDC-1, Fuel Cell Materials) was then applied to the outer surface of the cell and calcined at 1050°C for 1 h in open air. The currents were collected by silver wires attached on the outer surface of the cathode and the end of anode as shown in Figure 2.2 (b). To ensure good electrical contacts, a layer of silver prepared from silver paste (C8829, Heraeus) was coated prior to attaching the silver wires.

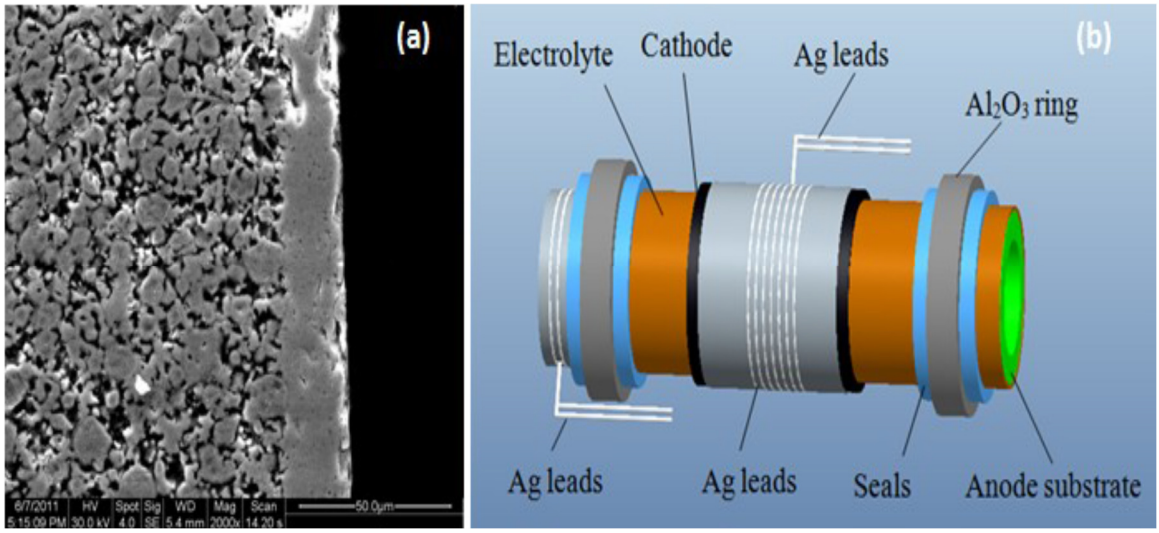

Figure 2.2 (a) Microstructure of an anode-supported tubular RSOFC employed in this study (b) A single battery cell subassembly

ii. **Commercial electrolyte-supported planar RSOFC:** Planar SOFeARB was also investigated during experiments. This also allowed to study the energy storage

characteristics at higher current densities. The compositions of the RSOFCs from a commercial NextCells as listed in Table 2.1

Table 2.1 Compositions and dimensions of the commercial NextCells

Component	Composition	Thickness (μm)
Fuel electrode	Ni-YSZ/Ni-GDC (interlayer)	50
Electrolyte	Hionic ZrO_2-based	150(+/-15)
Air electrode	LSM/LSM-GDC(interlayer)	50

2.1.2 Battery Assembly

During experiment two battery assembly configurations were employed. The first configuration is based on the anode-supported tubular RSOFC. The battery cell was cement-mounted onto two long Al_2O_3 tubes in which Fe-based baseline ESU pellets were installed close to the inlet end of the battery cell. Figure 2.3 shows a schematic view of the assembled anode-supported tubular battery cell [26].

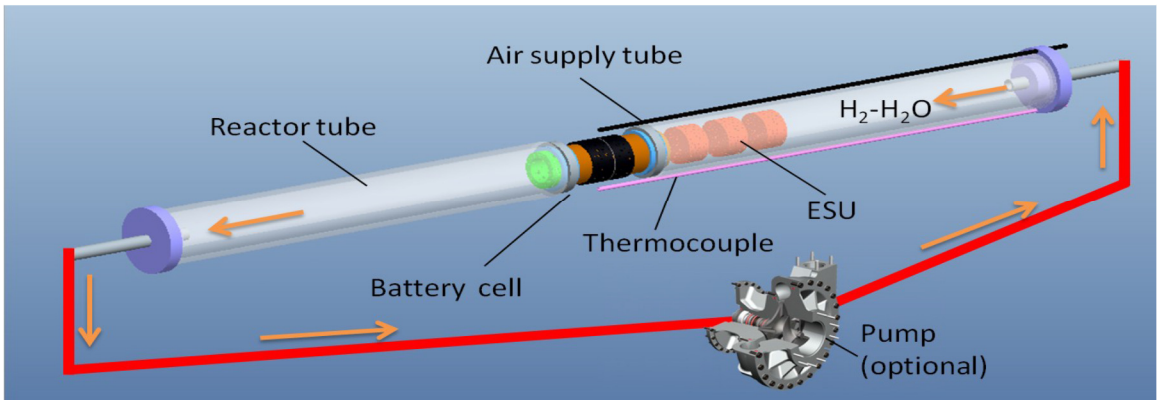

Figure 2.3 A single battery assembly with an anode supported tubular RSOFC and an Integrated ESU.

Another configuration is based on the planar RSOFCs, as shown in Figure 2.4. A specially formulated glass-ceramic was used as the hermetic sealant for the battery cell[27].

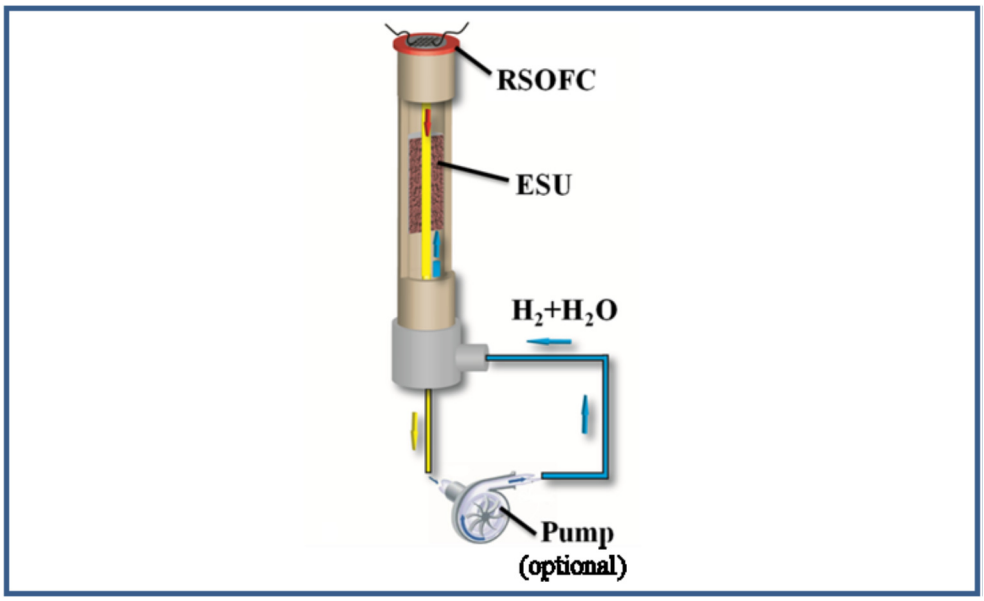

Figure 2.4 Schematic of a planar button SOFeARB configuration.

2.2 PERFORMANCE EVALUATION DURING EXPERIMENTS

To investigate the performance of SOMARB, Fe/FeO was taken as the redox material. The charging/discharging characteristic of the tubular SOFeARB is shown in Figure 2.5. The battery could produce an energy capacity of 348 Wh/kg-Fe and round-trip efficiency of 91.5% over twenty stable charge/discharge cycles. This novel solid oxide redox flow battery has been demonstrated in laboratory-scale tests with high storage-capacity, rate-capacity and round-trip efficiency even at relatively lower Fe loading and utilization. Its ability to store a large amount of electrical energy clearly originates from the fundamental charge/discharge reaction that essentially involves the transfer of two electrons in the electrode process [28].

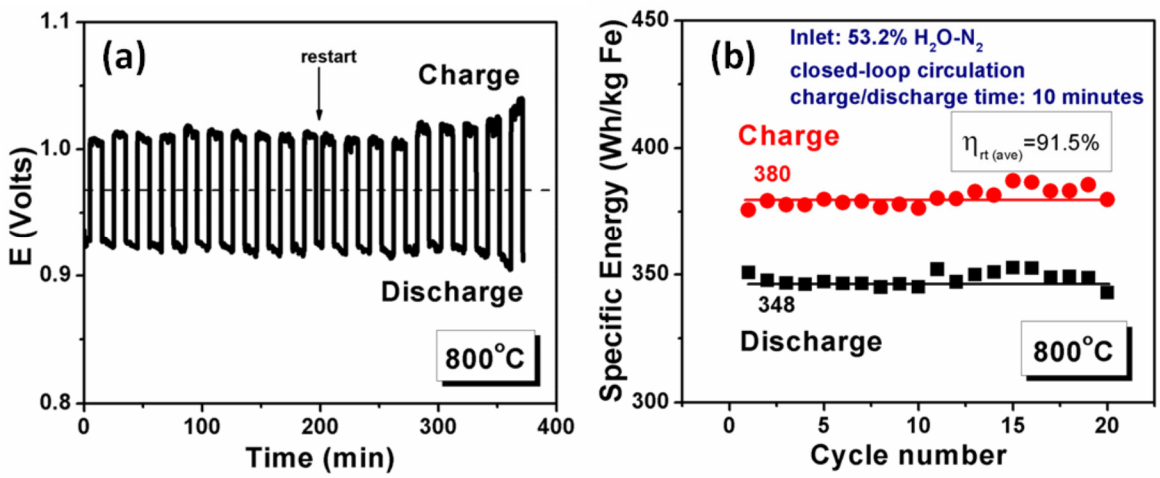

Figure 2.5 (a) Charge and discharge characteristic of the tubular battery at 800C and j=50 mAcm-2. The break on the curve at ~200 min marks the start of second 10-cycle run; (b) Plot of specific energy as a function of the number of charge and discharge cycles.

A pair of Mo/MoO_2 redox couple integrated with the reversible solid oxide fuel cell and investigated the performance of this system. The specific charge of this battery found 1117 A h per kg-Mo at 550°C, which is 45% higher than the non-rechargeable Mo-air battery. The corresponding discharge specific energy is 974 W h per kg-Mo with a round trip efficiency of 61.7%. In addition, the new Mo-air redox battery also exhibits 13.9% and 24.5% higher charge density (AhL^{-1}) and energy density (WhL-1) than the state-of-the-art solid oxide Fe-air redox battery, respectively [29].

Using CeO_2 modified ESU, The DSE reached 1,026 Wh/kg.Fe, yielding a round-trip efficiency of 52.2% when compared to the CSE=1,971 Wh/kg.Fe. These results represent a 15% and 29% improvement in specific energy and round-trip efficiency, respectively, over the baseline battery [30].

In the case of ZrO_2-supported nanoparticle Fe-Fe_3O_4 redox couple, the DSE reached 1,012 Wh/kg.Fe, yielding a round-trip efficiency of 59.9% with CSE=1,695

Wh/kg.Fe. These results represent 13% and 48% improvement in specific energy and round-trip efficiency, respectively, over the baseline battery [30].

Later, the performance, reversibility and stability of a solid oxide iron–air redox battery can be significantly improved by using ESU materials from a carbothermic reaction. The basic energy storage characteristics of the Fe/C–air battery evaluated over a 10-cycle period at 550 ℃. The performance results of this test are shown in Figure 2.6. The battery was continuously cycled at a current density j = 10 mA/ cm^2 for ten consecutive 10 min cycles, producing a constant discharge specific energy (DSE) of 1258 W h per kg of Fe, which is 93% of the maximum theoretical specific energy (MTSE) of 1360 Wh per kg of Fe. The conventional iron carbothermic reaction was investigated in this study as a means of producing a high surface-area nanostructured ESU. The electrochemical characterization of a SOMARB using the Fe/C ESM shows an improvement in DSE and RTE by 12.5%and 27.8%, respectively, over the baseline performance [31].

The effects of current density and cycle duration on specific energy and round trip efficiency of the new battery studied at 650 ℃ and 550 ℃. In this experiment, Fe–FeO_x redox couple material was synthesized from a carbothermic reaction. The battery for the tests were assembled in a planar button cell. In Figure 2.7 the effects of current density (j) and time (t) on discharge specific energy (DSE)/charge specific energy (CSE) and RTE are shown [32].

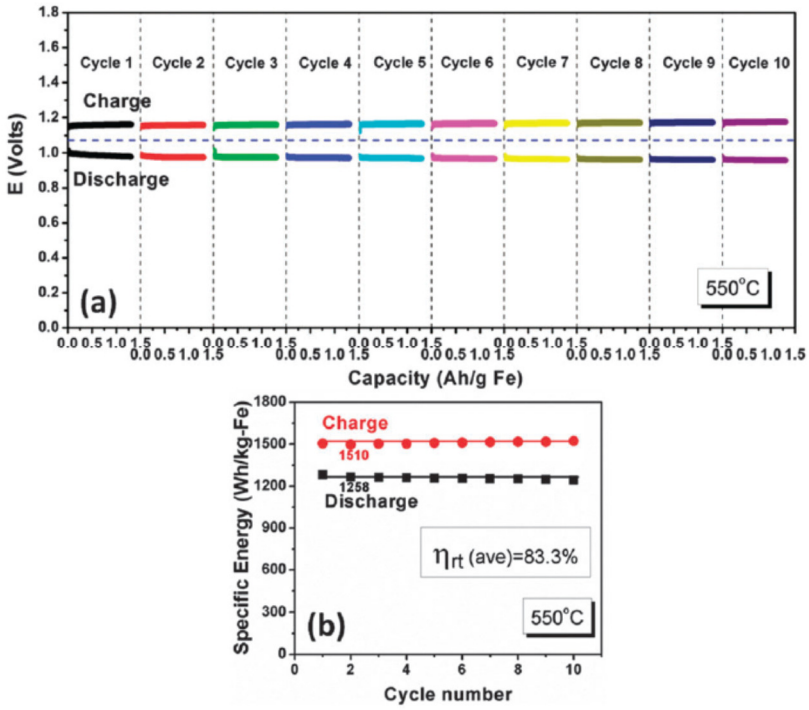

Figure 2.6 Cyclic performance of the Fe/C–air battery operated at 550℃ under a current density of 10 mA cm^2(a) E vs. charge capacity; (b) average specific energy vs. number of cycles [31].

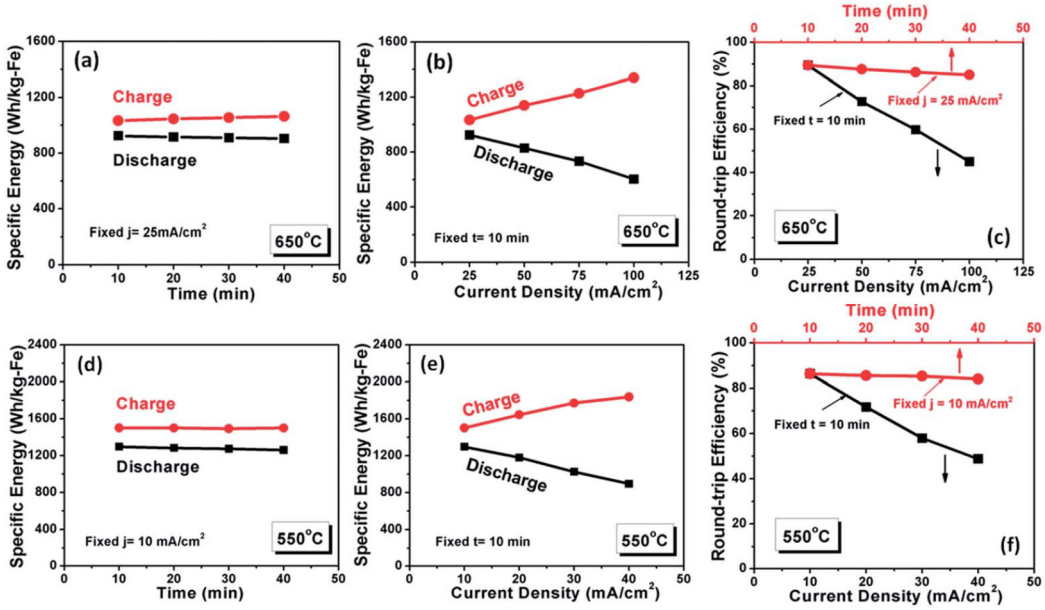

Figure 2.7 (a) DSE/CSE–t relationship with fixed j; (b) DSE/CSE–j relationship with fixed t; (c) RTE–t–j relationship of the battery measured at 650℃; similar relationships measured at 550℃ are shown in (d)–(f)[32].

In parallel to the laboratory investigations, some mathematical model also developed later to investigate the temperature effects, energy efficiency on SOFeARB [33],[34].

In this thesis, some initial performance assumptions were made in order to develop a cost model for such a battery. The cost model could also help a potential manufacturer to decide if there is a possible business case and identify components that could help drive costs lower.

CHAPTER 3
LITERATURE REVIEW ON TECHNO ECONOMIC ANALYSIS OF ENERGY STORAGE SYSTEM

Over decades, numbers of researcher have given a lot of effort on developing and evaluating new technologies of energy storage systems. So publications and reports on storage technologies and their applications are widely available. In this section we present a review on publications that provide cost estimations of energy storage systems. The cost estimation technique comprise a wide range of different approaches and procedures. Some cost model collect data from vendor and manufacturer and other collect data from existing reports.

Economic study on energy storage can be traced back in the mid-20th century. Arlie Graham Sterling developed a model to design a flywheel energy storage system for the grid peaking shaving application [35]. He first mentioned that the flywheel storage system was not economical and technically feasible for grid application. Later, The Sandia National Laboratories had started their energy storage system research at the end of 20th century [36]. Since then, the U.S. Department of Energy as well as Electric Power Research Institute (EPRI) had been developed a number of model to perform economic analysis of different kind of energy storage. Also reports published by the National Renewable Energy Laboratory (NREL) has significant importance in energy storage system. It can be seen that the technique of battery storage devices was improving gradually last century. But for the recent 15 years, the energy storage techniques have been developed rapidly and many

new researchers are getting involved in this area. The attention is to develop an energy storage system that can satisfy both cost and performance requirements.

In an extensive literature review, a number studies were associated that investigating economics of storage technologies across different applications. A lists of these studies are shown on Table 3.1. It provides information about different technologies, applications, input information and output parameters. Furthermore, it is investigate whether the publication provides a sensitivity analysis based on input parameters or not. For same technology, the lifecycle cost vary across publications. Because the cost analysis depend on application, data source etc.

Table 3.1 Publications on Techno economic analysis of battery technologies

Author, year	Source	EES Technologies	Applications	Input data	Output parameter	Sensitivity analysis
DOE/EPRI, Sandia Report 2015	[37]	PHS, CAES, flywheel, lead–acid, NaS, $NaNiCl_2$, Ni–Cd, Li-ion, Zn–Br, Fe-Cr, VRFB	Bulk energy service, Ancillary service, Transmission and distribution	Based on Previous EPRI published data	Present value, LCOE, Levelized cost of capacity	No
Abrams et al. (2013)	[37], [38]	Lead–acid, Li-ion, flywheel	T&D support and investment deferral, RES integration	Data from manufacturer and review, analyzed by their model	Total capital cost(per unit of power and energy) and O&M costs	No
Battke et al. (2013)	[38],[40]	Lead–acid, NaS, Li-ion, VRFB	Energy time shift, T&D support, frequency regulation, user-level storage	Data from review of other studies and manufacturers.	Costs of Storage, BOP and PCS cost O&M costs	yes

Hittinger, Whitacre, Apt, 2012	[40], [41]	Lithium-ion, sodium-sulfur	Frequency regulation, wind smoothing	Based on EPRI-DOE and manufacturer data[48]	Annualized cost of energy storage [USD]	No
Electricity Storage Association (2013)	[42][41]	PHS, CAES, flywheel, lead–acid, NaS, Ni–Cd, Li-ion	Energy storage	From plant operators	Capital cost of storage unit	No
Kintner-Meyer et. al., 2010	[40],[43]	Lithium-ion, sodium-sulfur	Balancing / ancillary services	Based on literature review (1996-2010)	Annualized cost of energy storage [USD]	Yes
Steward et. al., 2009	[40], [44]	Nickel-cadmium, sodium-sulfur, vanadium redox flow	Energy arbitrage	Input data based on EPRI-DOE [21], Schoenung and Hassenzahl [46], Schoenung and Eyer [46]	Levelized cost of electricity [USD/kWh]	yes
Poonpun, Jewell, 2008	[40], [44]	Lead-acid, sodium-sulfur, vanadium redox flow, VRLA, zinc-bromine	Generation, transmission and distribution level applications	Input data based on Schoenung and Hassenzahl [46] and manufacturer data	Levelized cost of electricity [USD/kWh]	no
Schoenung, Eyer, 2008	[40], [45]	Lead-acid (flooded / VRLAd), lithium-ion, nickel-cadmium, sodium-sulfur, vanadium redox flow, zinc-bromine	4 value propositions, mostly combined applications, e.g., T&Db deferral plus energy price arbitrage	Input data based on Schoenung and Hassenzahl [46] and manufacturer data	Levelized cost of electricity [USD/kWh	no
Schoenung, Hassenzahl, 2003	[40], [46]	Lead-acid (flooded / VRLAd), lithium-ion,	Bulk energy storage (load leveling / load management), distributed	Most data values derived from discussions with vendors /	Levelized cost of electricity [USD/kWh] and	no

		polysulfide bromide,	generation (peak	published	levelized costs of energy capacity [USD/kW] No / No 6	

CHAPTER 4
CONSTRUCTION OF COST MODEL OF SOLID OXIDE IRON AIR REDOX BATTERY

The main objective of this chapter is to provide a comprehensive cost analysis of solid oxide Fe–air redox battery (SOFeARB) storage system. A simplified diagram showing the full solid oxide iron air redox battery system in Figure 4.1. The schematic shows the major components of the battery system. The system consists of reversible solid oxide fuel cell (RSOFC) with energy storage couple, extra ESU materials store in separate tanks, and a pump which is needed to circulate air into the battery system. As the system is operating at high temperature (550°C), a thermal energy storage is considered in the battery system which can store heat from battery cycle.

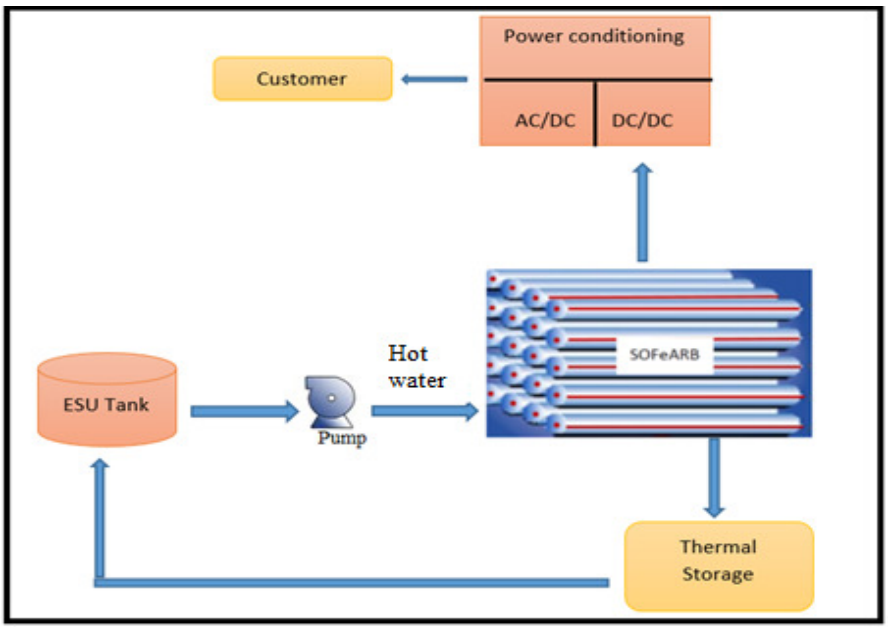

Figure 4.1 Simplified SOFeARB flow diagram.

The system cost was computed by considering the costs of its individual components. The battery system size and system characteristic was calculated based on some assumed performance characteristics.

4.1 DESIGN APPROACH

The cost analysis considers stationary solid oxide iron air redox battery (SOFeARB) system suitable for energy storage. The system consists of RSOFC, ESU, thermal storage unit, pump, balance of plant (BOP) and power conversion system (PCS). In Figure 4.2 the cost component of SOFeARB system is shown.

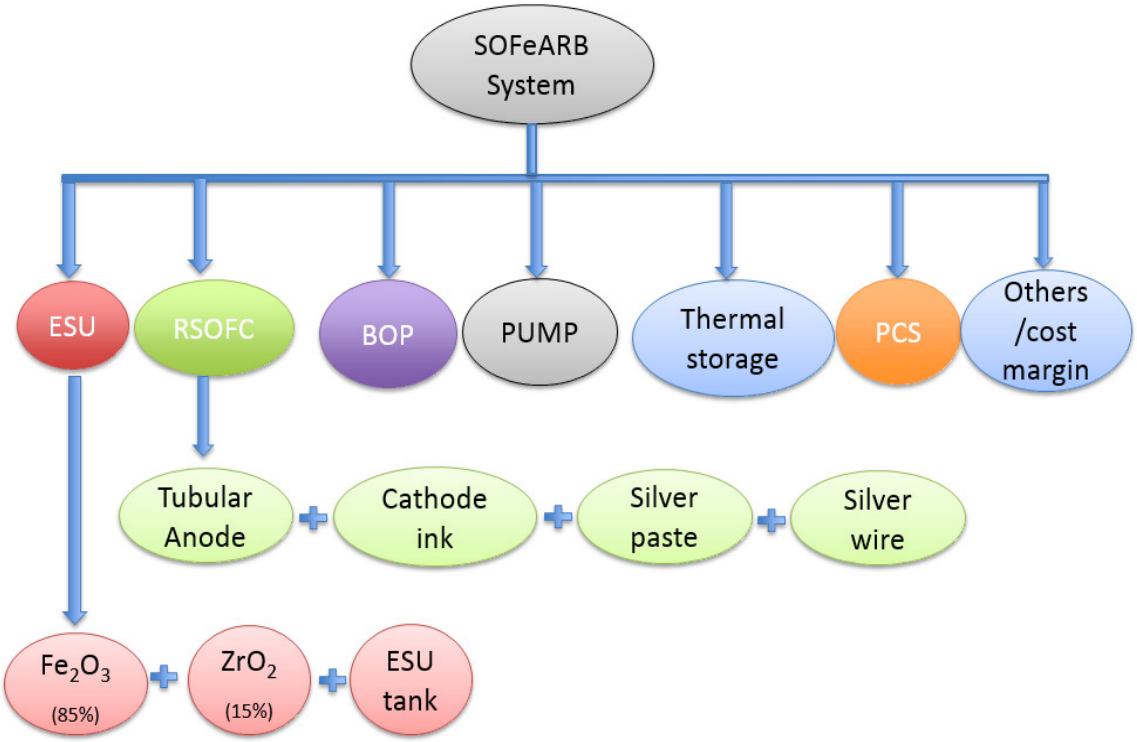

Figure 4.2 Cost component for SOFeARB system

The Fe–air redox battery system design was based on the following assumed system and performance characteristics.

Table 4.1 Assumed system and performance characteristics

System/Performance Characteristic	Value	System/Performance Characteristic	Value
Power capacity(P)	5 kW	Annual production	100,1000,10,000,50,000
Charge/Discharge duration(t)	10 hr	Electrode area(A)	231 cm^2
Nominal cell voltage(V)	0.83 V	External dia of tube(d_{out})	22.35mm
Current density(mA/cm^2)	100	Internal dia of tube(d_{in})	18.36mm
Porosity of ESU materials(ε)	50%	Effective Cell length(h)	409.48mm
Fe Utilization	20%		

Most of the assumed system and performance characteristics were chosen based on the V-I curve of 22.35 mm dia anode tube and rest of the characteristics were taken based on discussion with thesis supervisor.

RSOFC Reaction: $\frac{1}{2}O_2(g)+2e^- \underset{charge}{\overset{discharge}{\rightleftharpoons}} O^{2-}$

$$H_2(g)+O^{2-} \underset{charge}{\overset{discharge}{\rightleftharpoons}} H_2O(g)+2e^-$$

ESU Reaction: $3Fe+4O^{2-} \underset{discharge}{\overset{charge}{\rightleftharpoons}} Fe_3O_4+8e^-$

The first target is to calculate the number of RSOFC cell which can generate 5KW power. As the current density and voltage of cell given from experiments, the following formula can be used to determine the power density of cell

$$Power\ density = Current\ density * Cell\ Voltage = 100\frac{mA}{cm^2} * 0.83V$$

$$= 83\ \frac{mW}{cm^2}$$

Based on the power density and the electrode area, the nominal power per cell were calculated as follows:

$$Power\ per\ cell = power\ density * electrode\ area = 83\ \frac{mW}{cm^2} * 231cm^2$$

$$= 19.173\ W/cell$$

Next, the number of cells in the stack can be calculated based on the stack power capacity and power per-cell.

$$Number\ of\ Cell = \frac{Power\ Capacity(P)}{Power\ per\ cell} = \frac{5 * 10^3 W}{19.173W} = 261\ cell$$

The number of cells was rounded up to the next whole number since number of cells cannot be fraction in design. So, from above calculation 261 cell can generate 5kW power.

The next target is to calculate the quantity of ESU material which can store 50KWh energy. As it already mentioned, ESU material consists 85% Fe_2O_3 and 15% ZrO_2.

The quantity of current is an important parameter for battery design. The quantity of quantity of electricity or charge for current over specific time can be calculated as follows

$$Quantity\ of\ Electricity(Q) = Current(I) * Time(t\ in\ second)$$

We have

$$Current(I) = Current\ density\left(\frac{Amps}{cm^2}\right) * Electrode\ Area(cm^2) = 23.1Ams$$

So,

$$Quantity\ of\ Electricity(Q) = 23.1Ams * 10 * 60 * 60s = 831.6 * 10^3 coulomb$$

From Faraday's Law, we have

$$Moles(electron) = \frac{Quantity\ of\ electricity\ (Q)}{Faraday\ Constant(F)}$$

$$Moles(electron) = \frac{831.6 * 10^3}{96500} = 8.6\ moles$$

From ESU reaction, moles of Fe can be calculated using moles of electron in the following way

$$Moles(electron) = \frac{8}{3} * moles(Fe)$$

$$Moles(Fe) = \frac{3}{8} * moles(electron) = 3.23\ moles$$

By following operation, we can find the required amount of Fe to produce 100Ams/cm^2 current density per tube,

$$Mass(Fe) = Moles(Fe) * Fe\ atomic\ mass = 3.23 * 55.85 = 180gm$$

$$For\ 20\ \%\ utilization, weight\ of\ Fe$$

$$= (Weight\ of\ Fe\ which\ produce \frac{100Ams}{cm^2}\ in\ a\ cell)/0.2$$

$$= 902gm$$

$$Weight\ of\ Fe_2O_3 in\ a\ tube$$

$$= \frac{Molecular\ weight\ of Fe_2O_3}{2 * Atomic\ weight\ of\ Fe} * Weight\ of\ Fe\ in\ a\ cell$$

$$= \frac{159.69}{2 * 55.85} * 902gm = 1290gm$$

$$Weight\ of\ ZrO_2 in\ a\ tube = 227gm$$

$$Total\ weight\ of\ ESU\ material\ per\ tube$$

$$= Weight\ of\ Fe_2O_3 in\ a\ tube + Weight\ of\ ZrO_2 in\ a\ tube$$

$$= 1518gm$$

Using ESU material per tube and total tube number we can calculate total ESU material need to produce 50KWh energy

$$Total\ weight\ of\ ESU\ material$$

$$= Total\ weight\ of\ ESU\ material\ per\ tube * Number\ of\ Cell$$

$$= 1518 * 261gm = 396kg$$

Now we need to calculate how much ESU material can be inserted into the RSOFC tube. The density of Fe_2O_3 and ZrO_2 is 5.24gm/cm^3 and 5.68gm/cm^3 **Error! Reference source not found.**. As the density values are very close to each other, we take the density of iron oxides to calculate the amount of ESU materials that can store inside the cell. The amount of ESU materials per tube depend on the inside volume of the tube.

$$Inside\ Volume\ of\ Tube = \frac{pi * d_{in} * h}{4}$$

$$= \frac{pi * (\frac{18.36}{10})^2 * \frac{409.48}{10}}{4} cm^3 = 108.4\ cm^3$$

ESU materials contain some porosity. So the effective inside volume is lower than the actual inside volume. Considering Porosity,

$$Effective\ inside\ volume\ of\ tube = Inside\ Volume\ of\ Tube * (1 - porosity)$$

$$= 108.4 * (1 - 0.5) = 54.2\ cm^3$$

Using calculated effective volume of tube and density of Fe_2O_3, the actual weight of ESU material per tube can be estimated in following way

$$Weight\ of\ ESU\ material\ in\ tube = Fe_2O_3\ density * Inside\ Volume\ of\ tube$$

$$= 5.24\frac{g}{cm^3} * 54.2cm^3 = 284.033\ g$$

Using above calculated ESU material per tube and total tube number we can calculate actual amount of ESU material that can store 261 anode tube

$$Actual\ weight\ of\ ESU\ material\ that\ can\ store\ in\ RSOFC\ tube$$

$$= Total\ weight\ of\ ESU\ material\ per\ tube * Number\ of\ Cell$$

$$= 284.033 * 261g = 74.133kg$$

But, it has already been calculated that 386.193kg ESU material needed to produce 50kWh energy. Only 74 kg material can be inserted into the RSOFC tube. An extra storage tank can be used to store rest of ESU materials.

$$Weight\ of\ ESU\ material\ that\ needs\ storage\ tank = (396 - 74.133)kg$$

$$= 322kg$$

The capacity of storage tank can be calculated from the weight and density of ESU material.

$$Capacity\ of\ storage\ tank$$

$$= weight\ of\ ESU\ that\ store\ in\ tank * Density\ of\ Fe_2O_3$$

$$= 322 * \frac{1000gm}{\frac{5.24gm}{cm^3}} = 61407cm^3 = 61.4liter$$

As already mentioned ESU materials contain some porosity. So the actual volume of storage tank can be calculated by following ways,

$$Actual\ volume\ of\ Storage\ tank$$

$$= Calculated\ volume\ of\ storage\ tank/(1 - porosity)$$

$$= 61.4/(1 - 0.5) = 122.8\ liter$$

Finally, stack voltage can be calculated using the following formula

$$Stack\ Voltage = Cell\ Voltage * Nos\ of\ cell = 0.83V * 261 = 217V$$

Table 4.2 Calculated system and performance characteristics for a 5 kW/50 kWh SOFeARB System

System/Performance Characteristic	Value	System/Performance Characteristic	Value
Power density	83 mW/cm^2	Weight of Fe_2O_3 for 50kwh	336.5kg
Power per-cell	19.173 W	Weight of ZrO_2 for 50kwh	59.4kg
Number of cells	261	Stack voltage	217V
Capacity of ESU Tank	122.8liter	Specific energy	212.5Wh/kg-Fe

4.2 COMPONENT COST ESTIMATION METHODOLOGY

With the size and performance characteristics of the stack calculated, the next step is to calculate different component cost of the battery system. Component costs have been calculated based on some unit price assumption. There is a lot of uncertainties in unit price assumption. Because unit price changes vendor to vendor. According to S. Eckroad et al. there is some uncertainty in any cost methodology, because of cost gaps. There are gaps in the knowledge of even the best-informed investigators as far as cost estimates are concerned. In this type of assessment, there are two types of gaps: costs which are “known”

and understood by vendors, but which they consider secret or proprietary, and that they will not reveal to others. These might include costs for proprietary materials, manufacturing costs associated with proprietary processes, and expectations for future cost reductions through volume production. Costs which are unknown to both vendors and other interested parties, such as the future costs of commodity materials and costs for materials not yet developed. The cost will scale with a component proportional to power (RSOFC) and a component proportional to energy (ESU) [52]. The power capacity required for the battery will determine required power conditioning system (PCS) balance of plant (BOP) and pump. On the other hand, the energy capacity required for the battery will determine required ESU tank and thermal storage tank. RSOFC, ESU material and ESU tank costs are collected from manufacturer. On the other hand, cost for Power Conversion system (PCS) Balance of Plant (BOP), thermal energy storage and pump collected from literature search.

4.2.1 ESU cost for 5KW system

4.2.1.1 ESU material's cost

The Table 4.3 shows the unit price of iron oxide and zirconium oxide for 20 ton purchase volume. The unit price should be different for different manufacturing rate. But in this case no significant cost savings from volume purchase were assumed; because the ESU is a relatively small part of the overall cost and the unit price is for high purchase quantity(e.g. supplier provides this price if purchase quantity 20ton), volume pricing is unlikely to make a significant difference in overall cost .

Table 4.3 Assumed ESU materials cost

Materials	Price($/kg)	Source
Iron Oxide	$0.50	Alibaba.com
Zirconium Oxide	$4.00	Alibaba.com

As, the amount of iron oxide and zirconium oxide has already been calculated for 50KWh energy production, the total cost for the system shown in Table 4.4

Table 4.4 ESU materials cost calculation for 5KW/50KWh system

Materials	Unit Price($/kg)	Amount needed for 5KW system(kg)	Price($)
Iron Oxide	0.5	336.5	168.25
Zirconium Oxide	4	59.4	237.6
Total ESU price for 5KW system			405.85

The ESU cost was determined as price per kilogram iron, which is related to the energy through the operating specific energy of the system.

$$ESU\ cost\ per\ kg\ iron = \frac{total\ cost\ of\ ESU\ for\ 5KW}{Total\ amount\ of\ Iron\ for\ 5KW} = \frac{\$405.85}{235.34kg} = \frac{\$1.724}{kg - Fe}$$

Finally, the unit cost of ESU per kWh can be calculated based on total ESU cost and total energy of the system in the following way,

$$ESU\ cost\ per\ kwh, UnitCost_{ESU} = \frac{ESU\ cost\ per\ kg\ iron(\frac{\$}{kg\ Fe})}{Specific\ Energy(\frac{Wh}{kg\ Fe})} = \frac{\frac{\$1.724}{kg\ Fe}}{\frac{212.5\ Wh}{kg\ Fe}}.$$

$$= \$8.117/kwh$$

4.2.1.2 ESU tank cost

As already mentioned, a tank is needed to store the extra ESU materials. Stainless steel is considered as ESU storage tank material. Table 4.5 shows the storage tank cost assumption. As capacity of ESU storage tank for 50kWh system was calculated 122.8 liter, so the storage cost will become $20.5/KWh. Like ESU material no significance cost reduction assumed for volume production

Table 4.5 ESU tank cost information

Materia	Capacity(liter)	Source	Cost($)
Stainless steel	100	Alibaba.com	1000

4.2.2 RSOFC material's cost for 5KW system:

The cost of RSOFC depends on RSOFC tube and associated other materials. For RSOFC cost calculation, it is very difficult to get the tube price due to different manufacturing rate. But price for small quantity purchase of tube rather available. As the cost for high purchase quantity is unavailable, we collected price from vendor for small amount of purchase quantity, then convert it for different manufacturing rate using the learning curve factor. The learning curve function is defined as follows:

$$Y = aX^b \tag{4.1}$$

Where Y is the cumulative average time (or cost) per unit, X is the cumulative number of units produced (or brought), a is time (or cost) required to produce the first unit, b is the ratio of log of the learning rate and log of 2. Here Learning rate is assumed 96% [53],[54]. RSOFC materials cost are listed in Table 4.6.

Table 4.6 RSOFC material cost information

RSOFC Component	Cost ($/piece)	Cost basis
22.35 mm tubular anode	45	Coorstek.com
	Cost ($/kg)	
cathode ink (LSCFGDC-1)	2445	http://www.fuelcellmaterials.com/
Silver paste(C8829)	2620	http://www.heraeus-celcion.com/
	Cost ($/ft)	
Silver wire	0.35	http://www.artbeads.com/

The amount of cathode ink and silver paste needed per tube depend on the surface area of the tube. From vendor, cathode ink can cover 3-7m^2/g and Silver paste can cover 90cm^2/g surface area

$$Surface\ Area\ of\ Tube = \pi * d_{out} * h = \pi * \left(\frac{22.35}{10}\right) * \left(\frac{409.48}{10}\right) cm^2 = 287.51 cm^2$$

Using the surface area of tube and coverage of cathode ink, weight of cathode ink can be calculated using the following formula. Here we assumed area coverage of cathode ink 4 m^2/g

$$Weight\ of\ Cathode\ ink\ per\ cell$$

$$= \frac{Tube\ surface\ area}{Cathod\ ink\ area\ coverage} * cathode\ ink\ weight\ coverage$$

$$= \frac{287.51}{40000} * 1\ gm = 7.2 * 10^{-3}\ gm$$

Similarly

$$Weight\ of\ silver\ paste\ per\ cell$$

$$= \frac{Tube\ surface\ area}{Silver\ paste\ area\ coverage} * Silver\ paste\ weight\ coverage$$

$$= \frac{287.51}{90} * 1\ gm = 3.2\ gm$$

Now, using the above information,

$$RSOFC\ cost\ for\ one\ cell$$

$$= Tube\ cost + Cathode\ ink\ cost + silver\ Paste\ cost$$

$$+ silverwire\ cost$$

$$= \$\left(45 + 7.2 * 10^{-3} * \frac{2445}{1000} * 3.2 * \frac{2620}{1000} + 2 * 0.35\right) = \$53.5$$

Total RSOFC cost for 5KW system can be calculated based on RSOFC cost of one cell and number of cell of a 5KW system

$$RSOFC\ Cost\ for\ 5KW\ system$$

$$= RSOFC\ cost\ for\ one\ cell * \ Number\ of\ cell\ 5KW\ system$$

$$= \$53.5 * 261 = \$13941$$

Here, RSOFC cost is for one system and price assumed based on low purchase amount. For high manufacturing, need cost reduction factor to get real cost. So, we projected the above calculated cost for 100, 1000, 10000, 50000 production volume using learning rate 96%

First calculation for 50,000 production volume

$$Average\ RSOFC\ cost\ for\ 50{,}000\ production\ volume = price\ for\ one\ system *$$

$$Production\ Volume^{\frac{Log(learning\ rate)}{Log2}} = 13941 * 50{,}000^{\frac{Log0.96}{Log2}} = \$7371.4$$

$$RSOFC\ cost\ per\ KW, UnitCost_{RSOFC} = \frac{\$7371.4}{5kw} = \$1474.3/kw$$

For 10,000 production volume

$$Average\ RSOFC\ cost\ for\ 10{,}000\ production\ volume = price\ for\ one\ system * Production\ Volume^{\frac{Log(learning\ rate)}{Log2}} = 13941 * 10{,}000^{\frac{Log0.96}{Log2}} = \$8104.3$$

$$RSOFC\ cost\ per\ KW, UnitCost_{RSOFC} = \frac{\$8104.3}{5kw} = \$1620.85/kw$$

For 1000 production volume

$$Average\ RSOFC\ cost\ for\ 1{,}000\ production\ volume = price\ for\ one\ system * Production\ Volume^{\frac{Log(learning\ rate)}{Log2}} = 13941 * 1{,}000^{\frac{Log0.96}{Log2}} = \$9281.3$$

$$RSOFC\ cost\ per\ KW, UnitCost_{RSOFC} = \frac{\$9281.3}{5kw} = \$1856.3/kw$$

For 100 production volume

$$Average\ RSOFC\ cost\ for\ 100\ production\ volume = price\ for\ one\ system * Production\ Volume^{\frac{Log(learning\ rate)}{Log2}} = 13941 * 100^{\frac{Log0.96}{Log2}} = \$10629.2$$

$$RSOFC\ cost\ per\ KW, UnitCost_{RSOFC} = \frac{\$10629.2}{5kw} = \$2125.84/kw$$

4.2.3 Thermal Energy Storage

As SOFeARB is operated at very high temperature, a thermal energy storage has considered to achieve a heat balance in the system. Table 4.7 shows the price assumption for thermal storage

Table 4.7 Thermal storage price assumption [57]

Storage mediam	Temperature		Cost
	Cold(℃)	Hot(℃)	($/KWh)
Silica fire bricks	200	700	7

4.2.4 Power Conversion system

PCS converts DC power from the energy storage system to AC power for the grid during discharge. During charging, the inverse conversion takes place, i.e., grid AC grid power is converted to DC [48].

Several studies provide detailed explanation of PCS costs. According to Gyuk et al. type I PCS, is required for applications that must respond within 20 milliseconds and provide continuous supply and control of real and reactive power for durations greater than 30 seconds. The cost of this type PCS as a function of output power P (KW) is given by Equation (4.2) [50]

$$^{\$}/_{KW} = 300 * P^{-0.3} \tag{4.2}$$

For our cost model, PCS cost was taken from 257.8$/KW to 176.6 $/KW for different manufacturing rate [50].

4.2.5 Balance of Plant:

Balance of Plant includes structural and mechanical equipment such as protective enclosure, heating/ventilation/air conditioning (HVAC), and maintenance/auxiliary devices. Other BOP features include the foundation, structure (if needed), electrical protection and safety equipment, metering equipment, data monitoring equipment, and communications and control equipment. Other cost such as the facility site, permits, project

management and training may also be considered here [49]. Though Balance of plant (BOP) scope and cost components vary widely by site, application and technology, a BOP cost of $100/kW was proposed for underdeveloped systems, and $50/kW for developed systems [48]. A BOP cost of $100/kW was considered for our cost model for all production volume. As the cost assumption is from literature, the cost for BOP is not available for different volume production.

4.2.6 Pumps and flow control

A pump is needed to circulate steam and hydrogen into the battery system. The price for pump based on $/GPM or $/GPD. As the amount of hydrogen is very low, we only determine the volume of steam needs to circulate in the system. Then we can calculate pump flow rate using the volume of steam and time of circulation. From reaction of ESU and RSOFC, it is estimated that 36kg steam that is equivalent to 9.545 gallon need to circulate in the system to generate 5KW/50KWh. The following is the formulation for the pump flow rate

$$Pump\ flow\ rate = \frac{Volume\ of\ water}{Circulation\ time} = \frac{9.545gal}{12hr} = \frac{9.545gal}{0.5day} = 19GPD$$

Table 4.8 shows the pump cost assumption. If the pump operate in 80% efficiency, then actual pump flow rate can be calculated as follows.

$$Pump\ flow\ rate = \frac{19}{0.8}GPD = 23.75\ GPD$$

Table 4.8 Pump price assumption [55]

Component	capacity	cost	production volume
Pump	5GPD	$31/KW	10000

For 5KW system, we need 5 nos above mention pump. So the unit cost same for 5KW system. This is the cost for 10000 production volume. Learning curve formula (equation 4.1) was used to calculate cost for different production volume.

4.3 SYSTEM COST CALCULATION

The system total capital cost can be calculated using equation (4.3)

$$Cost_{total}(\$)=Cost_{pcs}(\$)+Cost_{BOP}(\$) + Cost_{RSOFC}(\$) + Cost_{ESU}(\$) + Cost_{ESUtank}(\$) + Cost_{Thermaltank}(\$) + Cost_{pump}(\$) \quad (4.3)$$

Where $Cost_{total}$ is total cost of the system; $Cost_{pcs}$, $Cost_{BOP}$, $Cost_{RSOFC}$, $Cost_{ESU}$, $Cost_{ESUtank}$, $Cost_{Thermaltank}$, $Cost_{pump}$ represent the cost due to power conversion system, balance of plant, reversible solid oxide fuel cell, energy storage unit, ESU tank, thermal tank and pump.

Table 4.9 shows the unit cost of different cost component of SOFeARB system for different production volume.

Table 4.9 A summarized list of unit cost of components considered for the cost estimation of a solid oxide iron air redox battery

Cost Component	100 system/year	1000 system/year	10000 system/year	50000 system/year
$Unitcost_{ESU}$($/KWh)	9.622	9.622	9.622	9.622
$Unitcost_{ESUtank}$($/KWh)	20.5	20.5	20.5	20.5
$Unitcost_{RSOFC}$($/KW)	2125.84	1856.3	1620.85	1474.3
$Unitcost_{thermaltank}$($/KWh)	7	7	7	7
$Unitcost_{PCS}$($/KW)	257.87	223.98	194.59	176.4
$Unitcost_{BOP}$($/KW)	100	100	100	100
$Unitcost_{pump}$($/KW)	40	35	31	28

The cost of the power conversion equipment is proportional to the power rating of the system

$$Cost_{pcs}(\$) = UnitCost_{pcs}\left(\frac{\$}{KW}\right) * P(KW) \tag{4.4}$$

Similar equation can be used for Balance of Plant, RSOFC and pump equipment's cost Calculation

For most systems, the cost of the storage unit is proportional to the amount of energy stored—

$$Cost_{storage}(\$) = UnitCost_{storage}\left(\frac{\$}{KWh}\right) * E(KWh) \tag{4.5}$$

Similar equation can be used for ESU tank and Thermal storage tank cost Calculation

When, the total cost of the system is known, it is possible to rewrite the capital cost in terms of the power rating and energy capacity:

$$Cost_{system}(\$/KW) = \frac{Cost_{total}(\$)}{P(kW)} \tag{4.6}$$

$$Cost_{system}(\$/KWh) = \frac{Cost_{total}(\$)}{E(kWh)} \tag{4.7}$$

4.4 ECONOMIC ANALYSIS

In this section, we present the economic assessment of SOFeARB when used as a storage Technology. Table 4.10 is listing the major assumptions in this economic analysis. Although the capital cost is vital, sometimes the levelized cost of electricity is more significant than capital cost of the system. The LCOE is the revenue for delivered energy

needed to cover all Life-cycle costs, and provide the target rate of return based on financing assumptions [47].

Table 4.10 Assumption for economic analysis

Economic characteristics	Values	Source
Discount Rate (%)	8.50%	[47]
Battery lifetime (years)	5	Based on tubular stack lifetime[55]
Levelized period (years)	20	Sandia National Laboratories[47]
Operation & Maintenance cost ($/KW)	15	Reference[22]
Cycle number (/year)	300	Assumption

Now, we calculate the levelized cost of electricity. Levelized cost of electricity (LCOE) can be determined by equation (4.8)[56].

$$LCOE\left(\frac{\$}{KWh}\right) = \frac{(Cost_{lifecycle})*U_{CRF}}{Q} \tag{4.8}$$

Where $C_{lifecycle}$, U_{CRF} and Q represent Total Life-Cycle Cost, Uniform Capital Recovery factor and Annual energy output or saved respectively.

Total Life-Cycle Cost Calculation life cycle cost can be determined by the following formula

$$Cost_{lifecycle}=Cost_{total}+ Cost_{Replacement}+Cost_{O\&M} \tag{4.9}$$

Here $Cost_{replacement}$ and $Cost_{O\&M}$ are the replacement cost and operation and maintenance cost of the battery.

Annual energy output or saved can be calculated by

$$Q = P(KW) * Cycle\ Time(hr) * Number\ of\ cycle(yr^{-1}) \tag{4.10}$$

Uniform Capital Recovery factor can be determined by

$$U_{CRF} = \frac{d(1+d)^N}{(1+d)^N - 1} \tag{4.11}$$

Where d and N represent interest rate and system lifetime in years.

4.5 SENSITIVITY ANALYSIS OF LEVELIZED COST OF ELECTRICITY

Sensitivity analysis, a technique used to determine how projected performance is affected by changes in the assumptions that those projections are based upon. It is very important to run sensitivity analysis to compare different scenarios of a project. We performed sensitivity analysis to explore different components which are significant to reduce cost. We performed sensitivity analysis on LCOE based on specific energy of battery, power density, Fe utilization, porosity of ESU materials charging/discharging time, lifetime and discount rate. Table 4.11 show the lower, baseline and higher estimate of sensitivity parameters.

Table 4.11 SOFeARB sensitivity data

Parameter	Lower estimate	Baseline estimate	Higher estimate
Discharging Time(hr)	6	10	14
Specific Energy Density	106.25	212.5	425
Discount Rate(%)	7.00%	8.50%	13.00%
Porosity(%)	30	50	70
Lifetime(yr)	3	5	10
Fe Utilization(%)	10	20	40
Power density(mW/cm^2)	41.5	83	166

CHAPTER 5
COST ANALYSIS RESULTS

5.1 CAPITAL COST OF ENERGY FOR SOMARB SYSTEM

The manufacturing cost of the SOFeARB calculated \$232 kwh^{-1} to \$309 kwh^{-1} for 5KW/50KWh system for different production rate per year. Figure 5.1 shows the capital Cost of Energy with different manufacturing rate per year. From figures, it can be seen that the capital cost per unit of energy output (\$/kWh) decreases dramatically with increasing manufacturing rate. As system manufacturing rate increase, system cost decreases. Almost 33 % cost reduction found with increasing manufacturing rate for both of the cases. Cost reduction would be high if we use higher system size (e.g.100KW).

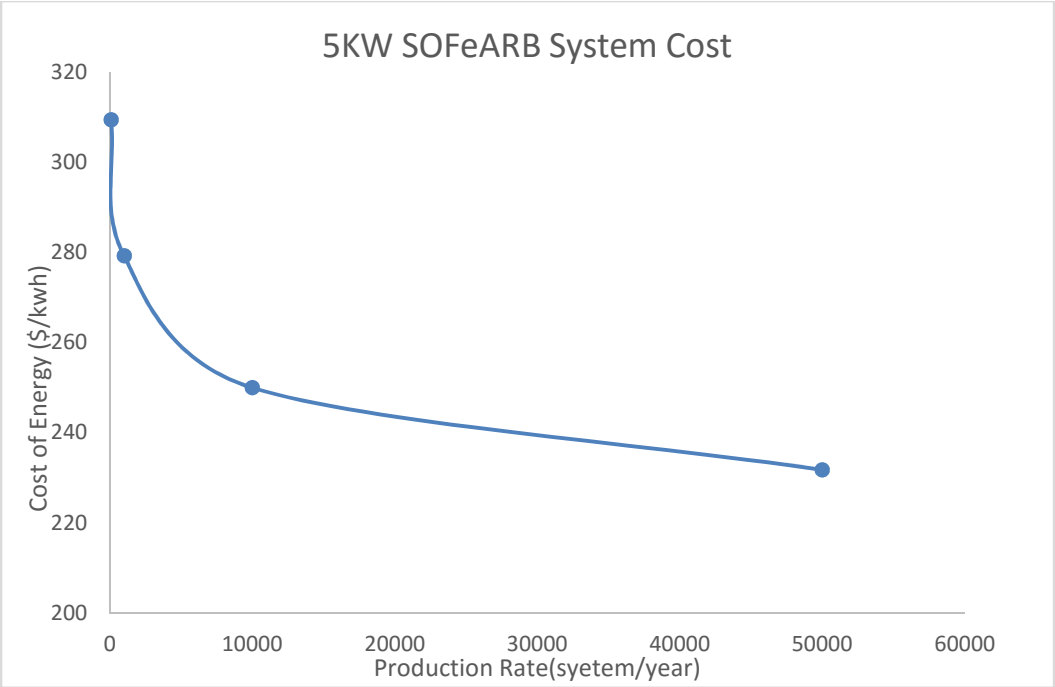

Figure 5.1 Cost Results for SOFeARB system

Figure 5.2 shows the cost breakdown of SOFeARB for 50,000 production rate. As evident from the figure, the greatest contributors to the capital cost of SOFeARB is the RSOFC units cost which is almost 64% of the system's capital cost. The second contributor is ESU storage tank cost which is only 9%.

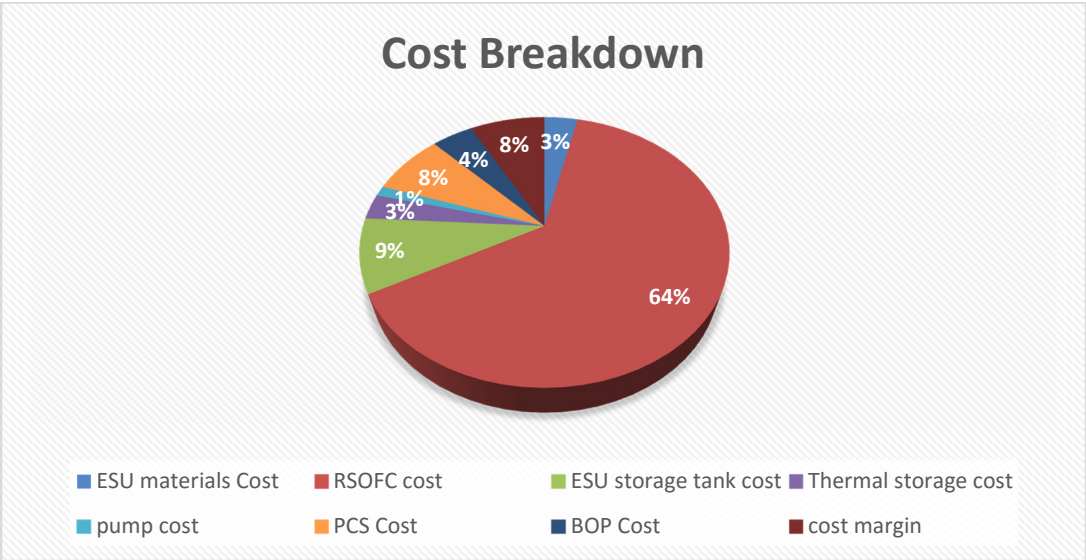

Figure 5.2 SOFeARB capital cost breakdown for 50,000 manufacturing rate

5.2 LEVELIZED COST OF ELECTRICITY FOR SOMARB SYSTEM

Although the capital cost is vital, sometimes the levelized cost of electricity is more significant than capital cost of the system. The LCOE is the revenue for delivered energy needed to cover all Life-cycle costs, and provide the target rate of return based on financing assumptions [47]. So the value of LCOE should be minimized, rather than minimizing capital cost. The lifetime for the SOMARB system is assumed as same as the RSOFC stack, which estimates the levelized cost as an over approximation. In a real system, the stack could be replaced without having to replace the entire system, which could decrease the levelized cost of electricity. Table 4.10 shows the economic assumptions for levelized cost calculation. The levelized cost of electricity for this system is found 27.5 ¢/KWh^{-1}cycle^{-1}.

As, DOE target for LCOE is 10 ¢/KWh/cycle, LCOE is little bit high comparing to DOE target. Though LCOE for the system is higher than the DOE target but its low if we compare it with other mature battery technology. Moreover, developer need to research how to reduce the SOFeARB system cost as DOE target. If we could reduce levelized cost of electricity in future, then the SOMARB system becomes more competitive than other energy storage systems.

5.3 SENSITIVITY ANALYSIS OF THE LEVELIZED COST OF ELECTRICITY

Sensitivity analysis tells us how sensitive the output value is to any change in an input. Here tornado diagrams is used to visualize the impacts of the different parameters. The most sensitive factor is at the top of the vertical axis. The baseline LCOE, which is $0.275/kWh-cycle, represented by the vertical line in the Figure 5.3 below. We observe that Power density, life time of storage and discharging time are the most sensitive factors for SOFeARB. The sensitivity to the power density is due to the large number of SOFC cell required for this power density. When power density is either doubled or divided in half, the net cost impact is the highest. To reduce the LCOE, we need to increase the power density per cell which can reduced the number of cell 5kW system. In addition to that, if we can reduce the unit price of RSOFC cell then the LCOE will also reduce. Lifetime has also a great effect on the LCOE, indicating the need for materials that can last for thousands of cycles. The battery system cost is also very sensitive to discharge time which means we need material that can store energy for longer time. We also consider four other parameters like discount rate, Fe utilization, porosity and specific energy to verify their effects. But, the total storage cost is not very sensitive to these parameters.

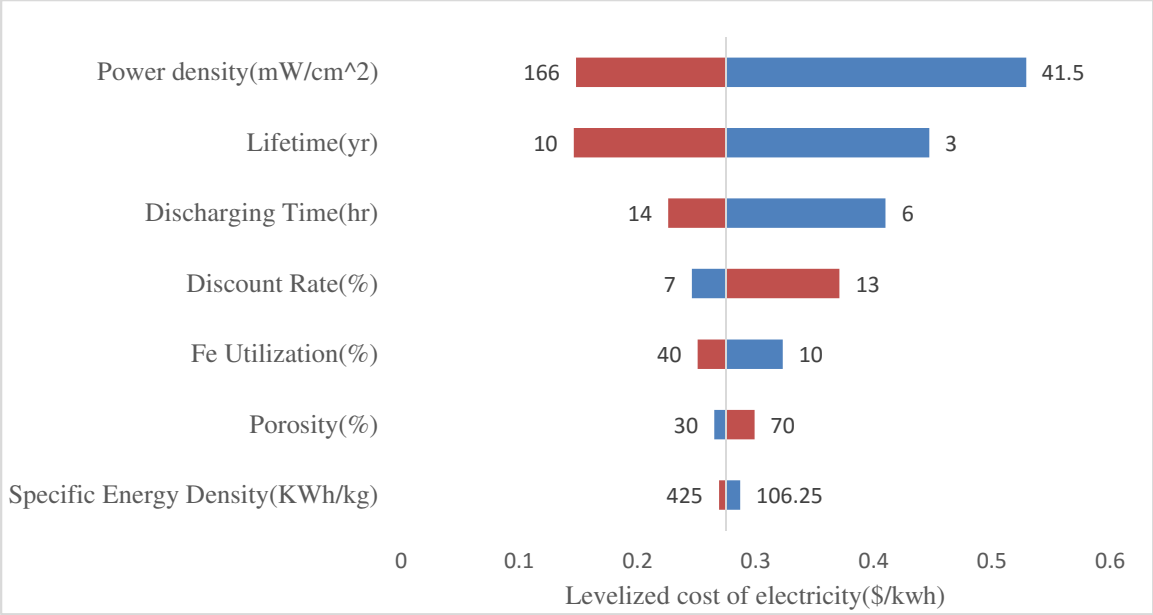

Figure 5.3 Sensitivity analysis of LCOE

5.4 COMPARISON WITH OTHER BATTERY SYSTEM

A number of storage technologies are commercially available and can be readily purchased from multiple vendors. Lead-acid batteries and lithium-ion batteries are the most common storage technology in small-scale (up to 10 MW) electrical systems. Though those are considered as a mature technology, we made a preliminary comparison with our battery in term of capital cost and LCOE. In this case, the LCOE calculation is based on only the total life cycle cost and total life cycle of the system. Because of simplicity we have not considered the discount rate. The specification of the system shown in Table 5.1.

Table 5.1 System Specification

Specification	Value
Stored Energy	50kWh
Discharge Power	5kW(or 10hours running time)
Cycling frequency	1 charge discharge/charge per day
Levelization period	20 years or 7300 cycles

Based on the estimated lifetime of the system, the lead-acid battery must be replaced 15 times (500 expected life cycle). Lithium-Ion need to replace 4 times during operation (2000 cycles are expected from the battery) and SOFeARB need to replace 6 times (1300 cycles assumed cycle life).

The cost per cycle, measured in $ / kWh / Cycle. From comparative analysis, the life cycle cost of SOFeARB is lower than other two mature technology for 60KWh system. The result is summarized in the table below:

Table 5.2 Comparative study

Parameter	Lead-Acid AGM	Lithium-ion	SOFeARB(
capacity	50KWh	50KWh	50KWh
Lifespan	500 cycles	1900 cycles	1500 cycles
Battery Cost($/KWh)	150.00	600	232
Battery Number	15	4	6
O&M Cost($\KW-yr)	15	25	15
Replacement Cost($\KWh)	2100	1800	4228
Total Cost	$106500.00	$122500	$71100
LCOE($/KWh-cycle)	0.292	0.336	0.195

5.5 COMPARISON WITH CONVENTIONAL SOFC SYSTEM

We assumed a conventional tubular SOFC system as Figure 5.4 which contains fuel tank, desulfurizer, SOFC stack, power conditioning unit. Generated power from the fuel cell system can be used by customer and/or can be stored in a battery system (e.g. Lead acid battery) for later use. By literature search, the SOFC system cost is nearly $3000/KW-$4000/KW [55]. The tubular SOFC looks alike our SOFeARB. But SOFeARB has dual

functionality, i.e. it is a battery as well as fuel cell. If fuel is supplied (oxygen and hydrogen), the cell can generate power as SOFC. Figure 5.5 shows the functionality of SOFeARB. Estimated capital cost of the system when operated as battery found $232/KWh.

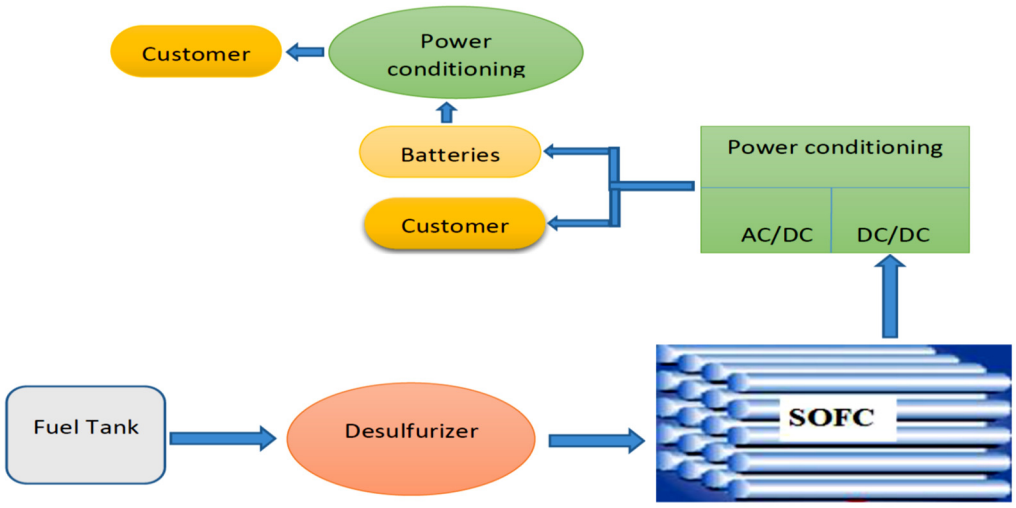

Figure 5.4 Conventional SOFC

Figure 5.5 Function of SOFeARB

Though conventional Tubular SOFC and SOFeARB have similar stack design, SOFeARB has some unique features like:

i. Energy Storage Unit (ESU) with Fe/FeO_x couple inside the tube makes the battery advantageous over tubular SOFC. In addition, Fe/FeO_x is cost effective ($1.5/kg) and environmental friendly.

ii. SOFeARB has duel functionality. It can be used as a battery for storing energy and it can also be used as power generation unit like fuel cell. On the other hand tubular SOFC is just a Fuel cell unit.

iii. In SOFeARB, the tube and ESU are physically separated, the tube or ESU could be replaced without having to replace the entire system.

CHAPTER 6
CONCLUSION

The aim of this research was to study the capital cost, LCOE and the effects of different parameter on the cost of SOFeARB. Specifically, the cost modeling methodology is developed in this work is demonstrated to support the analysis of different factors that have impact on manufacturing costs for SOFeARB systems. Cost models help researchers identify cost drivers, thus predictions of when these technologies will be usable. In addition, the installation of an energy storage system strongly depends on the economic viability of the system. Although the capital cost is high compare to ARPA-E target cost, the developer can improve the performance of battery based on the sensitivity analysis results, which can identify which components need to be modified or improved to lower cost. Summary of main observations are

i. The capital cost decreases with increase of production volume per year.
ii. The capital cost and LCOE is little higher than ARPA-E target cost. So further lowering capital cost and LCOE is needed to meet the ARPA-E target cost.
iii. Power density has the highest effect on the LCOE. The number of RSOFC tube is scaled with the power density of the cell. So if we want to reduce the capital cost of battery system we need to increase the power density per cell so that total number of cell can decreases for 5kW system. In addition unit cost of RSOFC tube is very high. So capital cost of SOFeARB can be reduced if we can fabricate RSOFC at lower price.

iv. Lifetime of the battery is another important factor which has great effect on LCOE. We assumed lifetime of SOFeARB five years which is based on SOFC lifetime. But the stack could be replaced without having to replace other components. Our assumption overestimated the capital cost.

v. Another important factor which increases the LCOE is discharging time of battery. The higher the discharge time the lower the LCOE would be.

vi. Some other factor like discount rate, Fe utilization, porosity and specific energy has negligible effect on LCOE.

REFERENCES

[1] http://www3.epa.gov/climatechange/ghgemissions/sources.html

[2] http://www.energyquest.ca.gov/story/chapter17.html

[3] D Rastler, Electricity energy storage application option, EPRI, 2010.

[4] EPRI-DOE handbook of energy storage for transmission and distribution applications. EPRI, 2003.

[5] Alaa Mohd, Egon Ortjohann, Andreas Schmelter, Nedzad Hamsic, Danny Morton. Challenges in integrating distributed Energy storage systems into future smart grid. IEEE International Symposium on Industrial Electronics, June 30 - July 2, 2008.

[6] Yang, Chi-Jen, and Robert B. Jackson. "Opportunities and barriers to pumped-hydro energy storage in the United States." *Renewable and Sustainable Energy Reviews* 15.1 (2011): 839-844.

[7] http://energystorage.org/energy-storage/technologies.

[8] Chi-Jen Yang, Pumped Hydroelectric Storage, Duke University. Retrieved from http://people.duke.edu/~cy42/phs.pdf

[9] http://energytopicstrends.blogspot.com/2014/07/pumped-hydro.html

[10] Ibrahim, Hussein, Adrian Ilinca, and Jean Perron. "Energy storage systems—characteristics and comparisons."*Renewable and sustainable energy reviews* 12.5 (2008): 1221-1250

[11] Chen, Haisheng, et al. *Compressed air energy storage*. INTECH Open Access Publisher, 2013.

[12] Ruddell, A., et al. "Flywheel Energy Storage Systems." *Rutherford Appleton Lab, UK*.

[13] Molina, Marcelo Gustavo.Dynamic modelling and control design of advanced energy storage for power system applications. INTECH Open Access Publisher, 2010.

[14] Winter, Martin, and Ralph J. Brodd. "What are batteries, fuel cells, and supercapacitors?" *Chemical reviews* 104.10 (2004): 4245-4270.

[15] Naveen Singamsetti, Sabri Tosunoglu, A Review of Rechargeable Battery Technologies.

[16] Shigematsu, Toshio. "Redox flow battery for energy storage." *SEI technical review* 73 (2011): 5-13.

[17] De Leon, C. Ponce, et al. "Redox flow cells for energy conversion." *Journal of Power Sources* 160.1 (2006): 716-732.

[18] Weber, Adam Z., et al. "Redox flow batteries: a review." *Journal of Applied Electrochemistry* 41.10 (2011): 1137-1164.

[19] Blurton, Keith F., and Anthony F. Sammells. "Metal/air batteries: their status and potential—a review." *Journal of Power Sources* 4.4 (1979): 263-279.

[20] http://www.superpower-inc.com/content/superconducting-magnetic-energy-storage-smes

[21] http://www.eolss.net/ebooks/sample%20chapters/c08/e3-14-02-00.pdf

[22] Akhil, Abbas A., et al. *DOE/EPRI 2013 electricity storage handbook in collaboration with NRECA*. Albuquerque, NM, USA: Sandia National Laboratories, 2013.

[23] KEMA, Market evaluation for energy storage in the united states : Retrieved from http://www.copper.org/about/pressreleases/pdfs/kema_report.pdf

[24] http://www.sandia.gov/ess/docs/other/Grid_Energy_Storage_Dec_2013.pdf

[25] http://www.eia.gov/forecasts/aeo/pdf/electricity_generation.pdf

[26] Zhao, Xuan.A new class of solid oxide metal-air redox batteries for advanced stationary energy storage. Diss. University of South Carolina, 2013.

[27] X. Zhao, N. Xu, X. Li, Y. Gong and K. Huang, RSC Adv., 2012, 2, 10163–10166.

[28] N. Xu, X. Li, X. Zhao, J. B. Goodenough and K. Huang, Energy Environ. Sci., 2011, 4, 4942–4946.

[29] X. Zhao, Y. Gong, X. Li, K. Huang, JOURNAL OF MATERIALS CHEMISTRY A 1(47):14858-14861

[30] X. Zhao, Y. Gong, X. Li, N. Xu, K. Huang, J. Electrochem. Soc., 160 (2013) A1241-A1247.

[31] X. Zhao, X. Li, Y. Gong, K. Huang, Chem. Commun., 2014, 50, 623 .

[32] Xuan Zhao, Xue Li, Yunhui Gong, Nansheng Xu and Kevin Huang RSC Adv., 2014, 4, 22621-22625.

[33] X. Jin, A.M. Uddin, X. Zhao, R. White, K. Huang, J. Electrochem. Soc. 162 (2015) A1476.

[34] Xinfang Jin, Xuan Zhao, Jingjing Tong, Farzana Yasmeen, Ralph E. White, Kevin Huang, Journal of Energy Storage 3 (2015) 1–9.

[35] A. G. Sterling. Flywheel energy storage for carrying the daily peak loads of electric power systems. 1949.

[36] http://www.sandia.gov/ess/publications/pubslist_06.html.

[37] http://www.sandia.gov/ess/publications/SAND2015-1002.pdf.

[38] Zakeri, Behnam, and Sanna Syri. "Electrical energy storage systems: A comparative life cycle cost analysis." *Renewable and Sustainable Energy Reviews* 42 (2015): 569-596.

[39] Abrams A, Fioravanti R, Harrison J, Katzenstein W, Kleinberg M, Lahiri S, et al. Energy storage cost-effectiveness methodology and preliminary results. California, USA: DNV KEMA Energy and Sustainability, California Energy Commission; 2013.

[40] Battke, Benedikt, et al. "A review and probabilistic model of lifecycle costs of stationary batteries in multiple applications." *Renewable and Sustainable Energy Reviews* 25 (2013): 240-250.

[41] Hittinger, Eric, J. F. Whitacre, and Jay Apt. "What properties of grid energy storage are most valuable?."*Journal of Power Sources* 206 (2012): 436-449.

[42] Electricity Storage Association (ESA). Electricity storage technology comparison Retrieved from: ⟨http://www.electricitystorage.org/⟩; 2013.

[43] Viswanathan, V., Xinxin Guo, and F. Tuffner. *Energy Storage for Power Systems Applications: A Regional Assessment for the Northwest Power Pool (NWPP)*. Vol. 19300. Pacific Northwest National Laboratory, 2010.

[44] Steward, D., et al. "Lifecycle cost analysis of hydrogen versus other technologies for electrical energy storage." *US National Renewable Energy Laboratory (NREL)* (2009).

[45] Poonpun, Piyasak, and Ward T. Jewell. "Analysis of the cost per kilowatt hour to store electricity." *IEEE Transactions on energy conversion* 23.2 (2008): 529-534.

[46] Schoenung, Susan M., and Jim Eyer. "Benefit/cost framework for evaluating modular energy storage." *SAND2008-0978* (2008).

[47] Schoenung, Susan M., and William V. Hassenzahl. "Long-vs. Short-term energy storage technologies analysis. a life-cycle cost study. a study for the doe energy storage systems program." *Sandia National Laboratories* (2003).

[48] Eckroad, S., and I. Gyuk. "EPRI-DOE handbook of energy storage for transmission & distribution applications."*Electric Power Research Institute, Inc*(2003).

[49] V Viswanathan, M Kintner-Meyer, P Balducci, C jin, National Assessment of Energy Storage for Grid Balancing and Arbitrage Phase II Volume 2: Cost and Performance Characterization.

[50] James, Brian D., Andrew B. Spisak, and Whitney G. Colella. "Manufacturing cost analysis of stationary fuel cell systems." *Strategic Analysis Inc. Arlington, VA* (2012).

[51] Gonzalez, A. "Ó Gallachóir B, McKeogh E, Lynch K. Study of electricity storage technologies and their potential to address wind energy intermittency." (2004).

[52] Eckroad, S. "Vanadium redox flow batteries: an in-depth analysis." *Electric Power Research Institute, Palo Alto, CA* 1014836 (2007).

[53] http://fas.org/news/reference/calc/learn.htm

[54] http://maaw.info/LearningCurveSummary.htm

[55] D. Herman, Fuel Cells: Identifying Promising Development Opportunities,A Product of EPRI solutions, Inc.1001243

[56] Walter Short, Daniel J. Packey, and Thomas Holt, A Manual for the Economic Evaluation of Energy Efficiency and Renewable Energy Technologies, NREL/TP-462-5173, 1995.

[57] http://www.nrel.gov/csp/troughnet/pdfs/uh_storage_overview_ws030320.pdf

[58] https://en.wikipedia.org/wiki/Iron(II,III)_oxide

[59] Ibrahim, H., & Ilinca, A. (2013). *Techno-economic analysis of different energy storage technologies*. INTECH Open Access Publisher.