Assessment of High-Temperature Self-Assembling Battery Implementation based on the Aluminum Smelting Process

by
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Submitted to the Department of Materials Science and Engineering
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Abstract

Renewable power sources are a promising alternative to the electrical generation by conventional sources of energy, limiting the emissions to the atmosphere and reducing the dependence on coal or oil. But some of these sources (wind or sun) have one major drawback, which is their variability.

Apart from that, electricity production has to match the demand at any moment, so the supply systems are built and operated to match the highest demand. Decoupling production from consumption can report great advantages and that is the main reason to develop cost-effective technologies that allow electricity to be stored on a large scale.

The high-temperature self assembly battery (also known as Liquid Metal Battery) is a promising technology. This battery works at high-temperature so that all its components are in liquid form. The absence of solid-liquid interfaces enables the achievement of high currents, apart from high diffusivities and fastest kinetics. That gives the battery the power of storing huge amounts of energy.

In order to evaluate the cost of these stationary storage systems, we are trying to look at similar electrolytic industrial processes, such as the Aluminum smelting processes. The Aluminum Hall-Héroult reduction cell has a configuration similar to the battery so we will base our estimation of the cost on this system.

The capital investment of an Aluminum Smelter will be analyzed in detail, and based on this, an estimation for the cost of the Liquid Metal Battery will be calculated.

Thesis supervisor: Donald R. Sadoway

Title: John F. Elliott Professor of Materials Chemistry

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To the friends I have made here and the ones I left back home, your support through the whole year has helped me to get the most of it. Thanks for believing in me.

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Abbreviations and Acronyms

ESS	Energy Storage System
LMB	Liquid Metal Battery
A	Amperes
V	Volts
MW	Mega Watts
kWh	Kilowatts per hour
Al	Aluminum
OCV	Open Circuit Voltage
F	Faraday constant
G	Gibbs Free Energy
H	Enthalpy
S	Entropy
PCS	Power Conversion System
BOP	Balance of Plant
DC	Direct Current
AC	Alternate Current
T&D	Transport and Distribution
PHES	Pumped Hydroelectric Energy Storage
CAES	Compressed Air Energy Storage
SMES	Superconducting Magnetic Energy Storage
EDLC	Electric Double Layer Capacitors
DOD	Depth of Discharge
LA	Lead Acid Battery
NAS	Sodium Sulfur Battery
VRB	Vanadium Redox Battery
I	Current
R	Resistance
LME	Local Metal Exchange
EPCM	Engineering, Procurement, Construction and Management
BOP	Balance of Plant
PV	Photovoltaic

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Chapter 1 Overview

1.1 Introduction

Electricity, unlike other commodities such as water, gas or steel, is difficult to store. The demand for electricity has constant daily and seasonal variations, and the maximum demand may only last a few hours each year (1). This is the main reason why electricity supply systems are built to operate so that production always matches demand. Without energy storage, the system has to be built in order to supply the highest demand. As a result, some power plants are only required to operate for short periods each year, causing great inefficiencies in the system. The production of electricity is also highly centralized and, often, a long distance away from its end users (2)

With Energy Storage Systems (ESS) electricity production can be decoupled from demand and it can help overcome other challenges such as (3)

- Improving low utilization of power facilities
- Relieving transmission congestion

- Improving the market potential of renewable energy generation
- Preventing losses from unreliable power quality for end-use consumer

Having large-scale electricity storage capacity available the system would need to be designed with a sufficient generating capacity to meet average electrical demand instead of peak demands. These peak demands could be covered by the ESS where energy is stored while the demand is below the average level.

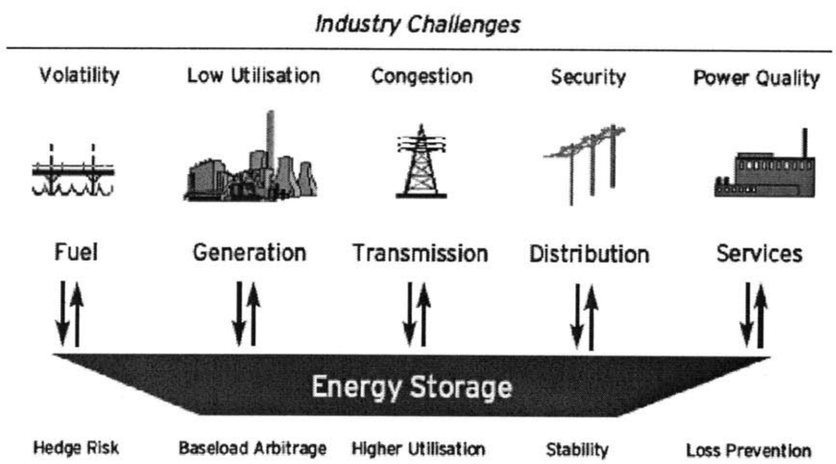

Figure 1-1 Energy Storage in the Electric Power Industry (4)

Enhancing grid stability can also encourage the use of large-scale ESS, avoiding situations such as regional blackouts, such as the one in Brazil and Paraguay in November 2009, which affected over 60 million people in Brazil (5) or the one that affected Germany, France, Italy, Belgium Spain and Portugal on November 2006, where over 15 million households were left without power after a big cascading breakdown (6).

Energy storage can be probably the best solution for these and other challenges, enabling better utilization of resources, better system efficiency, lower emissions, better reliability and security (1).

Nowadays there are several ESS, using different mechanisms to store the energy. A short review will be made of some of them since they are the competitors from the Storage System presented in this report.

Professor Donald R. Sadoway and his Research Group are currently working on the development of the so-called Liquid Metal Battery, a high-temperature self-assembling energy storage device with high energy/ high power capacity.

The technology, which will be analyzed in deeper detail later, can be explained as a battery whose components will be kept at high temperature so that they stay in liquid form. This configuration presents several advantages:

- liquid-liquid interfaces enable faster kinetics, faster ion transport, which leads to higher currents and higher storage capacity
- the absence of solid electrodes eliminates the problem of solid state degradation in electrodes, enhancing the lifetime of the battery

The inspiration for this new technology came from a very different one. A battery is an electrochemical device that transforms electricity into chemical potential energy and vice-versa. But there are other electrochemical processes that, although cannot be run in reverse has some other interesting features as the ability to sustain extremely high levels of electrical current over a sustained period of years.

Aluminum smelters have been running this process for more than a century. This thesis will focus on analyzing and understanding this technology and the cost structure of an aluminum smelter, and applying this information to develop a cost model for a grid-scale storage system based on the high-temperature self-assembling battery.

Chapter 2 will focus on the Liquid Metal Battery. Several aspects will be covered, including the cell design and operation and a better understanding of the battery as a part of the Energy Storage System will be given. A short review about applications and competing technology will also be included in order to be able to position this technology against its competitors.

The main topic dealt in Chapter 3 will be the production of Aluminum. The whole process will be analyzed, focusing on the reduction of Alumina in the Hall-Héroult cell and describing the structure of a smelter.

In Chapter 4, the cost structure of the Aluminum Industry will be analyzed, reviewing both the production cost as well as the capital investment required to build a smelter. This investment will be deeply analyzed up to the point where the results can be useful for the final aim of this work, reflected in Chapter 5, where a cost model for the Liquid Metal Battery is developed and analyzed. Sensitivity analysis will be made for a deeper analysis of the system.

In Chapter 6 main results and conclusions will be summarized as well as recommendations for future work.

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Chapter 2 The Liquid Metal Battery

2.1 Overview

The system described in this work consists of a new kind of battery, with some features that will make it highly robust, reliable, long lasting and cost effective (7).

The liquid metal battery resembles the Hall-Héroult cell, employed in the industrial reduction of aluminum, and it was this process which first inspired this new concept. A more detailed description of the Hall-Héroult cell will be given in section 3.3, but it is worth giving a brief description now.

Aluminum production in know to consume high amounts of electricity. Aluminum plants can consume up to 300,000A at 4V (1.2MW). This electrochemical process can be described as follows.

Aluminum oxide (alumina) can be obtained from bauxite trough the Bayer process.

Alumina undergoes later an electrochemical reaction, where the carbon anode is consumed in order to produce CO_2 and pure Al is produced, depositing at the bottom of the cell due to its higher density.

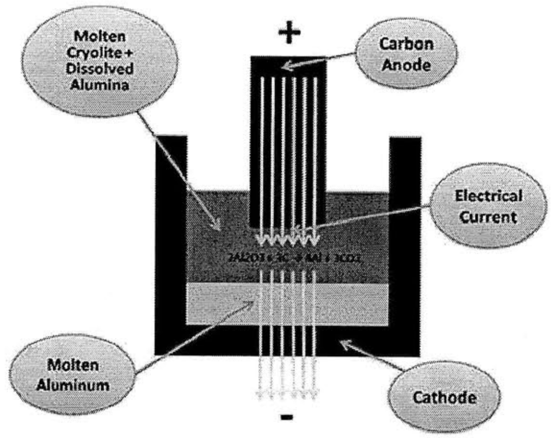


Figure 2-1 Aluminum Reduction Process (8)

The chemical reaction can be described as

$$2Al_2O_3 + 3C \rightarrow 4Al + 3CO_2$$

This is an irreversible process. CO_2 escapes due to its gaseous nature, so the carbon anode is consumed and has to be replaced frequently.

What if this process was made reversible? When run in reverse, the system could be used as a storage system, and energy could be injected back to the grid when required.

The reduction cells consist of an insulated rectangular steel shell. On the bottom of the cell sits the already reduced aluminum, acting as a cathode; above it, the electrolyte is comprised by a mixture of cryolite and molten alumina, while the anode is formed by carbon blocks. Current collectors are placed on the top and the bottom of the cell so that the electrical circuit can be closed. Above it all, the cell is covered to permit collection of off-gases.

Nevertheless, this battery has some features that differentiate it from the electrolytic production of aluminum.

Three layers of liquid metals and molten salt are placed inside a container. Due to the differences in densities of each liquid and the immiscibility between them, they will be able to separate naturally, enabling a much easier manufacturing process.

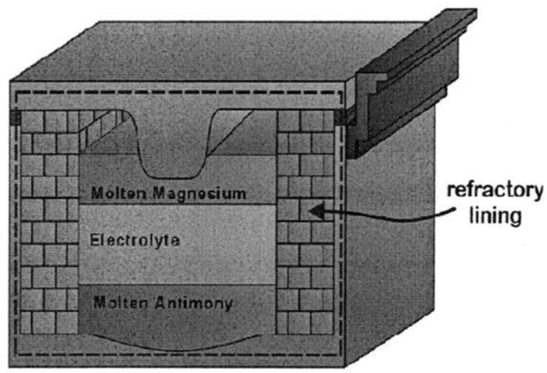


Figure 2-2 Liquid Metal Battery

The disposition of the layers of the battery can be described as follows:

The top and the bottom layers are respectively a low-density and a high-density metal alloys respectively, which will act as cathode and anode, while the middle layer will be a molten salt, acting as electrolyte.

This three all liquid layers disposition presents several advantages:

- Liquid-liquid interface enables faster kinetics. With faster ion transport, higher currents can be achieved, enabling huge energy storage capacity.
- The absence of solid electrodes presents another advantage. The most common problem in current batteries technologies related to lifetime is solid state degradation of the electrodes. If there is no solid electrodes, cycle life is expected to be highly increased.

2.2 Cell Operation

The battery operates at a temperature of about 700ºC. At this temperature, all three elements are in liquid state.

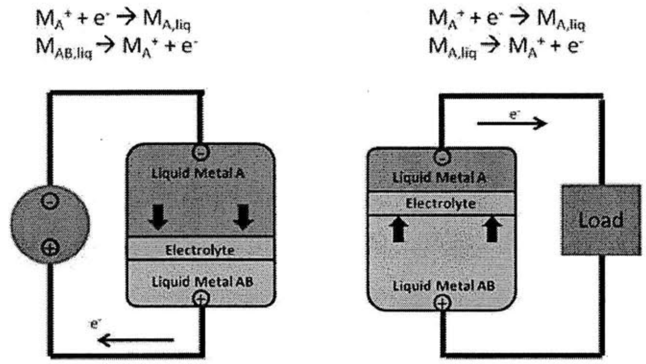


Figure 2-3 Diagram of the charging and discharging reactions of a LMB

The chemical reactions that take place during charging and discharging of the cell can be described as follows:

Charging reaction

$$M_{A^+} + e^- \rightarrow M_{A,liq}$$

$$M_{AB,liq} \rightarrow M_{A^+} + e^-$$

Discharging reaction

$$M_{A^+} + e^- \rightarrow M_{AB,liq}$$

$$M_{A,liq} \rightarrow M_{A^+} + e^-$$

While charging, the cathode ($M_{AB,liq}$) releases an electron and forms a positive ion (M_A^+), which travels through the electrolyte and recombines with an electron and transforms into anode material ($M_{A,liq}$).

During discharge, the process is reversed. An ion is formed at the anode (M_A^+) while an electron is released. The ion travels back through the electrolyte and recombines with an electron at the cathode, where forming ($M_{AB,liq}$) again.

One of the key characteristics of a cell is the cell potential, which along with the current is necessary to calculate the power of the cell.

The cell potential relates to the voltage difference between the terminals of the cell.

The Open Circuit Voltage (OCV) can be measured when the system is disconnected from a power supply or a load, and is a function of the level of charge or discharge of the cell. During charge or discharge the cell is subjected to slightly higher (charge) or lower (discharge) voltages than the OCV.

In order to calculate the OCV of a cell, there are several parameters that need to be determined.

The cell voltage or electromotive force (emf) can be written as two half-equation, a reduction equation and an oxidation equation:

$$E^0_{cell} = E^0_{reduction} + E^0_{oxidation}$$

The half-reactions for the Liquid Metal Battery can be written as

	Charging	Discharging
Reduction	$M_{A^+} + e^- \rightarrow M_{A,liq}$	$M_{A^+} + e^- \rightarrow M_{AB,liq}$
Oxidation	$M_{AB,liq} \rightarrow M_{A^+} + e^-$	$M_{A,liq} \rightarrow M_{A^+} + e^-$

Table 2-1 Half-equations for the Liquid Metal Battery

The dissociation potential (E^0) can be calculated by using the change in Gibbs free energy of formation

$$E^0 = -\frac{\Delta G^0}{nF}$$

where n is the number of electrons involved in the reaction and F is Faraday's constant, F=96,485C/mol.

The change in Gibbs free energy (ΔG^0) is related to two thermodynamic functions, enthalpy (ΔH^0) and entropy (ΔS^0), being all of them somehow temperature dependent.

$$\Delta G^0 = \Delta H^0 - T \cdot \Delta S^0$$

The "º" indicates a standard state where the activities of the components are unity or equal to one another, but does not specify a temperature. If the activity of the components differs from this standard state, it is required to use the Nernst equation, which relates the dissociation potential and the activity of the components.

For a given reaction $aA + bB \leftrightarrow cC + dC$, the Nernst equation can be written as:

$$E = E^o - \frac{RT}{n \cdot F}\left[\ln\left\{\frac{\mathrm{a_C^c \cdot a_D^d}}{\mathrm{a_A^a \cdot a_B^b}}\right\}\right]$$

Although the calculation of the cell voltage gives a theoretical value, this voltage is never achieved since there exist several mechanisms of voltage loss. The final voltage can be expressed as:

$$E = E^0 - \eta_{leak} - \eta_{act} - \eta_{ohm} - \eta_{mt}$$

- Leakage inefficiency (η_{leak}): partial short circuit (chemical or electronic) across the electrolyte
- Activation inefficiency (η_{act}): sluggish electrode kinetics
- Ohmic inefficiency (η_{ohm}): electrolyte or electrode resistance
- Mass transport inefficiency (η_{mt}): diffusion of active species to and away from the electrode interface

These losses are dependent on the current density of the cell, increasing with the current density of the cell.

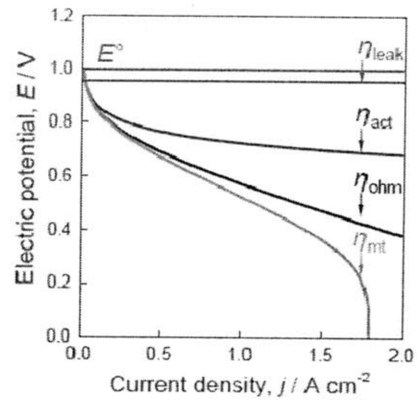


Figure 2-4 Mechanisms of voltage loss and their relation with current density (9)

The chemistry of the cell is therefore designed to minimize these losses, enabling a better performance of the battery. The liquid components and high temperature enable faster electrode kinetics, reducing the activation loss, as well as faster transport across the electrolyte, reducing ohmic losses.

2.3 Cell design

The design of the cell will be based on the design of the Hall-Héroult cell but adapted to the requirements of the system.

The materials for the cell are selected based on corrosion resistance, availability and low cost (7). The materials used as electrodes and electrolyte are still under research and therefore, several combinations of active materials will be analyzed in order to determine the best combination not only in terms of performance but also in terms of cost.

One of the requirements that the chosen materials have to fulfill is the difference in densities that allow the self-assembly of the cell upon melting. One of the electrodes need to have higher density than the electrolyte so that it stays at the bottom of the cell, while the density of the other electrode needs to be lower than that of the electrolyte so that it stays on the top of the cell.

Due to the characteristics of the cell, there are no initial reasons for the cell not to be scalable. The scalability of the cell is being researched, but for this study, it will be assumed that there is not limitation for the size of the cell in terms of cell surface. Nevertheless, the height of the cell (and therefore, volume of active materials) is determined by the energy capacity of the cell, which is related to the current density and discharge duration. The energy capacity is dependent on the volume of active materials (electrodes and electrolyte) present in the cell.

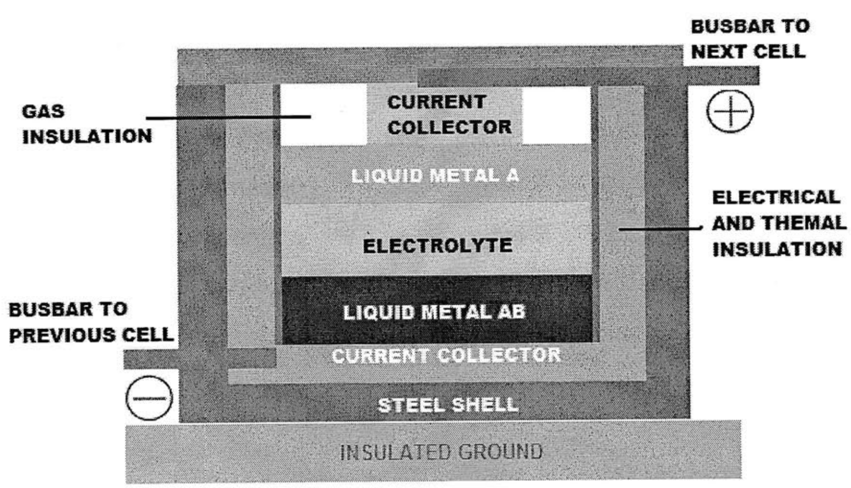


Figure 2-5 Conceptual Cell Design based on the Design of the Hall-Héroult Cell (not to scale)

The cell can be divided in several components:

- **Steel shell**: it serves as a container for the rest of the elements of the cell. It acts as the cell housing, giving mechanical support to the system.
- **Insulation**: it has two functions: regulate the heat losses from the bath and act as an electrical insulator. It also has to stand the high corrosive nature of the electrolyte.
- **Current collectors**: their main function is to allow the electrons to pass from the electrodes to the external circuit and vice versa.
- **Electrolyte**: it has to be immiscible with the materials that form the electrodes. It has to enable to movement of ions between electrodes but has to be electronically insulating.
- **Molten electrodes (Liquid Metal A and Liquid Metal AB)**: They are the active materials of the cell. They also enable to electrons to conduct from the current collectors to the electrode-electrolyte interface.
- **Gas insulation**: as result of the charge and discharge process, there is a slight change of volume of the molten components. This gas layer is intended to assume this volume change. It also acts as a protection against degradation of the top electrode.

In any case, the final design of the cell will be determined in the future, once it is clear the best combination of active materials to use, and being careful to get a good design that fulfills the requirement of heat dissipation to maintain the cell working at the right temperature.

This report will be based in the design and materials used at the Hall-Héroult cells currently used in the aluminum reduction industry, which have proven to have a long life (these cells operate in a continuous basis for several years) at higher working temperatures (around 950ºC).

2.4 The Energy Storage System

There is always the idea that the energy storage system is the battery by itself. The truth is that there are several subsystems that work together, each of them performing its own function and facilitating the overall operation of the storage system.

The complete system is therefore composed by these subsystems:

- Storage Medium (Active Materials)
- Power Conversion System (PCS)
- Balance of Plant (BOP)

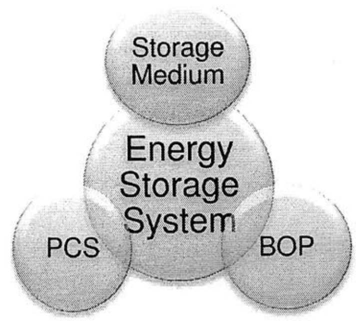


Figure 2-6 Energy Storage System Scheme

The Storage Medium is what we would call the battery itself. It is the energy reservoir where the chemical energy is stored. In terms of energy, high-density storage allows for smaller supporting equipment, which is very convenient for large scale applications.

The Power Conversion System is the electrical interface between the grid, the electricity source and the storage medium. Typical components include DC-AC converter (inverter), AC-DC converter (rectifier), DC and AC switchgears.

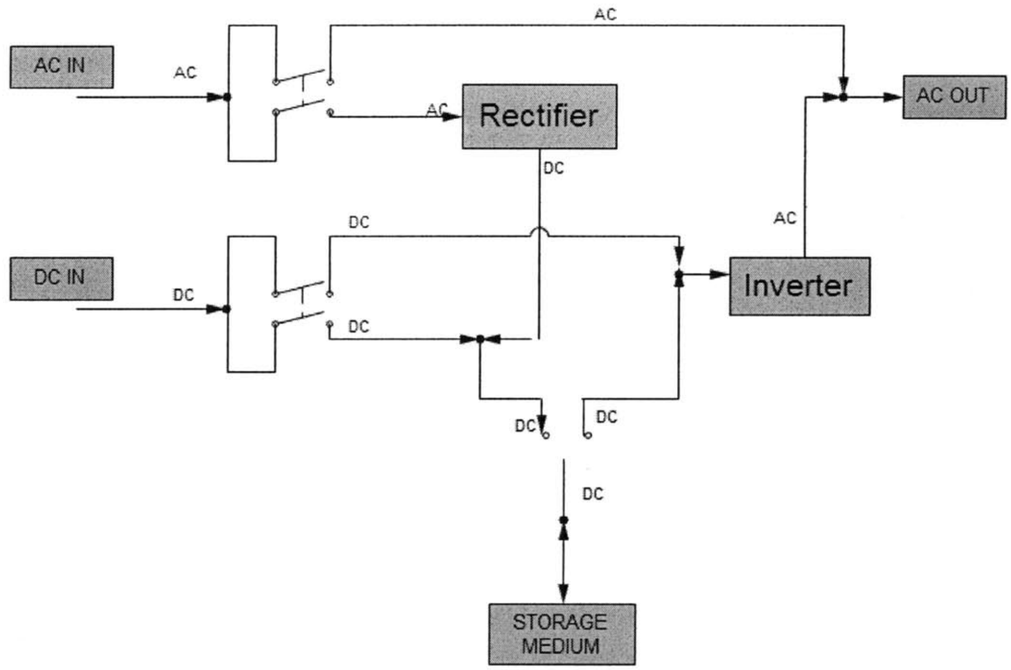


Figure 2-7 PCS Scheme with both AC and DC voltage input (DC voltage coming from Renewable Energy Sources)

The Balance of Plant is the facility and control system to house the ESS equipment. It includes transformers, electrical interconnects, surge protection devices, support racks for storage medium, control equipment…

Therefore, in order to account for the total cost of the storage system, we need to take into account each one of the subsystems.

The aluminum reduction process is a well known electrochemical industrial process. If the process could be run in reverse, a huge amount of energy could be stored in the system and be released back to the grid when needed. It is because of this that the Aluminum Smelter can be treated as a big energy storage system.

The following graph shows the aluminum reduction process where a subsystem formed by the power system, the reduction building and the aluminum itself is been treated as an energy storage system.

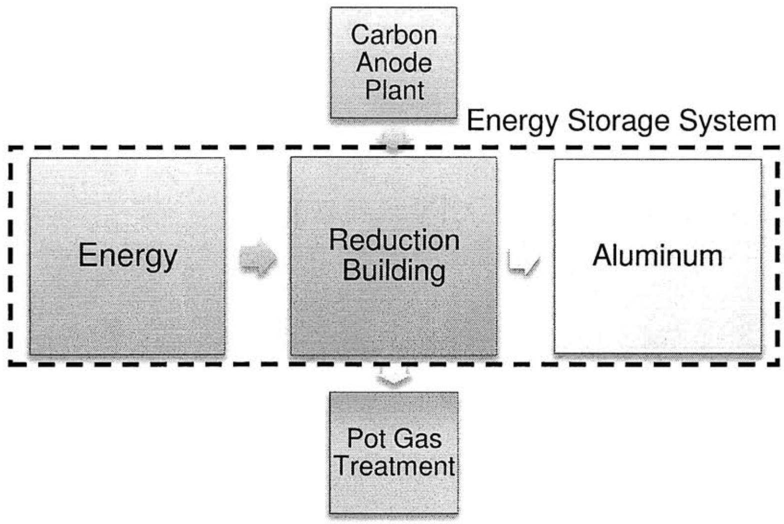


Figure 2-8 Aluminum Smelter acting as a Energy Storage System

The reduction building comprises a series of reduction cells that can be the equivalent to the battery cells in an energy storage system. The power from the electrical grid and is transformed from alternate current (AC) into direct current (DC) with the help of the power transformers and rectifiers.

In 4.3 capital cost of the aluminum smelter will be analyzed and it will be later compared with the expected capital investment of an energy storage system.

2.5 Characteristics of the Energy Storage System

There are several parameters that can help characterize the energy storage system, and enable the comparison between different technologies. Some of these parameters are listed here (10):

- *Unit size*: describes the intrinsic scale of the technology. It gives an idea of the suitability for small-scale or large-scale applications. If the unit size is small related to the required capacity of the project, the cost of the system can increase relative to the technologies with a larger unit size. At the same time, some technologies have a fairly large unit size that prohibits small-scale energy storage.

- *Efficiency*: is the ratio of energy output to the energy input. It can be defined as DC-DC efficiency or AC-AC efficiency depending on where the boundaries of the system are considered.

- *Cycle life*: is the number of consecutive charge-discharge cycles that the installation can undergo while maintaining the rest of the specifications within limited ranges. They are defined against a chosen DOD depending on the application of the device.

- *Specific energy*: measures how heavy the technology is. It is measured in units of energy per mass, and is usually reported in MJ/kg. The higher the specific energy, the lighter the device. In the case of the LMB, the device is suitable for stationary applications only, so this characteristic is relatively unimportant, although it can have some impact when considering stackabiliy of the cells.

- *Energy density*: measures how much space the technology occupies. It is measured in terms of energy per volume. The higher the energy density, the smaller the device. Once again, this is not very relevant to the LMB, as it is a stationary system.

In the case of our system, the size of the cell will be similar to the size of a modern Hall-Héroult cell (around 35m^2) with an initial cell power of 350kW and a cell capacity of 2,800kWh. A complete description of the characteristics of the cell will be given in 5.7

2.6 Applications and Competing Technology

The characteristics of this technology make it suitable for stationary systems only. The three-liquid-layers configuration does not allow the battery to be used in non-stationary systems, since the acceleration and deceleration of the system could lead to undesired flow of the liquid layers.

There are several applications where the proposed technology would be suitable. The following graph shows the range of possible applications for the system.

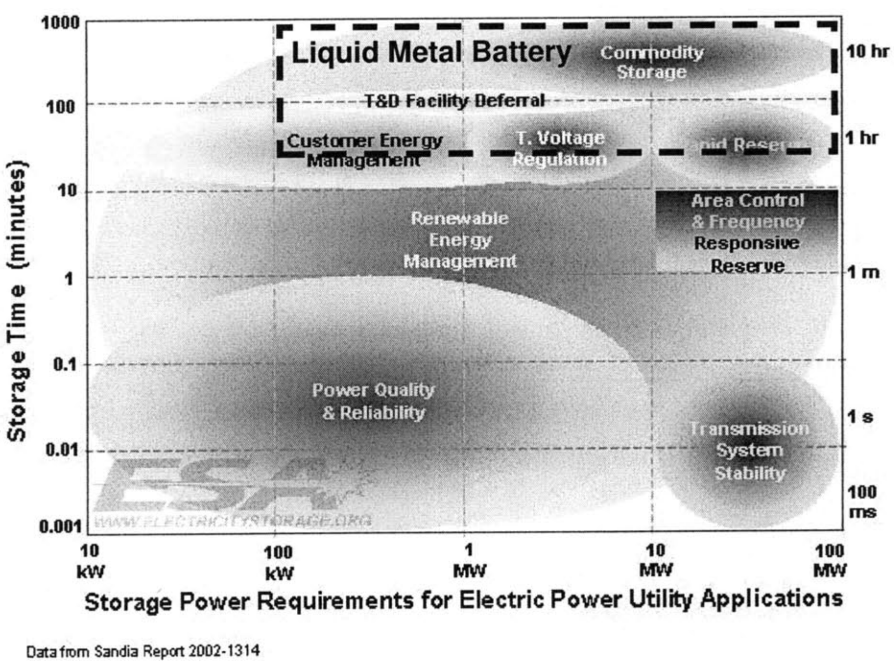


Figure 2-9 Applications for the Liquid Metal Battery [Modified from (11)]

From all the possible applications, the characteristics of the system make it suitable only for some of them, which include:

- Commodity Storage
- Customer Energy Management (UPS)
- Rapid Reserve
- T&D Facility Deferral
- Renewable Energy Management

In any case, the final design of the system will differ among applications, and will optimize the facility for that particular application. A short description of the different applications will be now given, although a deeper study and analysis of these applications is beyond the scope of this report.

Commodity storage, also known as peak shaving or load leveling is based on the daily fluctuations in the demand of electricity. In open electricity markets, electricity price follows demand. An energy storage device can generate revenue by purchasing electricity when it is cheaper (low-demand hours) and selling it back to the grid when the price is higher (peak hours). Load-leveling also permits the delay of the need of peak-load generators (with high marginal costs), enabling the base-load generators (with lower marginal costs) to maintain a constant production.

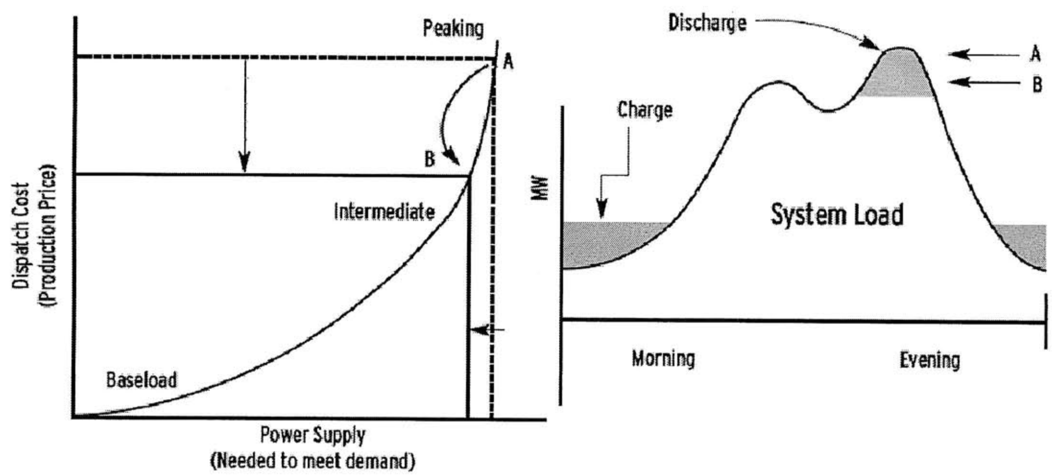


Figure 2-10 Energy Storage reduces Energy Prices, Peak Energy Demand is provided by the Energy Storage System (4)

For commodity storage, due to the characteristic of the generation facilities, only large-scale energy storage facilities measuring in the 100s of MWs with discharge endurance of many hours will most likely be successful (3).

In *Customer Energy Management (UPS)*, what is sought is to avoid any power outage that could cost the business millions of dollars. Uninterruptible Power Systems (UPS) are designed to supply energy to the facility in case of a power failure. A key requirement for this application is fast response time, as opposed to backup generators that require some time to reach full power. The system will need to supply full power for a short-time (5 to 30 minutes) while the main power source is reestablished or all the equipment is safely disconnected.

Rapid Reserve, also known as *Spinning Reserve,* is the generating capacity available in a short time in case a generator goes out of operation or any other disruption happens. The system is designed so that the group of generators has to be able to accommodate the loss of the largest generator in the group, and therefore, all the generators are working under their rated power, out of their optimum in efficiency. Having an energy storage device could reduce the need of over-sizing the generators, so that they could work at their rated power, increasing the efficiency of the grid.

T&D Facility deferral. When the demand for electricity approaches the capacity of the line, new lines and transformers have to be installed. These new lines and transformers are always larger than needed, so, as the demand grows steadily, the new facilities are underused for the first years of operation. A solution to avoid the installation of these new lines temporarily could be to install an energy storage facility close to the load center, and delay the installation of the new lines until it is economically justified.

In terms of *Renewable Energy Management*, there are two ways of enhancing the value of energy produced by renewable sources, such as wind or sun. These sources are weather dependent and intermittent so they need a storage device to be competitive. Electricity can be used therefore when needed and the storage device can enhance the quality of wind power, which due to its variability sometimes has problems with voltage and frequency. Besides, the energy storage device could act as a 'time-shifter' storing the electricity when its price is low and selling it back to the grid when it is high.

A deeper analysis of these applications can be made in order to study the suitability of the proposed energy storage technology, but this work is beyond the scope of this report but can be recommended as future work.

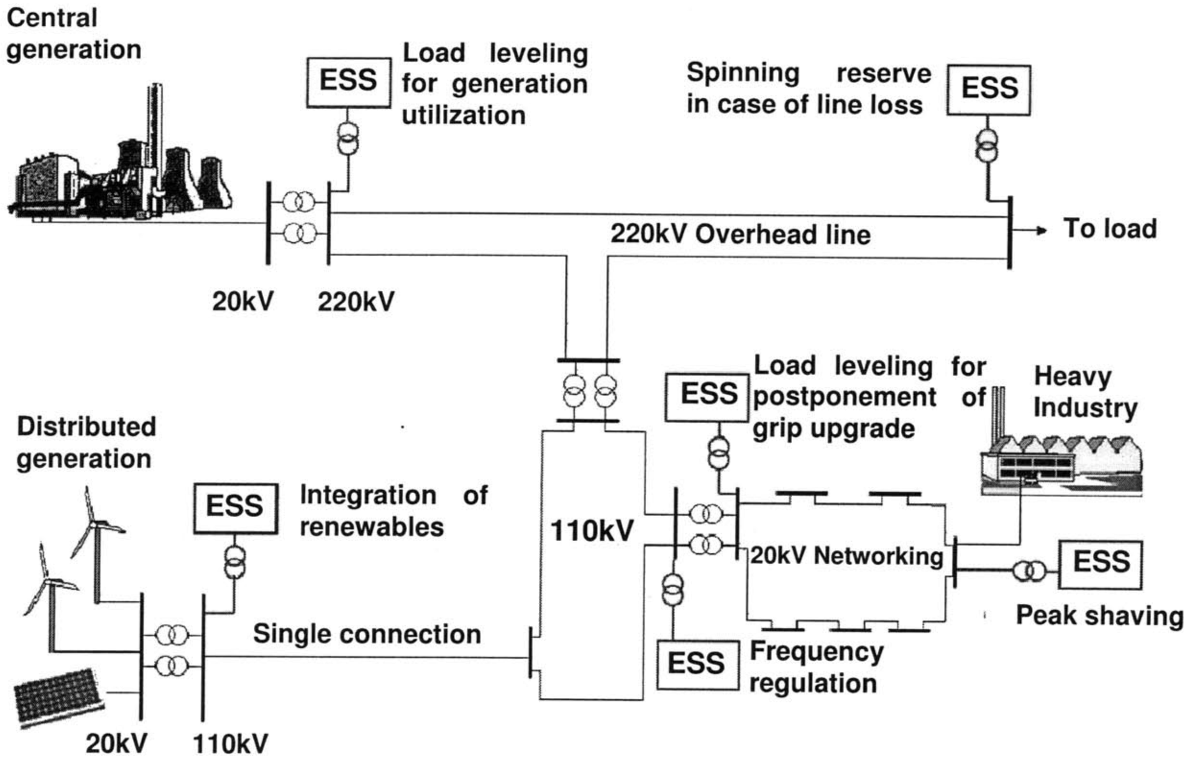


Figure 2-11 Energy Storage System Applications (12)

Nowadays there are several operating technologies allowing energy storage (13):

· **Pumped hydroelectric energy storage (PHES)**: it is the largest energy storage technology that is commercially available. Conventional systems comprise a reversible pump-turbine generator-motor and two large reservoirs at different levels. The reservoirs are connected to each other by water conduits via a pump-turbine. During off-peak periods, water is pumped from the lower reservoir to the upper reservoir, while during peak hours, the water is released back to the lower reservoir, thus generating electrical power.

· **Compressed air energy storage (CAES)**: it uses pressurized air as the energy storage medium. An electric compressor is used to pressurize the reservoir using off-peak energy, while air is released from the reservoir through a turbine during peak hours. Aquifers and caverns are used as storage locations, while small systems can use pressurized tanks.

· **Superconducting magnetic energy storage (SMES)**: these systems store energy in the field of a large magnetic coil with DC current flowing. DC can be converted back to AC when needed. Low temperature SMES cooled by liquid helium are commercially available.

· **Electric double layer capacitors (EDLC)**: electrostatic energy is stored in an electric double layer capacitor. The energy density is lower than that of secondary batteries, but it is suitable for fast discharge and charge applications as compared to secondary batteries.

· **Flywheel:** it is an electromechanical device that couples a motor generator with a rotating mass to store energy for short durations. The device is 'charged' and 'discharged' via an integral motor/generator. During a power outage or other disturbance, the kinetic energy stored in the rotor is transformed into DC electric energy by the generator and the energy is delivered at constant voltage and frequency through an inverter and a control system.

· **Batteries**: there are several types of batteries, which one of them has its own particular operational range and capability. Some examples of batteries are (3):

- *Lead Acid batteries:* there are two main types, flooded and valve-regulated. There batteries have high reliability and low cost, what make them suitable for a wide variety of market applications, although MW-scale facilities have been predicted to have operational difficulty. The average DC-DC round-trip efficiency is 75% to 85%, and a useful life of 250-1,000 charge/discharge cycles, being degraded by temperature, depth of discharge, fast cycling and other factors. LA batteries are the cheapest energy storage technology, although due to their short life, they can sometimes become more expensive than alternative technologies.

- *Nickel-Cadmium batteries:* these batteries are slightly more expensive than lead acid batteries, but they have better operating capabilities and reliability and longer cycle life, allowing for lower ownership cost. They have been proven to be suitable for large-scale energy storage[1] for frequency and voltage regulation applications. The average DC-DC round-trip efficiency is 60% to 70% and cycle life of 1,000-3,500 charge/discharge cycles, although at low depth of discharge (DOD) life cycle expectations can reach 50,000 cycles.

- *Flow batteries:* they store and release energy through a reversible electrochemical reaction between two electrolytes. In these batteries, power (MW) and energy (MWh) ratings are independent of each other in the unit's design. The power is related to the number of cells while the energy storage capacity is determined by the size of the electrolyte tank. As they are highly flexible, they can support a wide variety of applications in diverse markets. Vanadium redox flow batteries have an efficiency around 85%, with a cycle life of at least 10,000 charges and discharges; Zinc-bromine flow batteries have an efficiency around 80% and a cycle life of at least 2,000 charges and discharges; Polysulfide bromide flow batteries have an efficiency approaching 75% and an estimated life around 15 years; Cerium zinc flow batteries have a DC-DC efficiency of 70% and an estimated life of 15 years.

- *Sodium Sulfur (NAS) batteries:* these batteries present an average round trip efficiency of 90%. It works at a temperature of 320ºC to 340ºC and an output voltage of 2V. Unless other chemical batteries, it has no memory effect or self-discharge. NAS systems can provide power either in a single, continuous discharge or in a larger but shorter pulse of power which allows the system to perform a variety of market applications.

The following table shows a comparison of these battery systems, based on a 1-MW system operating 8h/day.

[1] The 40-MW Golden Valley Electricity Association facility

System	Cycle Life	AC-AC Round trip efficiency (%)	First-Time Capital Cost ($/kWh)	Environm. Risk	Usual DOD (%)	Deep Discharge Capability (>70%)	20-Year Capital and Operating Cost[2] ($/kWh)
Pb-acid[3]	2000	45	1550	Medium	25	No	11,769
Ni-Cd	10800	65	2000	Medium	30	No	4,644
Li-ion[4]	20000	85	2700	Very little	40	Yes	2,541
NaS	3000	58	500	High	33	Yes	5,003
Zn/Br_2	2500	60	1200	High	33	Yes	7,828
VRB	10000+	72	630	Very little	55	Yes	3,078

Table 2-2 Battery Systems Comparison (13)

In the last column, the costs calculated for a 20-year operation time are reported, showing that the systems with longer life have lower costs, making obvious that any extension of the battery life is a key factor to reduce overall costs (13).

The following graph shows the state of development of the different energy storage systems as well as their power capacity.

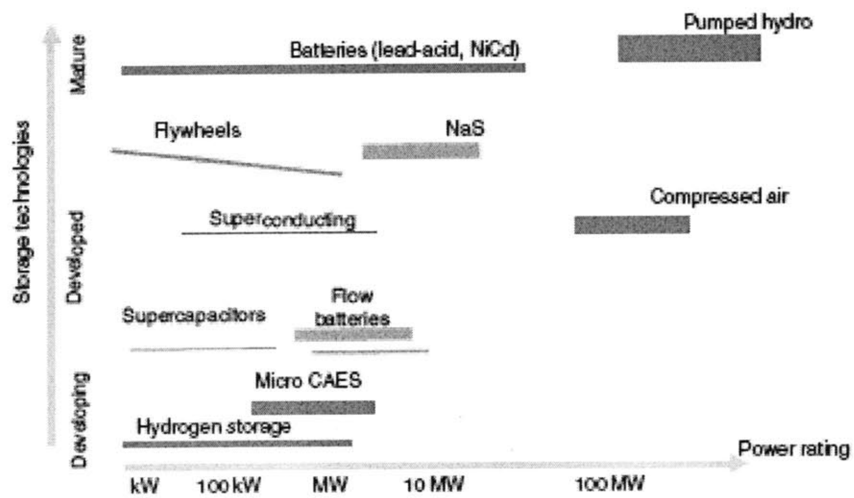


Figure 2-12 Development status and power capability of several energy storage systems. The width of the bar indicates storage capacity (13)

[2] At a cost of $0.05/kWh in the first year escalating at 3% per year with 8h per day of operation and a 20-year life of 10800 cycles

[3] Industry standard

[4] Small systems

All these energy storage technologies have very different performance characteristics, increasing the difficulty of comparison among them.

For applications that involve frequent charge/discharge cycles, such as load leveling, the best way to evaluate the cost of storing energy is to compare the per-cycle cost.

The following graph shows the relationship between capital cost, cycle life and efficiency. After evaluating the expected cost for the Liquid Metal Battery, it will be compared with these technologies.

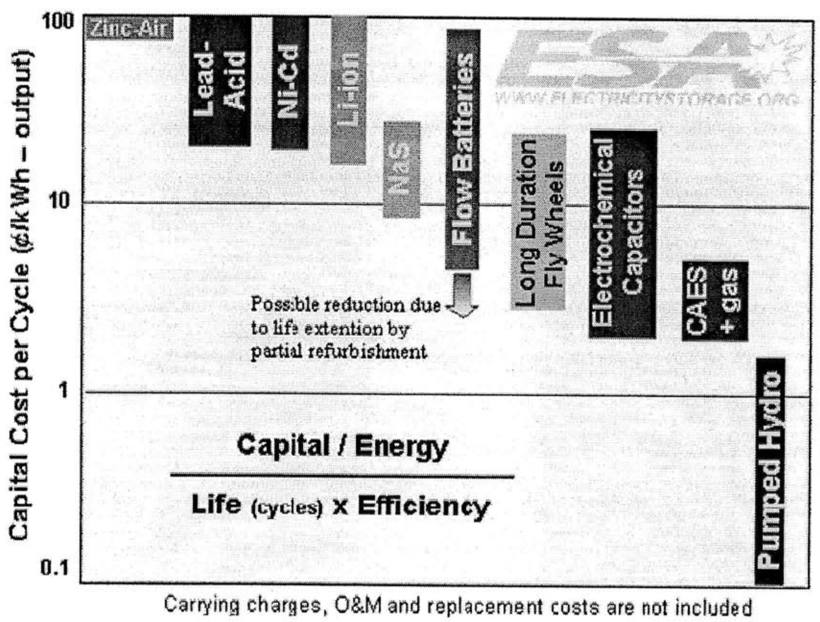


Figure 2-13 Per-cycle cost for different Energy Storage Systems (11)

In any case, every technology has different advantages and disadvantages that make them suitable for a certain range of applications. The following chart shows the different storage technologies, their advantages, disadvantages and possible applications.

Storage Technologies	Main Advantages (Relative)	Disadvantages (Relative)	Power (Application)	Energy (Application)
Pumped Storage	High capacity, low cost	Special Site Requirement		●
CAES	High capacity, low cost	Special Site Requirement, Need Gas Fuel		●
Flow Batteries	High capacity, Independent Power and Energy Ratings	Low Energy Density	◗	●
Metal-Air	Very High Energy Density	Electric Charging is Difficult		●
NaS	High Power & Energy Densities, High Efficiency	Production Cost, Safety Concerns (addressed in design)	●	●
Li-ion	High Power & Energy Densities, High Efficiency	High Production Cost, Requires Special Charging Circuit	●	○
Ni-Cd	High Power & Energy D		●	◗
Other Advanced Batteries	High Power & Energy Densities, High Efficiency	High Production Cost	●	○
Lead-Acid	Low Capital Cost	Limited Cycle Life when deeply discharged	●	○
Flywheels	High Power	Low Energy density	●	○
SMES, DSMES	High Power	Low Energy density, high production cost	●	
E.C. Capacitors	Long Cycle Life, High Efficiency	Low Energy density	●	◗

● Fully capable and reasonable ◗ Reasonable for this application ○ Feasible but not quite practical or economical

Table 2-3 Advantages and Disadvantages of different Energy Storage Technologies (11)

3

Chapter 3 Aluminum: The Solid Electricity

3.1 Introduction

Aluminum (Al), sometimes known as solid electricity (14), is the most abundant metal of the Earth's crust, comprising about 8.3% by weight of it. It does not exist as a metal in nature, due to its high affinity to oxygen. It is mainly found in bauxite ore, which contains hydrated forms of aluminum oxide, notably gibbsite ($Al_2O_3 \cdot 3H_20$) and boehmite ($Al_2O_3 \cdot H_2O$). The composition of the bauxite ore varies with the location of the deposit but its content in alumina (Al_2O_3) stands between 40% and 60%. Some of the highest quality bauxite deposits in Australia, Brazil, Guinea and Jamaica can present higher concentrations of alumina.

Although aluminium is now the second most used metal, it could be considered a 'newcomer' among the common metals, because of the difficulty in extracting it from its ores.

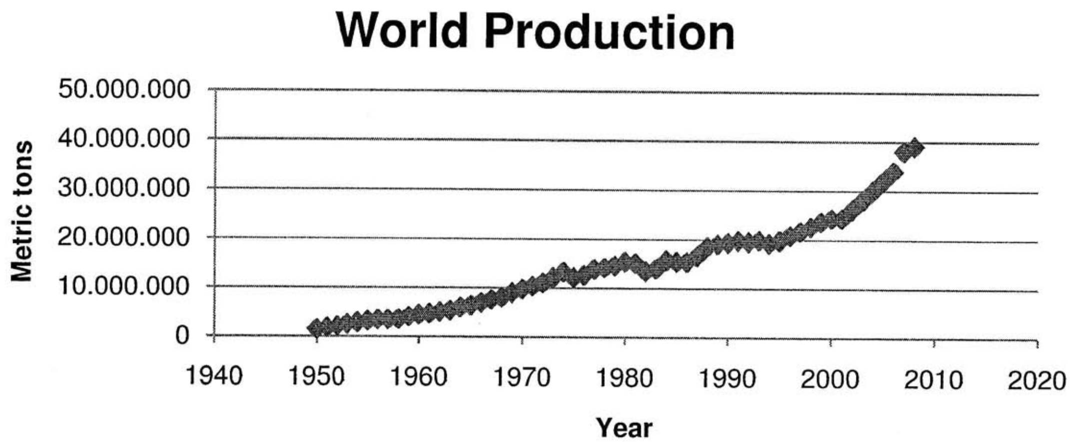


Figure 3-1 Aluminum Annual World Production (15)

The previous chart shows the evolution of the annual production of Aluminum. The current annual production is around 40 million metric tons, but this production increases as the demand increases due mainly to the development of the Asiatic economies.

3.2 Aluminum production

The production of aluminium includes two main stages:

- Production of aluminium oxide (alumina Al_2O_3) from aluminum ores (mainly bauxite) using the Bayer process.
- Production of aluminium from aluminium oxide by electrolysis using the Hall-Héroult process.

These two processes can be decomposed also in several stages.

The *Bayer Process*, invented in 1887 by Karl Bayer, enables the extraction of alumina from the ore. The whole process comprises several steps:

1. Raw material preparation
2. Digestion, in which Al_2O_3 is extracted as sodium aluminate ($NaAlO_2$) by a solution of sodium hydroxide (NaOH) at high temperature and pressure
3. Clarification, where the process residue is separated from the $NaAlO_2$ solution
4. Precipitation, where the aluminate is seeded with $Al(OH)_3$ to nucleate the precipitation of gibbsite, which goes through succeeding precipitations and is finally calcinated to anhydrous alumina.

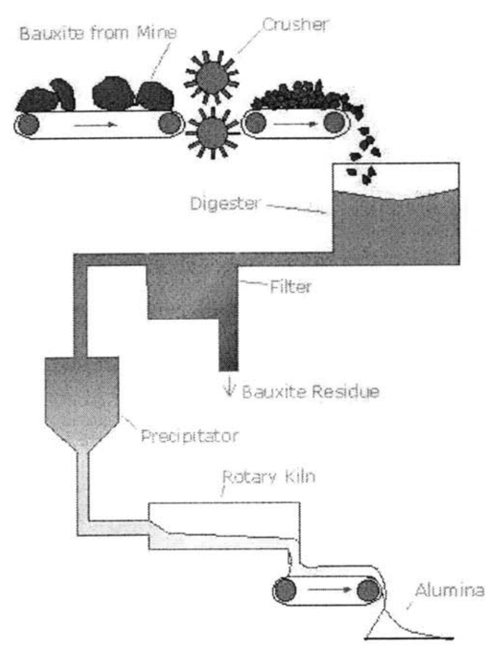


Figure 3-2 Bayer Process Scheme (16)

The *Hall-Héroult Process*, discovered simultaneously in 1886 by Charles Hall and Paul Héroult, is an electrolytic process that enables the extraction of aluminium from the aluminium oxide (alumina Al_2O_3).

In the Hall-Héroult process alumina (Al_2O_3) is dissolved in molten cryolite (Na_3AlF_6) inside a carbon-lined vessel, known as the *cell*. So Aluminum fluoride, AlF_3, is also added in order to reduce the melting temperature of the mixture. The operating temperature of the cell is around 960ºC. This mixture is known as the *bath*.

This *bath* has four main functions:

- Passing electricity from the anode to the cathode
- Being a solvent for alumina to enable its electrolytic decomposition
- Providing a physical separation between the cathodically produced aluminum metal and the anodically evolved carbon dioxide gas
- Acting as a heat-generating resistor that enables the cell to be self-heating

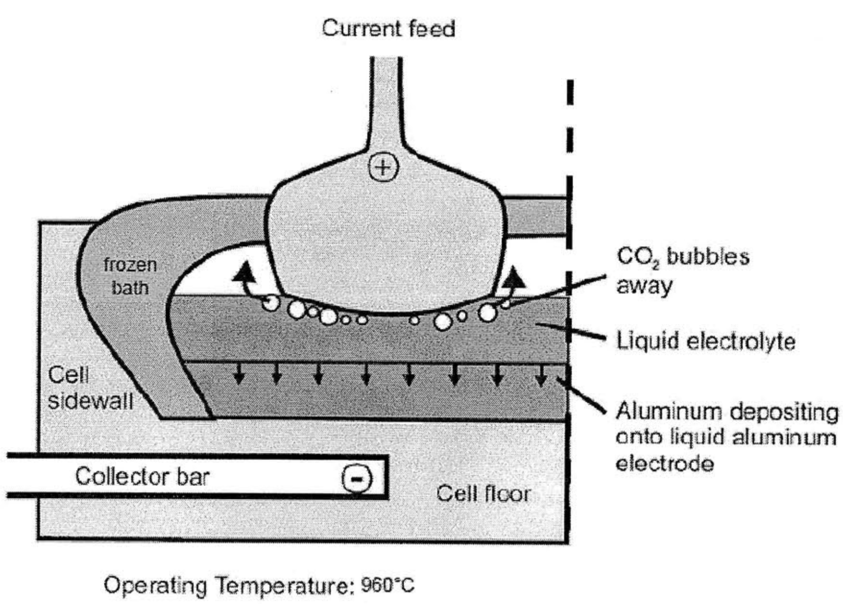


Figure 3-3 Alumina Reduction Cell

Carbon anodes are immersed into the bath, carrying electrical current which then flows into the molten cryolite containing dissolved alumina. As a result, the chemical bond between aluminum and oxygen in the alumina is broken; the aluminum is deposited in the bottom of the cell, where a molten aluminum deposit is found, while the oxygen reacts with the carbon of the anodes producing carbon dioxide (CO_2) bubbles. Once passed through the bath, the electrical current flows into the molten aluminum deposit and is then collected by the bottom of the pot, usually known as the cathode (17).

The alumina reduction process can be described with these reactions (18)

Cathode reaction: $Al^{3+} + 3e^- \rightarrow Al$

There are no Al^{3+} ions present in the electrolyte, but other complex ions, so a more representative reaction could be

$$AlF_6{}^{3+} + 3e^- \rightarrow Al + 6F^-$$

Anode reaction: $C + 2O^{2-} \rightarrow CO_2 + 4e^-$

As oxygen is complexed in the electrolyte, the anode reaction presumably involves complex ions according to

$$2Al_2OF_6{}^{2-} + 2AlF_6{}^{3-} + C \rightarrow 6AlF_4{}^- + CO_2 + 4e^-$$

The overall equation can therefore be explained as

$$2Al_2O_3 + 3C \rightarrow 4Al + 3CO_2$$

Theoretical production and energy consumption

From the alumina reduction reaction $Al_2O_3 + \frac{3}{2}C \rightarrow 2Al + \frac{3}{2}CO_2$ the theoretical production of aluminum can be calculated.

The production of 2 moles of Aluminum involves the consumption of 6 moles of electrons, which corresponds to 6 Faradays of electrical charge.

$$2 \cdot Al\ atomic\ weight = 2 \cdot 26.98 \frac{g}{mol} = 53.96\ g$$

$$6 \cdot Faraday = 6 \cdot 96{,}485\ coulomb = 578910\ coulomb$$

$$\frac{53.96\ gAl}{578{,}910\ Coulomb} = 9.32 \cdot 10^{-5} \frac{gAl}{Coulomb}$$

The daily production of the cell can therefore be calculated as

$$9.32 \cdot 10^{-5} \frac{g\ Al}{Coulomb} \cdot I\ \frac{\text{Coulomb}}{\text{second}} \cdot 86{,}400 \frac{\text{seconds}}{\text{day}} = 8.05\ \text{I}\ \frac{\text{g Al}}{\text{day}}$$

Together with the alumina reduction reaction there is always a parasite back reaction

$$2Al + 3CO_2 \rightarrow Al_2O_3 + 3CO$$

which implies that the total production is less than the calculated originally. Therefore, a term of current efficiency (η) has to be added to calculate the cell production. Most cells operate with current efficiencies of 90-95%. The best prebake available technology consumes 13.0kWh/kg Al with a current efficiency of 95%. Industrial average stays around 90% efficiency and a consumption of 15.0kWh/kg Al.

The energy consumed by the cell is a function of the voltage of the cell and the current flowing through it and can be calculated as

$$Energy = V_{cell} \cdot I \cdot 24 \frac{h}{day}$$

The production of aluminum by this electrolytic process involves the consumption of other raw materials apart from alumina.

In order to produce 1 kg of aluminum, the following materials are needed approximately:

- 2 kg aluminum oxide (Alumina Al_2O_3)
- 0.45 kg carbon
- 20 g aluminum fluoride (AlF_3)
- 20 g cryolite (Na_3AlF_6)
- 13-15 kWh of electrical energy

Apart from this, other aspects as cell relining, labor or plant amortization are to be taken into account when calculating the cost of aluminum production, what will be treated in Chapter 4.

3.3 The Hall-Héroult cell

The reduction cell where the electrolytic process is carried receives the name of their inventors, and is known as the Hall-Héroult cell.

There are two different types of cells, depending on the way that the carbon anodes are produced. These two types are known as *Soderberg* cell and *Pre-bake* cell.

For the *Pre-bake* cells, the carbon anodes are manufactured in a different facility. Petroleum coke is mixed with pitch; the mixture is given a parallelepiped shape and then baked into furnaces to be transformed into a solid carbon block. These blocks are joined to rods and placed inside the cell. When the block is consumed it needs to be replaced.

On the other hand, in a *Soderberg* cell there is only one big anode per cell, housed inside a steel container. The mix of petroleum coke and pitch is introduced from the top of this container. The mix is baked while it moves from the top to the bottom, requiring some extra heat achieved by increasing the pot voltage. These anodes have a lower quality than the prebaked ones, and therefore Soderberg cells are always characterized by lower current efficiency.

The subject from this report will be mainly Pre-bake cells, since they are more common due to their better performances.

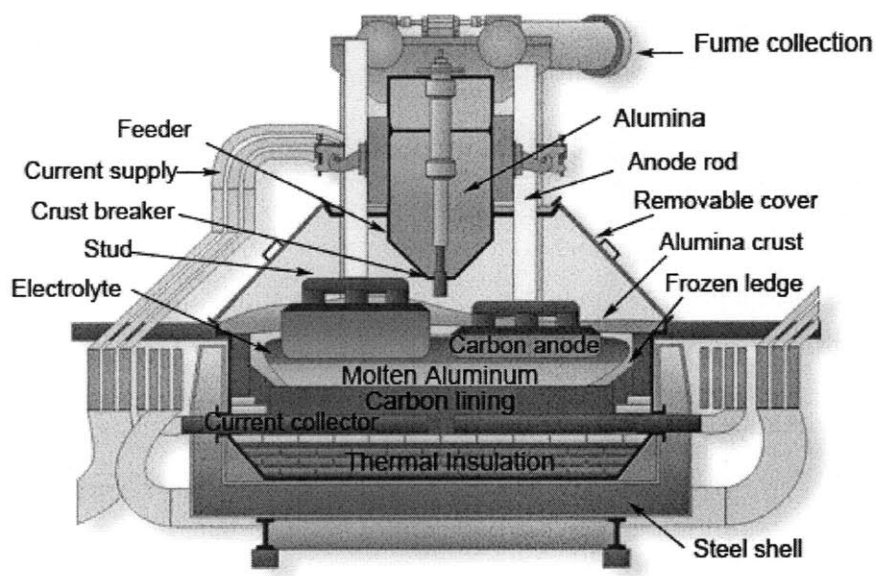


Figure 3-4 Hall-Héroult Cell (Pre-bake Cell) [modified from (19)]

The picture above shows the typical configuration of a Pre-bake cell. The cell is composed of several elements with different functions. The cell has evolved since it was invented more than 100 years ago to accommodate the larger currents used nowadays. A typical modern reduction cell is about 6-9m long, 3-4m wide and 1-1.3m high.

The alumina reduction occurs in a vessel designed to fulfill several functions (17)

- Act as a container for the molten bath and aluminum
- Resist to the high temperatures (around 950ºC) of the molten liquids it contains
- Resist to chemical attacks brought especially by the molten electrolyte constituents
- Resist to wearing caused by alumina abrasive behavior
- Reduce heat losses to a technical and economical optimal minimum
- Be mechanically enough resistant, but also with sufficient elasticity in order to accommodate for the thermal and physical expansion of the materials it contains
- Collect the electrical current coming from the anodes with a minimum voltage drop

The vessel can be decomposed in several parts with a combination of different materials. The outer shell, usually referred as potshell, is made out of steel and serves as a container for other elements. At the bottom there are placed some layers of insulating and refractory bricks, which mission is mainly reduce the heat losses from the bath as well as stand the high temperatures from the bath

The inside of the cell is lined with carbon blocks, which are joined together with a mixture of pitch and carbon dust. These blocks constitute the container for the molten aluminum and the electrolyte. The bottom carbon lining collects the current exiting from the metal pad and transfers it to the current collector bars, made of iron, and whose mission is to transport the current outside the cell.

Due to the difference of densities between the molten aluminum and the electrolyte, the metal pad stays on the bottom of the cell while the electrolyte floats on top of it. It is in the electrolyte where the electrolytic reduction of alumina takes place, with the help of the carbon anodes which are placed on top.

On the inner walls of the container we can find a frozen ledge. The formation of this ledge is due to the difference of temperatures between the bath and the cell surroundings, and has two important functions. This ledge acts as a protective layer for the carbon lining, preventing the electrolyte from attacking the carbon lining. Without this protective layer, the aluminum and the carbon would form aluminum carbide, which would dissolve in the electrolyte causing the erosion of the wall. And it also acts as a temperature controller, being able to absorb the excess of heat produced in the bath and melt or grow thicker if the bath heat input decreases.

The carbon anodes can be also decomposed in several parts. It comprises a carbon block, a rod made with copper or aluminum, a yoke and studs made with iron. The carbon block is joined to the metallic stud pouring molten cast iron. Typical sizes for a carbon anode are 70cm wide, 125cm long and 50cm high (20). Up to 40 anodes can be found per pot, since the carbon of the anodes is consumed during the chemical reaction, and needs to be replaced on a regular basis. All the anodes are fixed to a structure, which distributes the electrical current to the anodes. An electrical motor and several levers are also placed in the structure, allowing the anodes to be raised or lowered, in order to control the voltage of the cell while operating.

The high temperature of the electrolyte makes it very reactive, so in order to avoid it burning to the air, on top of it there is a layer of material made of alumina and solidified bath, called 'crust'.

As the alumina reduction proceeds, the alumina dissolved into the cryolite is consumed and therefore needs to be restored on a regular basis. The mission of the alumina feeder is to restore the levels of alumina in the bath. To do this, it is equipped with a crust breaker, which opens a hole in the crust through which the alumina can reach the bath. Each cell can has from 1 to 6 alumina feeders and crust breakers, depending on the size.

As the reaction proceeds, CO_2 is produced in the anode, apart from other fumes that need to be removed. These gases cannot be released into the atmosphere because they are contaminant so they need to be collected and directed towards the gas treatment center. The pots are therefore completely closed and equipped with removable covers and gas collectors.

The following table shows some typical performance data of a 150kA pre-baked anode cell (21)

Production per day	1,000 kg Al
Specific energy consumption (range)	13-15 kWh/kg Al
Anode gas composition (range)	78-85% CO_2 + balance CO
Cathode current efficiency (range)	88-92%
Al_2O_3 consumption	1.9kg/kg Al
Fluorides consumption (Na_3AlF_6+AlF_3)	approx. 3kg/100kg Al
Purity of the Aluminum produced	99.85%
Cell life	1000-2000 day

Table 3-1 Typical performance data of a 150kA pre-baked anode cell (21)

In order for the cell to operate in an efficient way, there are several parameters that need to be controlled. The following table resumes some of these parameters.

Temperature	940 - 980ºC
Interpolar distance	4 - 6 cm
Excess of AlF_3 in Na_3AlF_6	3 - 10 wt%
Bath ratio (molar)	2.2 – 2.9
Al_2O_3	2 – 8 wt%
CaF_2	2 – 8 wt%
Cell voltage	
Anode voltage drop	0.3 V
Cathode voltage drop	0.4 V
Bus bar voltage drop	0.2 V
Bath voltage drop	1.3 – 1.8 V
Decomposition voltage drop	1.2 V
Overvoltage	0.5 V
Voltage drop due to anode effect	0.3 V
Current density (anode)	0.7 – 1.2 A/cm^2
Metal pad depth	14 – 40 cm

Table 3-2 Range of operating variables for reduction cells (21)

The next graph displays the different components of the cell voltage and power consumption from a typical cell. In terms of power consumption we can identify three terms:

Total power consumed: 13.040 kWh/kg Al

Q1: net enthalpy to produce aluminum + CO and CO_2: 6.324 kWh/kg Al

Q2: heat losses from cell: 6.250 kWh/kg Al

Q3: heat losses external to cell: 0.466 kWh/kg Al

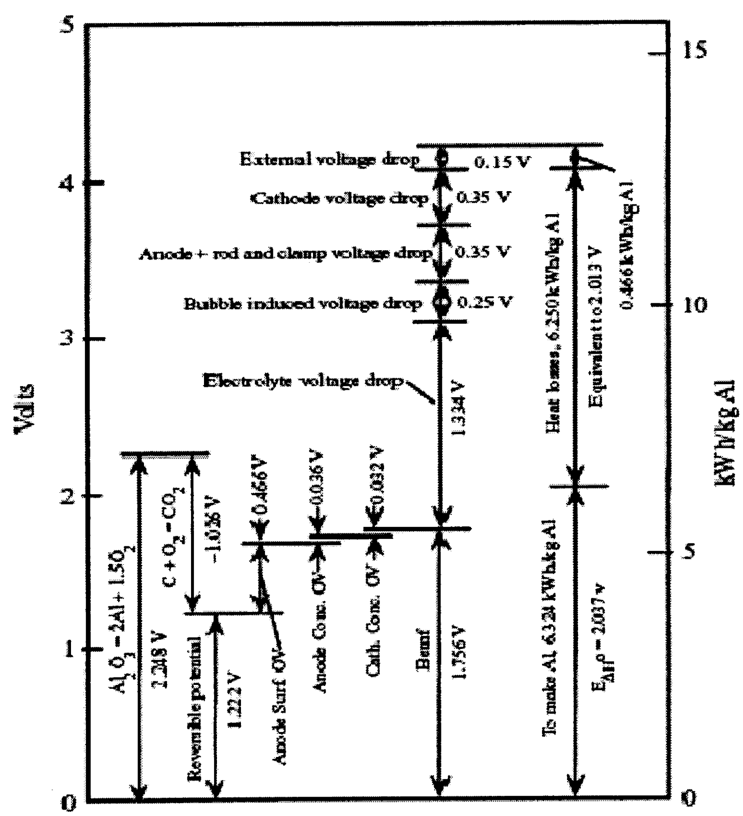


Figure 3-5 Components of cell voltage and power consumption at 95% Faradic efficiency (22)

Therefore we can observe that the actual efficiency of the cell is about

$$\eta = \frac{6.324 \frac{kWh}{kg\ Al}}{13.040 \frac{kWh}{kg\ Al}} = 0.4849$$

The thermal insulation of the cell has to be designed so that the heat loss in sufficient to form the protective frozen ledge on the sides of the cell but not at the bottom.

The cell voltage is made up of a number of components (23):

$$E_{cell} = E^0 + \eta_{CA} + \eta_{SA} + \eta_{CC} + \eta_{SC} - I(R_A + R_B + R_C + R_X)$$

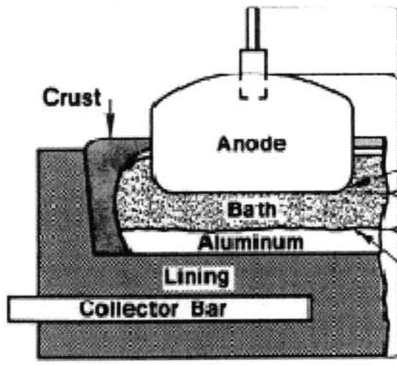
$E^{º}$ is the thermodynamic equilibrium voltage; η_{CA} is concentration overpotential at the anode and η_{SA} is surface overpotential at the anode which can be either activation or reaction overpotential. η_{CC} is concentration overpotential at the cathode; η_{SC} is surface overpotential at the cathode. Total cell current is represented by I. R_A is the electrical resistance of the anode. R_B is the effective resistance of the electrolyte including the resistance caused by gas bubbles. R_C is the cathode resistance and R_X is resistance external to the cell which also influences in power consumption.

According to the terms displayed on the figure typical values for a Hall-Héroult cell are

$E^{º}$ = 1.222 V	η_{CA} = 0.036 V	η_{SA} = 0.466 V
η_{CC} = 0.032 V	$I \cdot R_B$ = 1.584 V	$I \cdot R_A$ = 0.35 V
$I \cdot R_C$ = 0.35 V	$I \cdot R_X$ = 0.15 V	

The following graph gives a better visualization from the different terms in the equation.

It can be seen that only around 30% of the total voltage corresponds to the decomposition voltage, while the rest of the terms are voltage drops external to the electrochemical reaction. When working on the Liquid Metal Battery, these terms (not all but the ones who apply) need to be minimized in order to achieve greater efficiency.



Voltage Component	Volts	% of Total
External	0.15	3.6
Anode	0.32	7.6
Anode Ov.	0.51	12.2
Bubbles	0.25	6.0
Decomposition	1.22	29.1
Electrolyte	1.36	32.4
Cathode Ov.	0.03	0.4
Cathode	0.35	8.4
	4.19	100.0

Figure 3-6 Typical distribution of voltage in a state-of-the-art aluminum production cell. Ov indicates overvoltage (20)

Heat losses

The following graph shows the typical heat loss distribution in a Hall-Héroult cell.

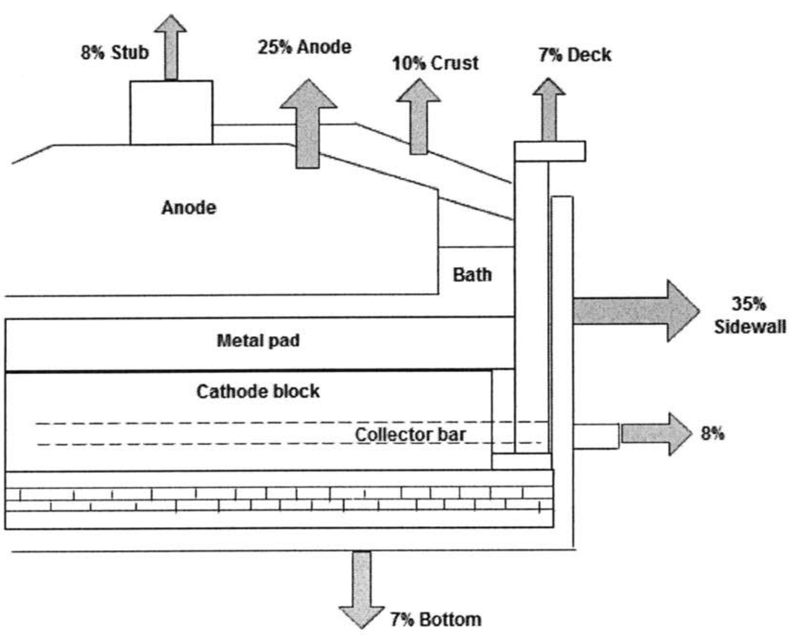


Figure 3-7 Typical Hall-Héroult cell heat loss distribution. Modified from (24)

The loss distribution depends on several factors, but mainly on insulation, and the correct design is essential to achieve the optimal operating temperature. If the temperature rises excessively, the frozen ledge melts and the side walls are exposed to the attack of the bath. If the temperature is too low, the frozen ledge grows and alumina does not dissolve so easily.

The refractories and insulation used in the Hall-Héroult cell include (24):

- high temperature refractories, which provide a refractory barrier for the bath at high temperature and protect the insulation beneath
- low thermal conductivity insulation, which keeps the desired heat balance to maintain a sufficient ledge formation, reduces the heat losses from the cathode and the sidewall and increases the cell life, related to the thermal balance of the cell.
- silicon carbide bricks

The materials used in the cells should meet the following requirements (24):

- Thermomechanical and structure stability over the temperature up to the cell temperature
- Adequate mechanical strength at room temperature and elevated temperature
- Low thermal conductivity
- Resistance to the attack of the bath components, sodium and molten aluminum
- Dimensional stability and low dimensional tolerances
- Safety of handling

These requirements have to be taken into account when designing the insulation for the Liquid Metal Battery treated in this report.

3.4 The Aluminum Smelter

Industrial production of Aluminum requires facilities much more complicated that a single reduction cell. These factories are called Aluminum Smelters and they usually follow the disposition shown in the next figure.

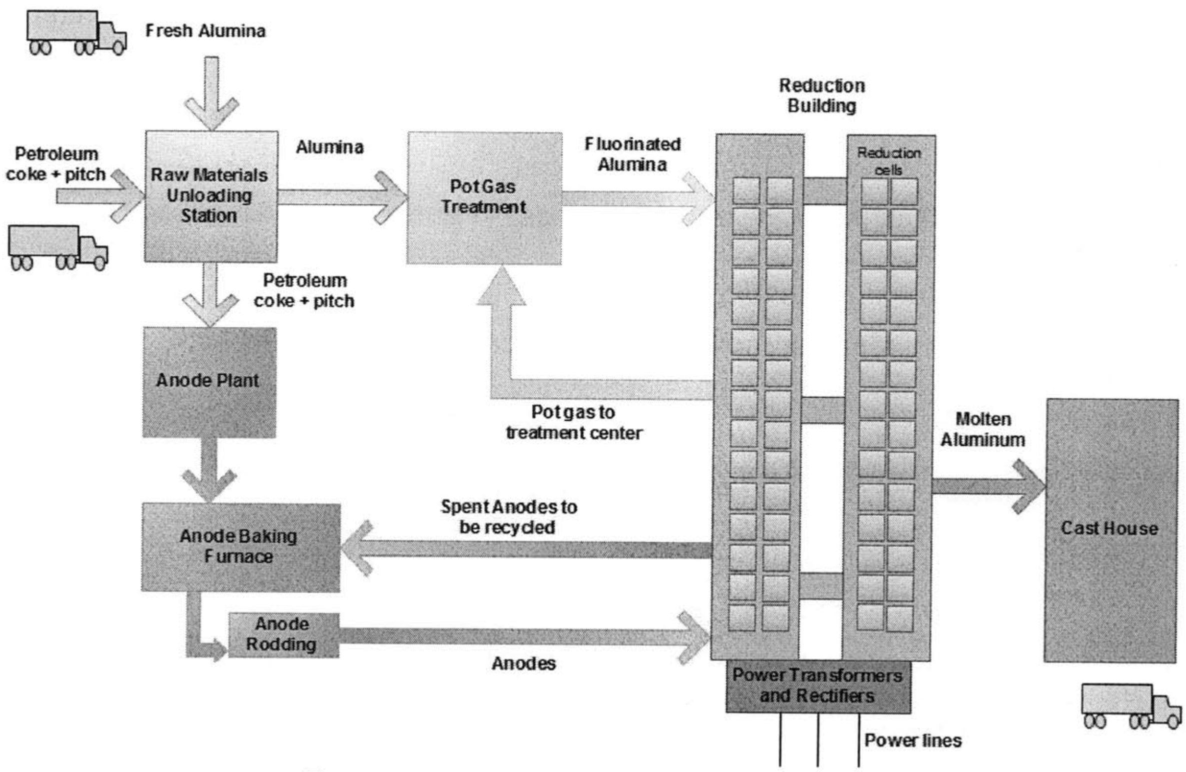


Figure 3-8 Aluminum Smelter Basic Configuration

The raw materials (alumina, petroleum coke and pitch) arrive to the installation by several means (road, rail, water) and are afterwards stored in silos. Some smelters don't own their own anode plant, so instead of receiving petroleum coke and pitch just received the carbon anodes ready to use.

Carbon anodes are produced in the anode plant. They are made out of petroleum coke, pitch and recycled anodes. The coke and the recycled anodes are grinded and mixed with the pitch. The mixture is then heated and stirred, forming what is called green paste. This paste is compacted and baked until a solid carbon anode is formed. The anodes are then taken to the rodding room where they are joined to the anode rods and transferred to the reduction building.

Alumina is conveyed from the silos to the gas treatment plant, where it is used to clean the exiting gases from the reduction cells. The alumina acts as adsorbent for the fluoride present on the exiting fumes, which is afterwards taken back to the reduction cells together with the alumina.

The electric power arrives to the plant from the external grid in form of alternate current (AC). The reduction process is carried on using direct current (DC) so the entering current needs to be converted. There is an external plant dedicated to this function. It is comprised by power transformers and current rectifiers. The transformers convert the entering energy into low voltage, high amperage current. This AC current is then rectified and converted into DC current using a series of diodes in parallel.

After the reduction building, the cast house receives the molten aluminum produced in the cells, where is processed and leaves the installation in form of billets, ingots or slabs.

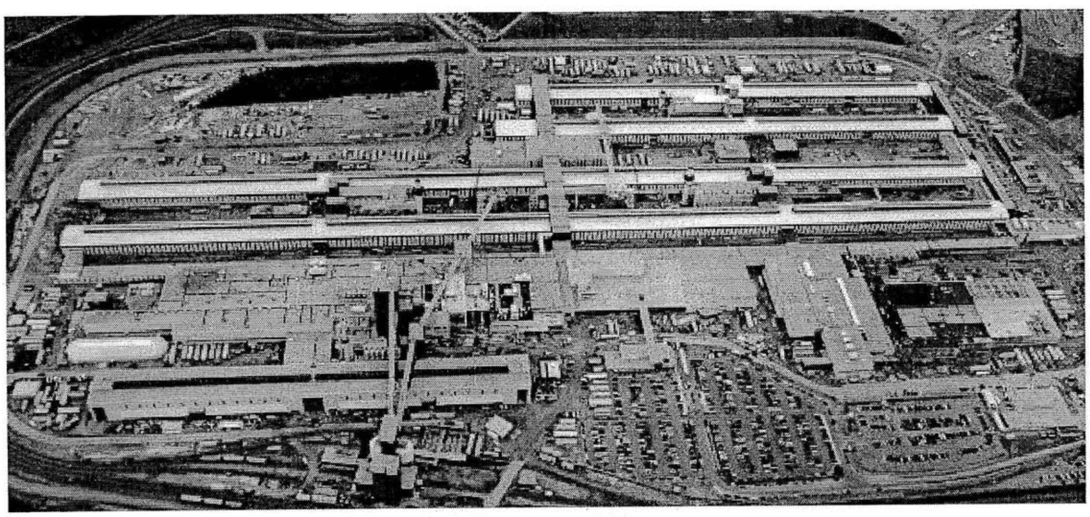


Figure 3-9 Alcan Aluminum Smelter, Alma, Canada (25)

The reduction building is the most important part in the smelter. The reduction building is formed by several hundreds of pots, housed in one or more large buildings called potrooms. Inside each potroom, the cells are electrically connected in series, so that the cathode of a cell is connected with the anode of the next cell. The electrical connection is made with aluminum busducts, suitable to transport the high currents present in the process, minimizing the voltage drops. The cells are usually arranges in a side-by-side configuration so that the adverse effects of the magnetic fields are minimized.

Common values of DC voltage go from 440Vdc to 880Vdc (21), with an average of 4-4.4Vdc per pot, so each pot-room houses from 100 to 200 pots connected in series.

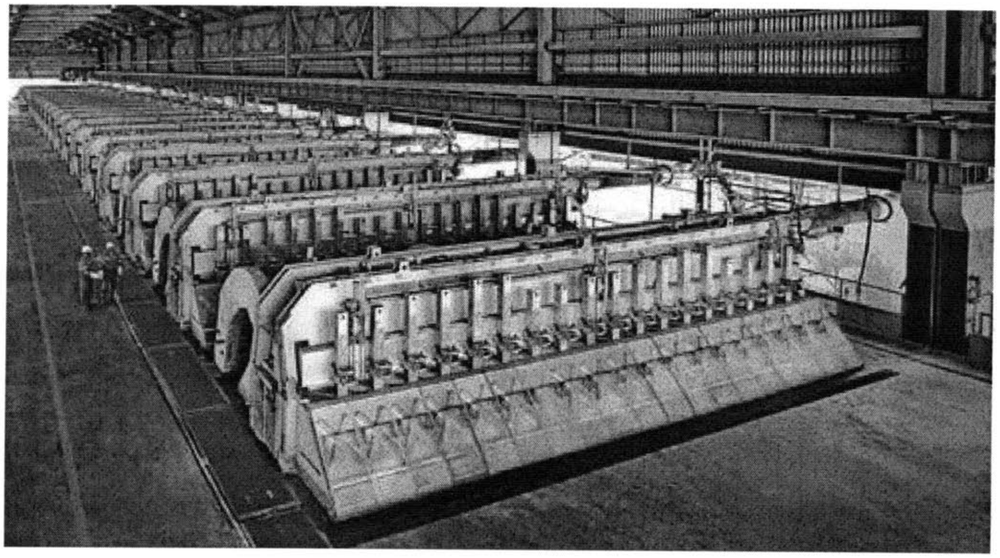


Figure 3-10 Potline at Dubal Smelter (26)

Apart from the reduction cells, the reduction building comprises other equipment such as alumina feeders, whose mission is to supply alumina to the cells in a regular basis as the alumina dissolved in the bath is being consumed; and aluminum tapping system, which is in charge of siphoning the molten metal from the cells and transferring it to the cast house.

The next chapter will focus on trying to understand the cost structure of a smelter, analyzing the cost of the different subsystems explained earlier.

4

Chapter 4 Cost Analysis of the Aluminum Industry

4.1 Overview

Aluminum has been produced at an industrial scale for the last 100 years. In 1888 Charles Hall set up a company to manufacture aluminum, which later became known as Aluminum Company of America of Alcoa.

World production in 1900 totaled 7330 tons and took place in only four countries. In 2000, approximately 24.5 million tons of primary aluminum were produced in 43 countries (27). The following graph gives an idea of the distribution of Aluminum Smelters around the world.

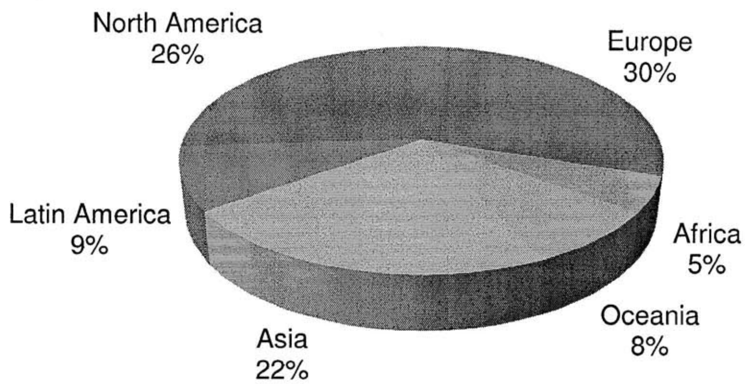


Figure 4-1 Regional location of aluminum smelting capacity, 2000 (28)

The continuous increase of demand of aluminum has attracted many competitors to the industry. Nowadays the smelting industry is dominated by a handful of companies, being the five largest Alcoa (4.2 Mt), Russky Aluminy (RusAl) (2.45 Mt), Alcan (2.25 Mt), Pechiney (1.145 Mt) and BHP-Hilton (1 Mt) (28).

China is estimated to have around 20 major smelters, with capacity close to 2.6 Mt per annum but the smelters are mainly owned by central and regional governments, although a number have been vested by Chinalco (28).

This increase in the number of competitors and the lack of differentiation of the final product make this industry quite opaque in terms of disclosure of information about current costs of production. Nevertheless, the information presented in this report has been contrasted with experts in the Aluminum Industry and has been found to be quite accurate.

4.2 Raw materials requirement and production costs

The price of Aluminum is set by the London Metal Exchange (LME). Rather than being controlled by a cartel of large, integrated producers, the price is set in the trading ring based primary on supply and demand (29).

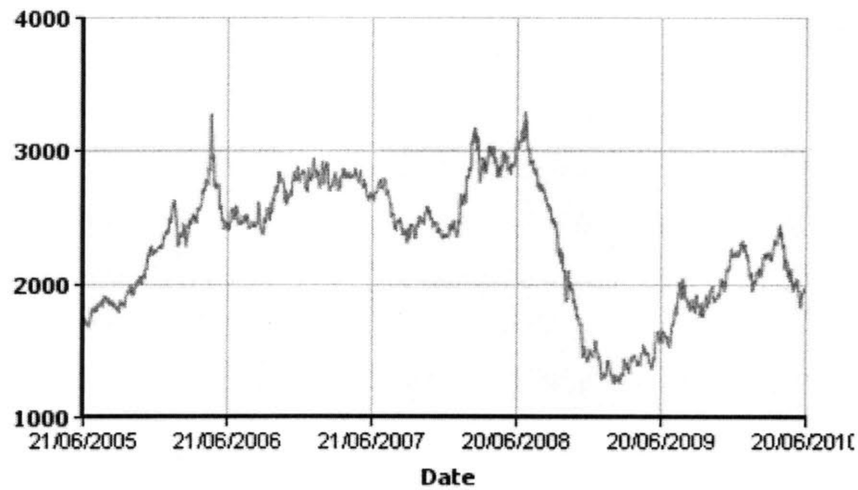


Figure 4-2 LME Aluminum Price ($/ton) 2005-2010 (30)

Profitability is therefore highly related to the cost of production against the LME price. This situation makes the producers be reluctant to give information about their actual cost, increasing the difficulty of getting data to prepare this report. While no one organization knows the production costs of all the smelters in the world, several services such as CRU International have built models on the information they glean from the industry and public documents (29).

Smelter operators have to be very careful with their operating cost. If these happen to be higher than the price from LME or other sales end market, the smelter will be losing money and that could lead eventually to be shut down.

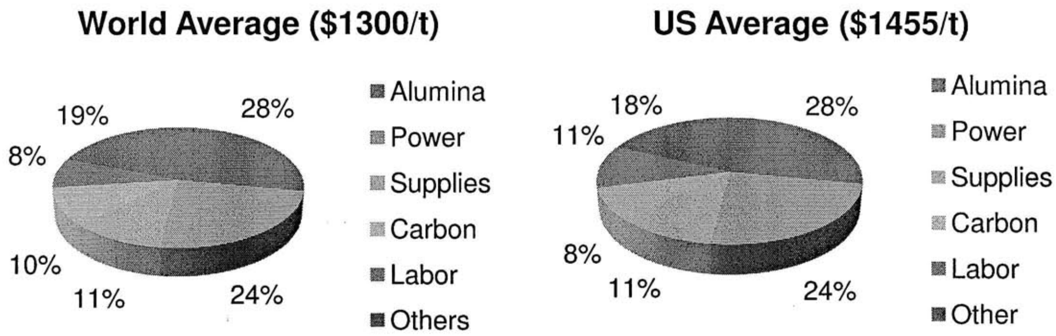


Figure 4-3 Smelter's total operating cost (29)

Although the percentages are almost the same for the US and the World average, the actual cost for the United States is higher, mainly power and labor, being this a reason why smelter production is moving from the United States and other western countries to lesser developed countries where labor and electricity are not so expensive. For example, wage rate for smelter operator in US are around $30/h while in Africa and Asia they are paid around $3.0/h.

Smelting aluminum is an energy-intensive activity requiring large amounts of electricity. Electricity contracts between smelters and electricity suppliers are sometimes on a variable power cost contract, such that the power generators are paid a fixed percentage of the world ingot price.

The following chart shows the distribution of the different sources of electricity used by the smelting industry.

	Africa	*North America*	*Latin America*	*Asia*	*Europe*	*Oceania*	*World average*
Hydro	39.1	72.9	91.0	9.8	47.6	23.6	54.1
Coal	59.8	25.4	0.0	35.7	20.0	76.4	30.5
Oil	-	-	1.9	0.4	2.4	-	0.9
Gas	1.1	-	6.7	54.1	6.1	-	8.1
Nuclear	0.0	1.6	0.4	-	24.0	-	6.4

Table 4-1 Smelting Electricity Fuel Source, 1998 (%) (28)

The higher cost of electricity and labor in the United States and other western counties is the main reason why smelter production is migrating to lesser developed counties where power and labor are less expensive (29).

4.3 The Aluminum Smelter and its capital costs

As it has been explained before, the Aluminum Smelter is a quite complex facility and therefore the investment depends on the complexity of the system.

According to experts on the field (31), there are several key drivers of the investment cost, such as:

- **Location**: This determines the main cost inputs for materials (steel and concrete) and construction labor. Proximity to existing infrastructure such as ports, road and rail, and town services can also have a major impact
- **Replication**: Smelter projects should benefit significantly from replication of design and EPCM teams, building on the learning from prior projects. In the past decade this would have been facilitated by the domination of AP30 cell technology in new smelters.
- **Smelter Size**: Larger smelters potentially capture some economies of scale through all of the EPCM activities.

Several new smelters are planned to be built and commissioned in the next few years. The complete table can be found in Annex A, extracted from (32).

The next graph shows the data collected, showing the relationship between the investment (in million dollars) and the capacity of the smelter (in tons per year).

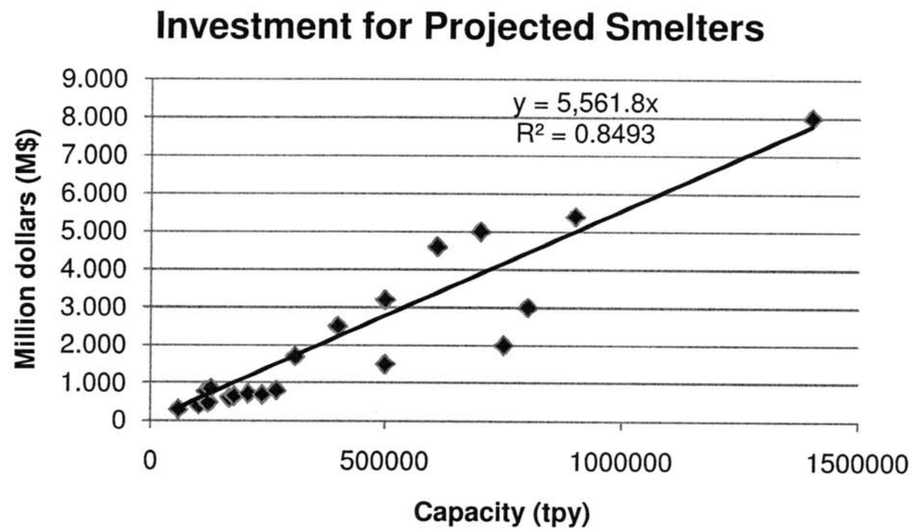


Figure 4-4 Relationship Investment-Capacity for New Smelters [Data extracted from (32)]

The same analysis was made for some smelters built in the past few years and the relationship can be seen in the following graph.

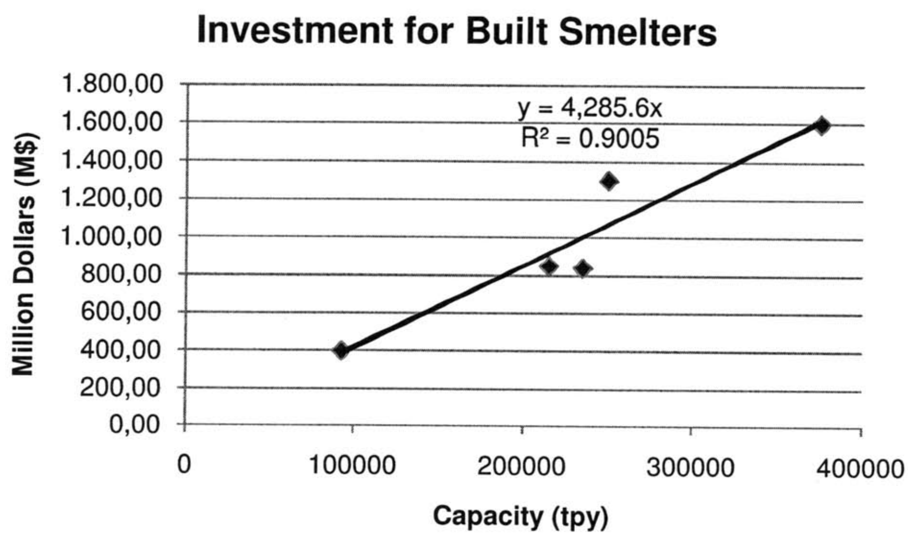


Figure 4-5 Relationship Investment-Capacity for Existing Smelters [Data in Annex B]

The data collected were analyzed in order to check that they fit with the information found in some articles (29).

Published Information[5]	\$4,500-\$5,000 per ton installed
Information by experts[6]	\$4,500-\$6,000 per ton installed
Future smelters	\$5,560 per ton installed
Built smelters	\$4,285 per ton installed

Table 4-2 Average \$/tpy investment

The average investment for planned investment is place above the upper bound of the information found in specialized publications, while the investment for smelters that are already in operation lies slightly below the lower bound, but it is totally consistent, due to the effect of inflation (33).

In order to get a deeper knowledge of the cost breakdown in an aluminum smelter, experts in the field were contacted. An estimate of the breakdown cost for an aluminum smelter was provided by Max Wiestner from ABB (33). This information was confirmed by different experts in the field.[7]

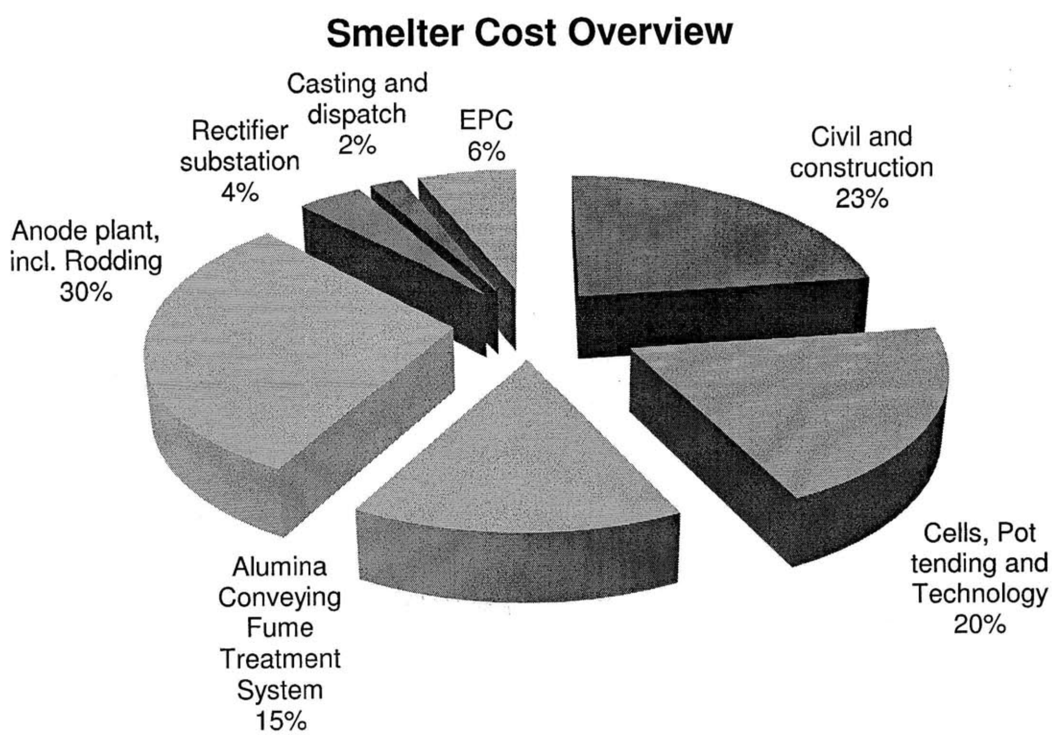


Figure 4-6 Aluminum Smelter Cost Overview (Courtesy from ABB)

[5] Information published in 2000.
[6] Information provided by César Inostroza (37)
[7] Anthony Jones, from WorleyParsons; César Inostroza, from SNC-Lavalin and Michel Kuntz from Rio Tinto Alcan.

For a $2billion investment / 360,000tpy capacity project (based on ABB information) the total investment can be divided as follows.

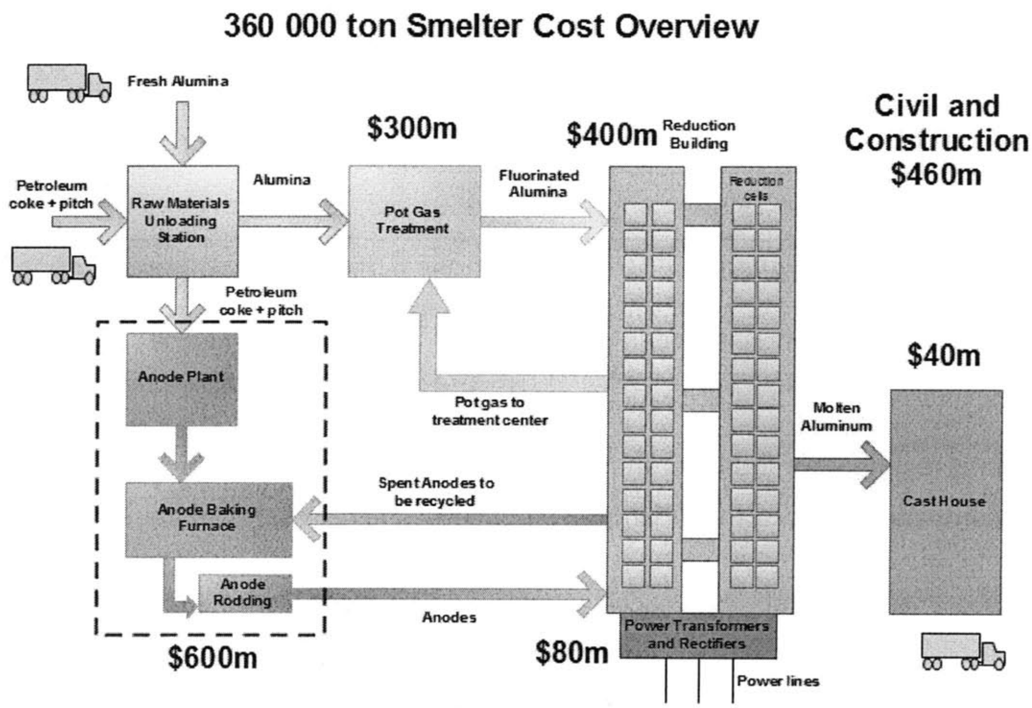


Figure 4-7 Smelter Subsystems Cost Overview (Investment $2billion, Capacity 360,000 tpy)

This information can also be used now to analyze the data available for the smelters that are currently in operation. The number of smelters with a significant amount of data available is quite reduced, due to the difficulty of getting data because of the opacity of the sector.

Smelter	Owner	Total Investment (M$)	Installed Capacity (tpy)	Number of cells	Cell type
Deschambault	Alcoa	840	235,000	264	AP30
Alma	Rio Tinto Alcan	1,600	375,000	432	AP30
Dunkerque	Rio Tinto Alcan	850	215,000	264	AP30
Mozal	BHP Billiton	1,300	250,000	288	AP35
Laterriere[8]	Rio Tinto Alcan	500	210,000	432	P155

Table 4-3 List of Smelters

The investment for the different smelters can be analyzed, but in order to be able to make a comparison among the different type of cells, it is necessary to unify the metric.

Smelter	Total Investment (M$)	Est. Cost Substation (M$)	Est. Cost Cells, Pot Tending and Technology (M$)	Est. Cost civil and Construction (M$)
Deschambault	840	33.6	168	193.2
Alma	1,600	64	320	368
Dunkerque	850	34	170	195.5
Mozal	1,300	52	260	299
Laterriere	500	28.57	142.85	164.28

Table 4-4 Investment breakdown (in million dollars)

It can be noticed that the substation investment is related to the power installed, and can be therefore extracted from the total investment and be analyzed afterwards.

The installed power can be calculated if the cell voltage and current is known. For this calculation, the cell voltage has been estimated to be 4.2V (typical value), and therefore, the total power installed can be calculated using the equation

$$Total\ Power = Number\ of\ cells \cdot Cell\ Voltage\ (4.2V) \cdot Cell\ current\ (A)$$

[8] This Smelter does not include an Anode Plant

By this mean, the substation investment can be analyzed in terms on \$/kW installed, what will be more convenient when analyzing the investment required for the energy storage system.

In the case of the different cell types, one way of comparing them is relating each concept to the surface area of each cell.

As explained in section 3.3, the size of a typical reduction cell is about 6-9m long and 3-4m wide, which gives surface areas from $18m^2$ to $32m^2$.

Current density in the reduction cells ranges from 0.7 to 1.2 A/cm^2. In order to estimate the size of the cells a value of $1A/cm^2$ has been used, trying to be neither too optimistic nor too conservative in the estimations.

Cell type	Current (kA)	Estimated Area (m^2)	Estimated Cell Power (kW)
AP30	300	30	1260
AP35	350	35	1470
P155	155	15.5	651

Table 4-5 Cell types, rated current and estimated surface area

Combining all the information we can infer the approximate investment per kW of power installed in the case of the substation and per m^2 in the case of cell investment and construction work.

Smelter	Substation (\$/kW)	Cell Technology (\$/m^2)	Civil and Construction (\$/m^2)
Deschambault	101	21,212	24,394
Alma	118	24,691	28,395
Dunkerque	102	21,465	24,684
Mozal	123	25,794	29,663
Laterriere	102	21,334	24,534

Table 4-6 Investment unit installed

The average values and standard deviation for these values are:

· **Substation**	Average:	\$110/kW
	Standard deviation:	\$10.4/kW
· **Cell technology**	Average:	\$22,900/m^2
	Standard deviation:	\$2,176/m^2
·**Construction**	Average:	\$26,335/m^2
	Standard deviation:	\$2,502/m^2

A deeper analysis of these terms will be developed in the following sections.

4.4 The Rectifier Substation

As it has already been mentioned, the investment of the rectifier substation can be measured as $/kW installed.

As explained in section 3.4, the electrical substation transforms the AC current from the grid into DC current, which is needed for the electrolytic process.

The equipment required for this task comprises:

- *Power transformers*: which convert the high voltage-low current energy coming from the grid into low-voltage high current.
- *Rectifiers*: which transform the incoming AC current into DC current.
- *Power factor correctors*: responsible of partially compensate the reactive power generated by the rectifiers.
- *Switchgears* and *control system*.

An approximate cost breakdown of the investment from a substation was provided by Max Wiestner from ABB (33) and can be seen in the following graph.

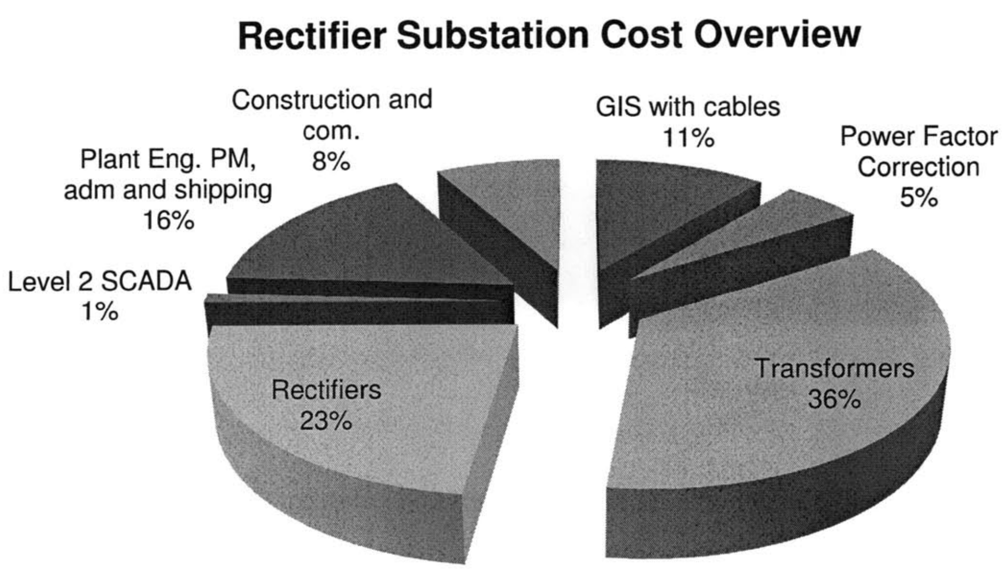


Figure 4-8 Rectifier Substation Cost Overview (Based on $2billion investment/ 360,000 tpy capacity) [Courtesy of ABB (33)]

With this information, an estimation of the investment in the different components can be made. It has to be noted that the Control System (Scada Level 2) is hardly dependent on the power installed and will therefore be subtracted as whole.

This way, the investment, for this specific project can be split as follows:

· Transformers	\$57.7/kW
· Rectifiers	\$36.5kW
· Power factor correction	\$7.9/kW
· GIS with cables	\$17.5/kW
· Construction	\$12.7/kW
· Project Management	\$25.4/kW

It has also to be noted that the cost of the rectifier is mostly dependent on the rated current and not so dependent on the output voltage. Experts in the field[9] were consulted and an approximation of the cost per kW for different current/voltage configurations was calculated.

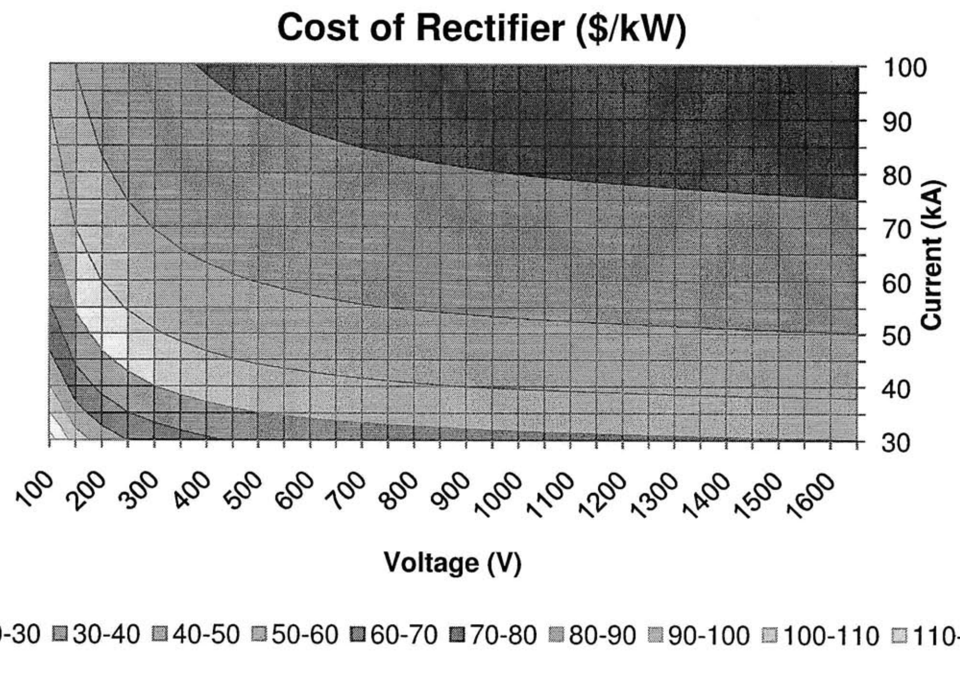


Figure 4-9 Cost per kW-Current-Voltage relationship for High Power Rectifiers

[9] Power Electronics Suppliers were consulted, as well as ABB Experts in the Aluminum Industry

It can be noted that the cost per kW decreases as the voltage and/or current increases. At the first sight, it seems that installing equipment with higher rated power can be beneficial in terms of initial investment, nevertheless other aspects such as robustness of the installation should be considered.

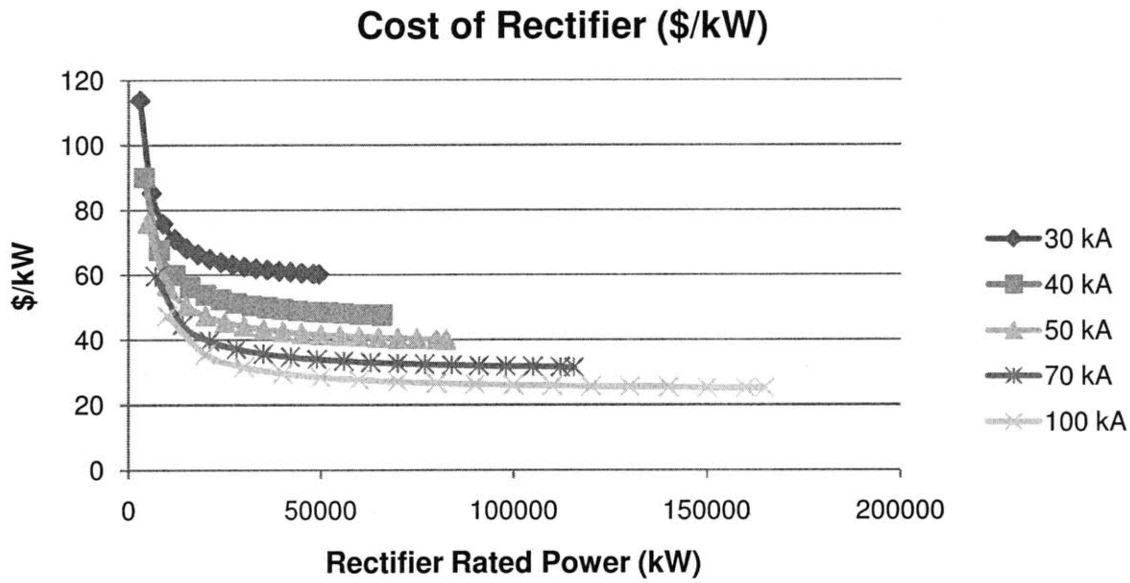


Figure 4-10 Cost of the Rectifier depending on the Rated Current

The cost of a Scada Level 2 system stays around $800,000. It is out of the scope of this report decide which is the best Control System for the Energy Storage System, but the cost of a system similar to the one used in a smelter will be considered.

4.5 Cell, Pot Tending and Technology

According to the information provided about the breakdown of the investment of an aluminium smelter, around 20% of the total investment can be attributed to the cells, cells tending and other related technology.

Taking as an example the aluminium smelter from Figure 4-6, the estimate investment in the reduction building excluding construction is $400 million.

The smelter used as an example consists of 360 pots, and therefore, the investment per cell rises up to $1,1 million. If each pot has an approximate area of 35m^2, the investment per m^2 of reduction surface reaches $31,746/m^2.

It has to be noted that this investment not only include the cost of the cell and the cell lining, but also other elements such as the busbars and conductors, the fume collectors, the alumina feeders and crust breakers, the cranes, and other supporting equipment.

It has to be noted that some of these elements will not be present in the energy storage system and therefore, the cost per cell will be lower than the initial $1.1 million.

An estimate of the breakdown cost of a reduction cell can be found in the next figure.

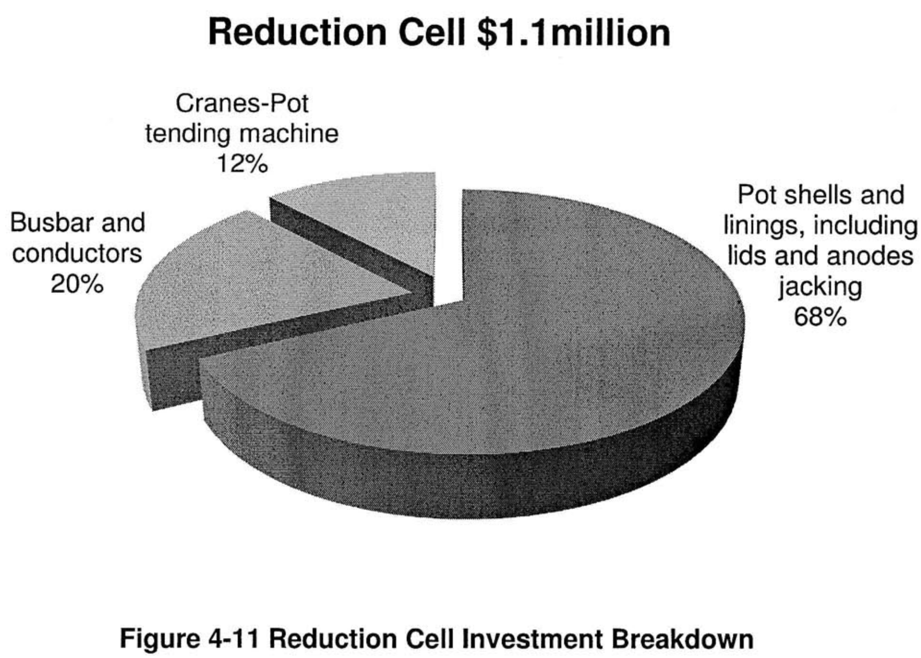


Figure 4-11 Reduction Cell Investment Breakdown

With this information, we can estimate that out of the investment of $1.1 million per cell (AP35), the potshell and lining represents the 68% of the total investment, around $750,000 per cell ($21.560/m^2 per reduction surface). This value will be useful when calculating the cost of the energy storage system.

About 20% of the investment can be assigned to the busbars and other electrical conductors. This means around $223,000 per cell, what will be necessary to include in the energy storage system model.

On the other hand, no cranes or pot tending machines will be needed in the energy storage system, so the cost of these elements (around $135,000 per cell) will be required to be subtracted from the total investment of the reduction cell.

4.6 Civil and construction

From the initial breakdown, around 23% of the smelter investment is due to civil and construction works. According to experts in the field, this investment can be further divided into several items.

The following graph gives an idea about these items and their impact in the total investment in civil and construction works in an aluminum smelter project.

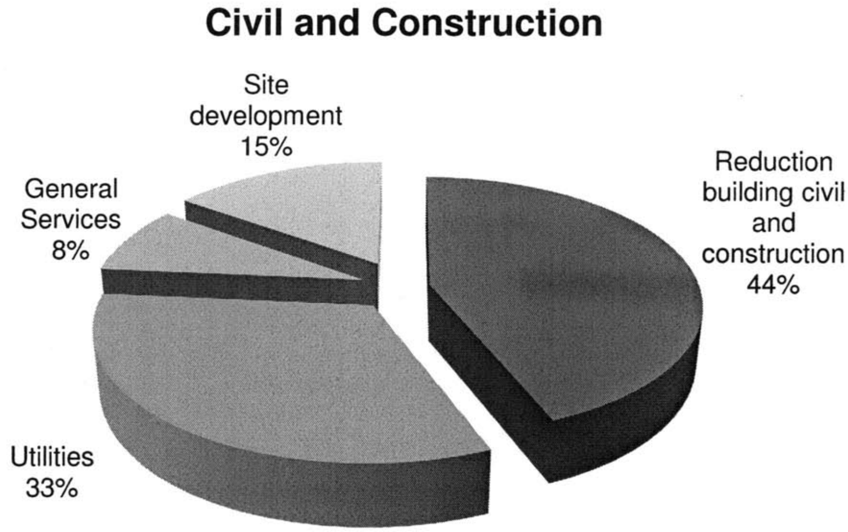


Figure 4-12 Civil Works Investment breakdown

The most important item for this report considered in this breakdown of the investment is the one related to the reduction building. Around 44% of the total investment can be attributed to the construction of the reduction building. For the smelter taken as an example, out of the $460 million invested in construction, around $200 million are invested in the construction of the reduction building. With an approximate area of 30,000m^2, the estimated investment per square meter is expected to be around $6,700/m^2.

As for the rest of the items, the energy storage system will differ from the aluminum smelter since no workers will be there during hours, making it unnecessary to build other facilities such as offices, services and others. Therefore, these items will not be taken into account when constructing the cost model for the energy storage system.

5

Chapter 5 Cost Analysis for a Large-Scale Energy Storage System

5.1 Introduction

After analyzing the structure of cost of the aluminum industry, an approach to the investment required for a large scale energy storage system will be developed based on the previous information.

In the cost analysis, several aspects will be analyzed:

- Layout of the system: different configurations will be analyzed, in terms of number of cells, cell size and possible stackability of the cells.
- Active materials: several combination of active materials will also be analyzed

The cost of the system can be broken down into three subsets (3):

- costs that scale with energy (storage capacity of the unit)
- costs that scale with power (conversion module)
- BOP costs (system housing, monitoring system, etc) that only vary slightly with the size of the unit

The different terms that have been taken into account when constructing the cost model are:

- *Construction and civil works cost*, which relates to the cost of the facility where the energy storage system will be installed. The unit of measure is $/m^2 of facility.

- *Cell cost*: it includes the shell, cell lining, busbars and other conductors. In this case, the unit of measure is $/cell.

- *Power conversion system cost*: which accounts for the cost of all the equipment needed to make the energy conversion from AC to DC and back. It includes the transformers, inverters, rectifiers, switchgear and control system. It is measured in $/kW

- *Active materials*: three combinations of active materials will be considered for the energy storage system. The cost of the active materials will be measured in $/kWh since it is related to the capacity of the system.

A deeper description of each of the terms that have been considered in the elaboration of the cost model will be given next.

5.2 Construction and civil works costs

Due to the similarities between the reduction building in an aluminum smelter and the proposed energy storage system, the disposition of the cells will be similar to the one found in the reduction building. A scheme of a typical disposition is displayed in the next figure.

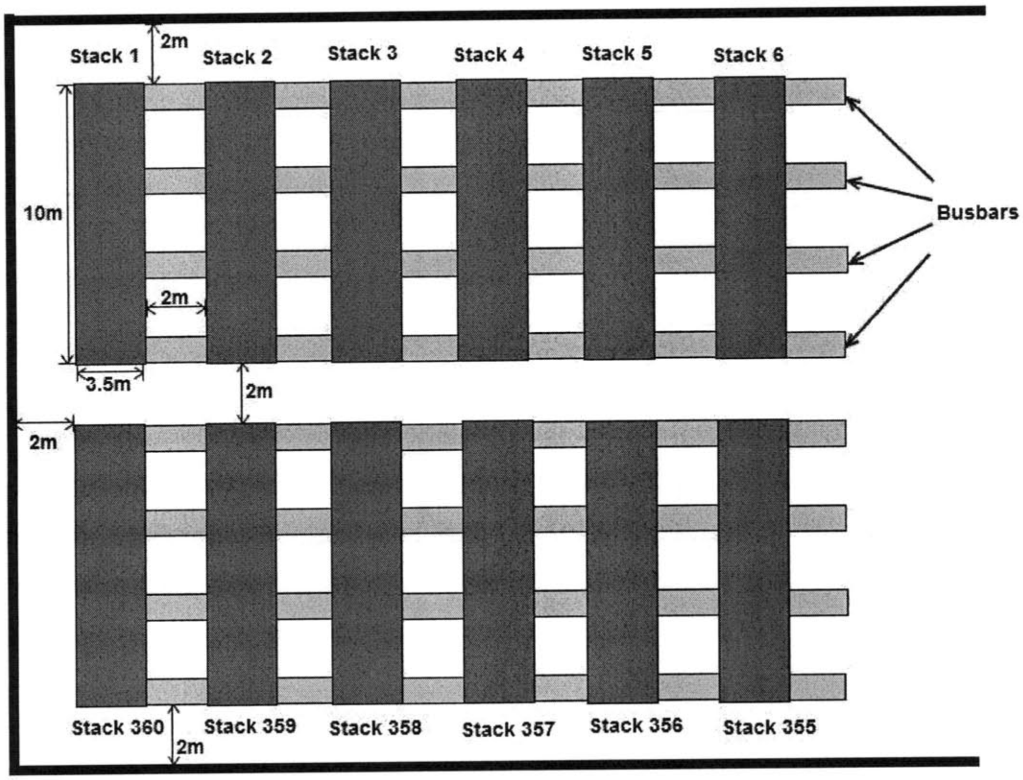


Figure 5-1 Energy storage system disposition

In order to get the model as simple and accurate as possible, the size of the cells considered will be the same as in the Aluminum Smelter analyzed earlier in section 4.3. The dimensions of the cell, as well as the separation considered between cells are listed in the next chart.

Cell		
	Length	3.5 m
	Width	10 m
	Height	0.3 m
Stack		
	Length	3.5 m
	Width	10 m
	Height	1.2 m
Distance between stacks		2 m
Distance between lines		2 m

Table 5-1 Dimensions of the cell

Inferred from the information extracted from the analysis of the investment in the aluminum smelters, the cost considered for construction and civil works (including housing building) is **$6,700/m^2.**

As it has already been mentioned, this cost varies highly depending on the site, local construction cost and level of earthwork that needs to be done. The value used in this report is supposed to lie in the middle of the range, but it can vary depending on the site where the system is installed.

5.3 Cells cost

From the analysis of the aluminum reduction cell, an approximate cost of the reduction cell was inferred. The value calculated in section 4.5 was **$21,560/m²**.

As it has already been mentioned in 4.5, this value corresponds to the investment related to the pot-shell and the lining. For a pot sized 35m2, the average investment in the pot-shell and the lining is $754,600.

Apart from this, other elements such as busbars and conductors have also to be included in the cost. Busbars are in charge of transferring the electrical current between pots. From the aluminum smelter used as an example, an investment of $223,000 per pot is required.

The cell used in the aluminum reduction process has an average height of 1.2m. In the case of the battery cell, the height of the unit cell has to be reduced, so several cells could be stacked inside one of the reduction cells from the aluminum industry.

An initial height of 30cm has been supposed for each cell, ensuring that the stated capacity can be achieved. Within this height it is included the current collectors and the top and bottom separators. This way, up to 4 cells can be stacked in what it would have been a reduction cell in the smelting process. The extra cost of the supplementary current collectors and insulators have to be included in the cost of the system.

As part of the sensitivity analysis, an extreme case will also be considered, where the height of the cell is reduced to the minimum that can ensure the proposed discharge time of 8 hours. It has been determined that the minimum height of the cell, including the top and bottom collectors can be reduced to 15cm. This way, up to 8 cells can be installed inside one of the reduction cells.

5.4 Power Conversion System costs

The power electronics required by the system differs from the one required by the aluminum smelter. The main difference is that, while for the reduction process it only needs to convert AC into DC, for the Energy Storage System, an inverter device in also required in order to convert the direct current that the battery supplies into alternate current required by the grid.

The equipment that comprises the Power Conversion System can be listed as:

- Transformer
- Rectifier
- Inverter
- Control System
- Electric panels and Switchgears

In section 4.4 a graph with the cost per kW due to the rectifier was displayed. It could be noticed that the cost per kW was lower as both the output voltage and current increased. Although it may seem reasonable trying to install the equipment with the highest rated power, which implies lower cost per kW, other aspects such as robustness and redundancies should also be considered.

For example, installing one rectifier rated 1000Vdc/60kA in less expensive than installing two rectifiers rated 1000Vdc/30kA each. But in case of failure of one rectifier in each case, the replacement cost will be much higher in the first situation. The same reasoning can be applied in terms of installing redundant equipment.

It also has to be noted that the cost of the transformer is dependent on the level of voltage required. There will be cases in which no transformer will be needed since the rectifier and the inverter work at the same voltage as the grid, but there will be other situations where the installation of a voltage transformer will be needed. In the case of this cost analysis, the cost of the transformer has been included, so that the final cost of the system will be an upper bound that will be able to be reduced in determinate situations.

In the case of the inverter, there is not much information about high capacity inverters, although it is known that Insulated Gate Bipolar Transistors (IGBT) have reached 1600V/1200A, and 3300V/1200A have already been announced (34).

Most of the information available is for low voltage inverters used in photovoltaic systems. Nevertheless, high capacity systems have already been designed and installed[10], and experts in the field have confirmed that the proposed system is feasible[11].

The information about small inverters for the PV industry is displayed in the next graph. It can be noticed that there is a reduction in cost per kW as the rated capacity of the inverter increases. The same effect was observed with the rectifiers, and it is due to economies of scale. The absence of data for high voltage systems makes it impossible to elaborate a graph similar to Figure 4-9 related to inverters.

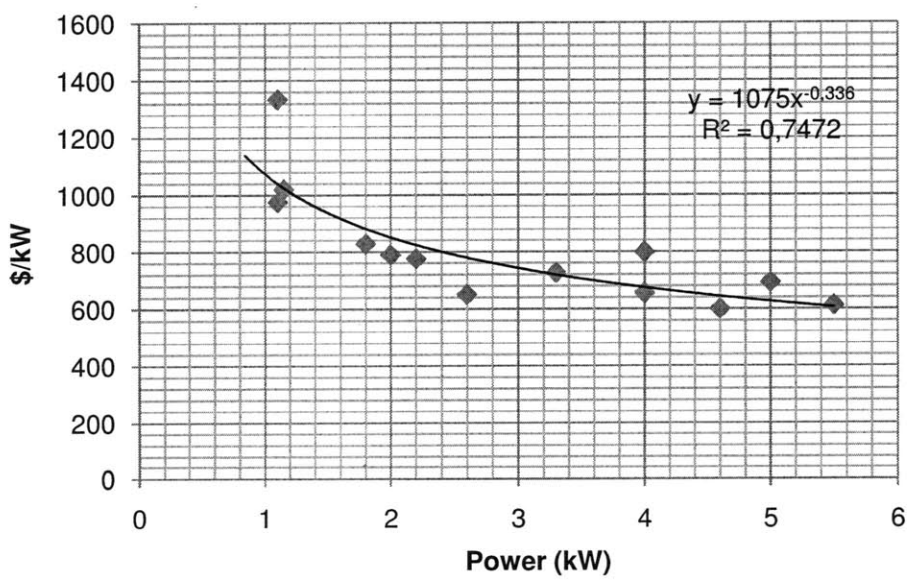


Figure 5-2 Cost per kW/Power Relation for Low Voltage Inverters [Data from (35)]

It also has to be noted that in determinate situations, such as the combination of the energy storage system and renewable energy sources, the inverter is an element that is

[10]As an example: Battery Energy Storage System installed in Fairbanks, Alaska
[11] Personal conversation with experts from ABB.

already present in the generation system due to the nature of the electricity produced by these sources (initially DC current is produced). This way, the impact of the cost of the inverter can be divided between the generation and the storage system, lowering this way the initial cost of the energy storage system. The cost of the energy storage system without the taking into account the PCS will also be calculated in order to get an idea of the real cost for such situations.

For the elaboration of the cost model of the Liquid Metal Battery, data provided from Max Wiestner (33) was employed.

With the information available, the cost of the different elements considered for the Power Conversion System can be summarized in the next chart.

Transformer	Average: $57/kW
Rectifier[12]	Minimum: $25/kW Maximum: $113/kW
Inverter[13]	Maximum: $715/kW Minimum: $530/kW
Switchboard	$17.5/kW
Control system	$800,000

Table 5-2 Cost of the different elements of the PCS

The exact values employed for each scenario are displayed in the cost models included in Annex D.

5.4.1 High Voltage Direct Current Electric Power Transmission

For future work, there is another area that could be studied, related to High Voltage Direct Current electric power transmission. In such systems, direct current is used to transport electrical power, since it more convenient for long distances, incurring in lower cost and lower electrical losses.

[12] Estimated from 100Vdc/30kA and 1650/100kA respectively
[13] Maximum based on LV Inverters for PV cells (38); minimum based on data provided by Max Wiestner (33) for a 190MW inverter.

The lines run at High Voltage (several kV) and Low Current (few kA). The rectifying and inverting process use typically insulated-gate bipolar transistors, which offer simple control and reduced cost. Some HVDC substations are set up so that they can act as both rectifier and inverter. These substations should be analyzed in terms of technology and cost and see if this technology can be applied to the Liquid Metal Battery.

5.5 Active materials

Different chemistries are being analyzed for the implementation of the Liquid Metal Battery. For this study, three possible candidates of combinations will be analyzed, and throughout this document they will be referred as

- Liquid Metal Battery A (LMB A)
- Liquid Metal Battery B (LMB B)
- Liquid Metal Battery C (LMB C)

The cost of the active materials will also be considered and its impact in the total cost of the energy storage system will be analyzed.

For the different active materials the cost per kWh has been calculated, considering for all of them an output voltage of 1V and a current density of $1A/cm^2$. The costs are summarized in the next chart.

Battery type	*Cost ($/kWh)*
LMB A	150
LMB B	50
LMB C	30

Table 5-3 Cost of active materials

The cost has been calculated considering a discharge time of 8 hours, so that it can be ensured that the amount of active materials fits into the proposed cell size.

5.6 Simplifications and assumptions

When writing this report, the lack of information has made it necessary to estimate some of the values used.

First of all, the breakdown of the cost of an aluminum smelter has been built out of data from three different sources, that although the values were within the same range, there were always some slight variations.

The investment per installed ton that has been employed to make an approximation of the cost of the smelter has been $5,500/tpy, a value that is positioned towards the upper bound (namely $6,000/tpy). This assumption has been made since this upper bound corresponds to smelters installed in the Western world. The lower investment costs correspond to smelters installed in India and China, and employing these values would have given a result that would not be realistic for this study.

Another major simplification has been made when considering the costs of the electrical equipment. The cost for the rectifier system is considered to be pretty accurate, since such devices are commonly sold for industrial applications. On the other hand, the inverter system has been slightly more complicated to estimate. Devices with the rated power (and especially rated current) as the one needed for this system are built upon request, and therefore, the cost of the equipment depends also on other factors. The value employed in this report has been provided by experts in the field, but could vary depending on the final design of the system.

In relation to the battery, the technology is already being developed, so it has been necessary to estimate some technical parameters.

For the initial calculations, the current density has been set to 1A/cm2. The cell voltage has been set to 1V. At the same time, the efficiency of the cell has been considered to be 100% (very optimistic value), and the efficiency of the Power Conversion System has been considered to be 90%. Nevertheless, sensitivity analysis will be performed in order study the behavior of the cost structure when these parameters (current density, cell voltage and efficiency) are modified.

5.7 Base Scenario

As a base case for the analysis of the cost of the energy storage system, a system equivalent to the smelter depicted in section 4.3 was designed. This disposition was chosen in order to be as accurate as possible in terms of building size and power installed.

The characteristics of the system are:

- Two parallel lines of stacks were considered.
- Each line comprises 180 stacks, making it 360 stacks in total.
- Each stack is formed by 4 cells, making the total number of cells 1440.

The complete cost model for this Base Case can be found in Annex D.

The following chart shows the characteristics considered for each cell:

Cell design		
Length	3,5	m
Width	10	m
Height	0,3	m
Cell area	35	m2
Cell characteristics		
Cell voltaje	1	V
Current density	1	A/cm2
Total current	350	kA
Cell efficiency	100%	
Roundtrip efficiency	90%	
Charge/discharge time	8	hours
Cell power	350	kW
Cell capacity	2800	kWh

Table 5-4 Cell Characteristics in Base Case

The characteristics of the complete system are summarized in the following chart:

Number of groups	360	
Total number of cells	1440	
Total Voltage	1440	V
Total Current	350	kA
Power	504	MW
Capacity	4032	MWh
Surface	30,000	m^2

Table 5-5 System Characteristics in Base Scenario

The following charts summarize the results obtained with the given data considered for the base case:

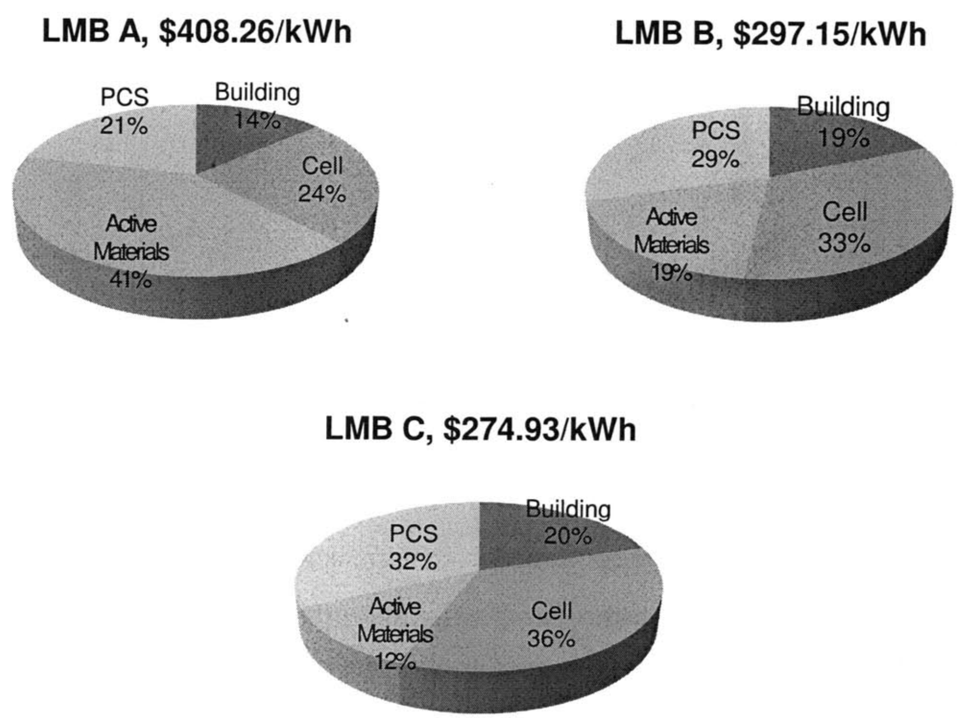


Figure 5-3 Cost per kWh Estimation for the different cathodes considered

The cost estimates for the different batteries are LMB A **$408.26/kWh**; LMB B **$297.15/kWh** and LMB C **$274.93/kWh**. The cost of the building (**$55.5/kWh**); cell

(**$98.18/kWh**) and PCS (**$87.87/kWh**) are common for the three configurations, being only the cost of the electrolyte the reason of the difference in cost.

As a reminder, the cost of the active materials for the different batteries is LMB A $150/kWh; LMB B $50/kWh and LMB C $30/kWh. In the case of the LMB A, this cost represents the **41%** of the total cost, while in the case of LMB B and LMB C it only represents the **19%** and **12%** respectively. How the price of the active materials affect the total cost of the system will be studied in the following sections, where other cases will be analyzed.

A better comparative of the three systems in terms of Active Materials, PCS and BOP can be seen in the next figure

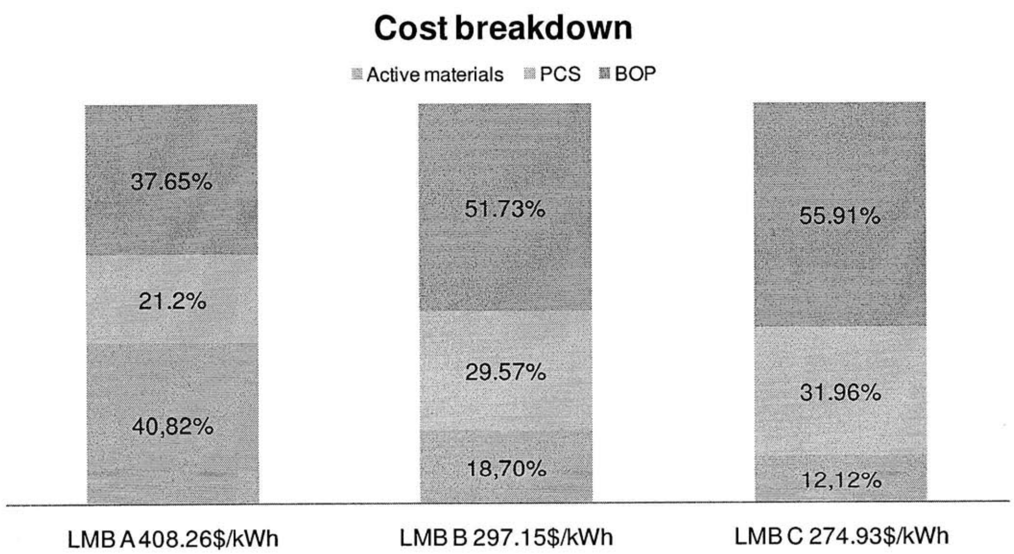


Figure 5-4 Batteries cost breakdown

The only difference among the three systems is the price of the active materials. Therefore, an analysis of the different cost of the rest of the elements will be useful to know the key factors for the cost of the system. Without taking into account the cost of the active materials, the investment required for the cell shells and all the supporting elements (PCS, conductors and building) rises up to $241.6/kWh. When compared with the price of the active materials from LMB A, it represents about the 59% of the total cost of the cell, while in the case of LMB C it goes up to the 87%.

This means that depending on the choice of the active materials, the reduction the cost of the installation will be a key factor in order to position this technology ahead of its direct competitors.

The following graph shows the breakdown cost for the all the elements different from the active materials. It can be noticed that the highest cost of the system is due to the Power Conversion System (36%) followed by the cost of the structure and lining of the cell (31%) and the building (23%). The cost of the busbars and other current collectors represents only 10% of the total cost.

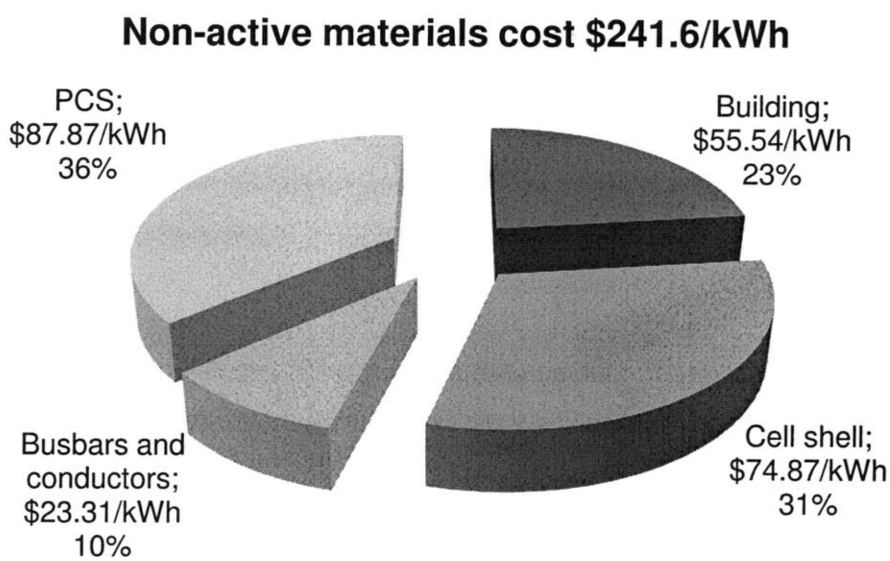


Figure 5-5 Non-active materials costs breakdown

A deeper study of the cost of the Power Conversion System will be helpful to determine the key factors that have to be addressed if a reduction of the total cost of the system wants to be achieved.

The following graph shows the breakdown of the total cost of the Power Conversion System. Out of the $88/kWh that has been estimated for the system, more that 80% is due the cost inverter. It has to be noticed that the data used for this model were estimates since such high power systems are designed individually. Nevertheless, economies of scale can be expected, as it was observed for the inverters used in the PV industry referred in section 5.4.

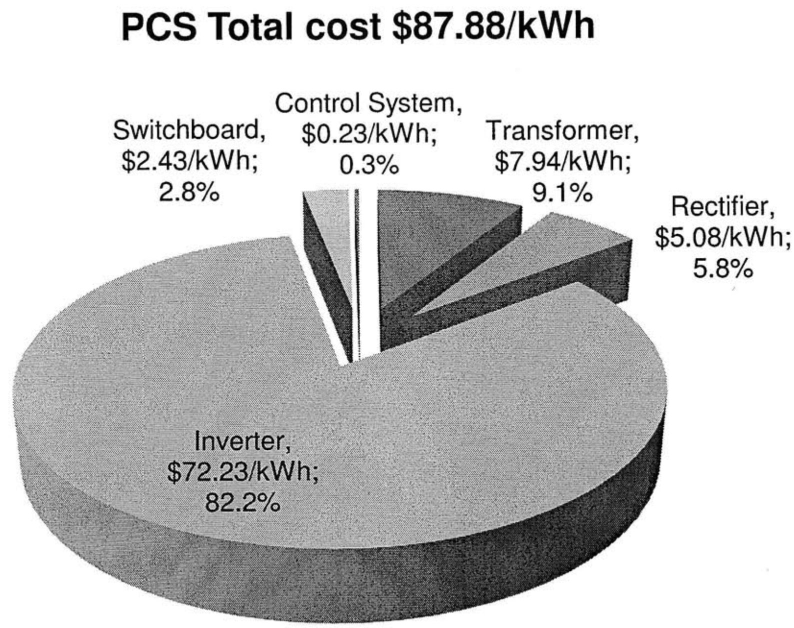


Figure 5-6 PCS costs breakdown

Other elements such as the power transformer or the rectifier have a much lower impact (9% and 5.8% respectively), while the costs of the control system and switchboards are almost negligible.

Sometimes, the different storage technologies evaluate their cost without taking into account the cost of the power conditioning equipment. According to this, the estimate cost for the different systems would be

LMB A	$320/kWh
LMB B	$209/kWh
LMB C	$187/kWh

These values will help comparing the LMB against its competing technologies.

5.8 Sensitivity analysis

In this section a sensitivity analysis of the system will be performed, trying to best describe the behavior of the cost per kWh of the system when some parameters are changed.

The first case will correspond to the situation where the capacity of the systems remains unchanged with respect to that from the base scenario, while instead of only one level of groups of cells, one cell will be placed on top of another up to five levels. This way the footprint of the system will be reduced.

The second situation that will be analyzed will be the situation where the height of the cell will be reduced to the minimum value that guaranties the cell capacity. The height considered will be 15cm in comparison with the 30cm from the base scenario. This way, instead of forming groups of 4 cells, they will be formed by 8 cells, reducing also this way the footprint of the system. The power and capacity of the system will be kept unchanged with respect to the initial configuration.

The third aspect that has been analyzed corresponds to the relationship between the size of the cell and the cost per kWh. The initial size has been considered as the maximum size for the cell (since it is the most profitable in the aluminum industry), and the impact in the cost that reducing the size of the cell has been analyzed.

And lastly, some sensitivity analysis has been made in terms of cell voltage, current density and cell efficiency. The result will help know how the costs will behave once the technology has been further developed.

5.8.1 Same capacity, smaller footprint

The first variation of the base case will consist on a system with the same power and capacity as the base case but where, instead of one level of stacks of cells, five levels will be stacked one on top of another. This way, the cell surface will be kept unchanged while the total surface of the installation will be reduced. The impact that this reduction has in the total cost per kWh of the system will be determined.

If five stacks are piled up one on top of another, the group will have a height of 6m. With a surface dimensions of 3.5m x 10m, the system will be approximate 1.7 times larger than the shortest dimension of the base, which confers stability to the system. The cells are supposed to be mechanically sound to support the weight of the stack of cells without extra external support.

The characteristics of the cells remain the same as expressed in Table 5-4. The characteristics of the complete system are described in the following chart.

Number of groups	360	
Total number of cells	1440	
Number of levels	5	
Number of groups per level	72	
Total Voltage	1440	V
Total Current	350	kA
Power	504	MW
Capacity	4032	MWh
Surface	6,000	m^2

Table 5-6 System Characteristics in Case 1

As in the Base Case, the three sets of different active materials have been considered, analyzing the impact of this disposition in the cost per kWh of the system.

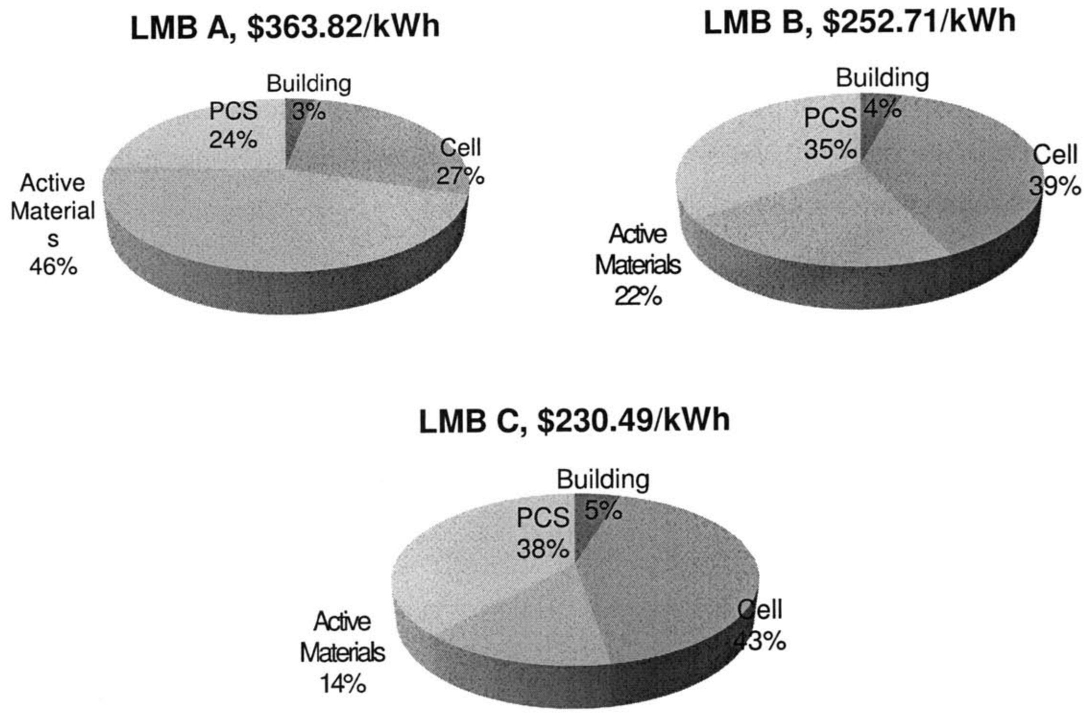


Figure 5-7 Cost per kWh Estimation for the different cathodes considered

The following chart shows the comparison between this configuration and the one presented in the base case.

	LMB A		LMB B		LMB C	
	Base Scen	*Scen One*	*Base Scen*	*Scen One*	*Base Scen*	*Scen One*
$/kWh	408.26	363.82	297.15	252.71	274.93	230.49
Ratio	0.89		0.85		0.84	
% Building	14%	3%	19%	4%	20%	5%
% Cell	24%	27%	33%	39%	36%	43%
% Active Materials	41%	46%	19%	22%	12%	14%
% PCS	21%	24%	29%	35%	32%	38%

Table 5-7 Comparison between Base Scenario and Scenario One

It can be noticed that reductions from 11% to 16% can be achieved if several levels of cells are place on top of one another. In this case, the cost of the Power Conversion System turns more significant in the case of the low cost active materials systems (LMB B and C) while in the case of LMB A the cost of the active materials turn out to be the key factor, representing around 46% of the total cost.

5.8.2 Minimum height, group comprised by eight cells

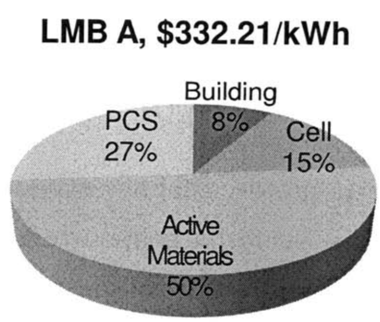
As it was already described in section 5.3, the initial height of the cell has been set to be 30 cm. Nevertheless, this height can be reduced up to 15cm without decreasing the storage capacity of the system. In this section, the impact of the reduction of the cell height will be analyzed.

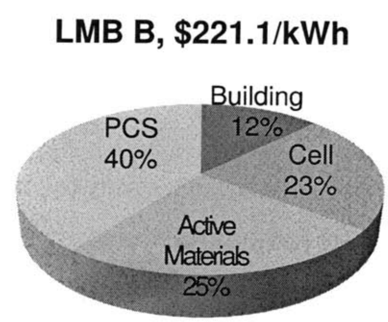
In order to keep it as simple as possible in order to compare with the initial configuration, a system with the same power and energy capacity as the initial situation was designed. The characteristics of the complete system are summarized in the following chart.

Number of groups	180	
Total number of cells	1440	
Voltage	1440	V
Current	350	kA
Power	504000	kW
Capacity	4032000	kWh
Surface	15,000	m^2

Table 5-8 System Characteristics in Scenario Two

The results given by this set of data are shown in the next figures:





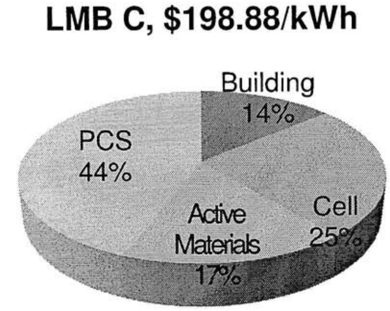


Figure 5-8 Cost per kWh estimation for the second scenario

The results are summarized in the following chart, where they are also compared with the results obtained in the base case:

	LMB A		LMB B		LMB C	
	Base Scen	*Scen Two*	*Base Scen*	*Scen Two*	*Base Scen*	*Scen Two*
$/kWh	408.26	332.21	297.15	221.1	274.93	198.88
Ratio	0.81		0.74		0.72	
% Building	14%	8%	19%	12%	20%	14%
% PCS	21%	27%	29%	40%	32%	44%
% Active Materials	41%	50%	19%	25%	12%	17%
% Cell	24%	15%	33%	23%	36%	25%

Table 5-9 Comparison between Base Scenario and Scenario Two

It can be noticed that a reduction from 19% to 28% can be achieved by reducing the height of the cell but without varying the cell power, which is the same as increasing the power density of the cell.

The cost of the PCS and the active materials has grown in terms of significance, while the percentages of the cost of the cell and the building have been reduced. By stacking eight cells inside one pot we can get a reduction in the cost of the building and the cell.

5.8.3 Cell size sensitivity

The relationship between the cost and the cell size has been analyzed. The initial cell size considered has a surface area of $35m^2$. The reason for choosing this size is that it corresponds to the size of an AP35 cell used in the aluminum industry and in which the complete cost breakdown has been based.

The cost of the cell has been considered to be proportional to its surface, although to get a more accurate estimate, it would be necessary to get more information about the cost of the different type of cells in the aluminum industry and try to get a better approximation. Nevertheless, for an initial estimation, which is what this analysis intends to be, this first approximation can be expected to be acceptable.

The cell characteristics have been kept unchanged from those employed in the base scenario, and can be seen in Table 5-4

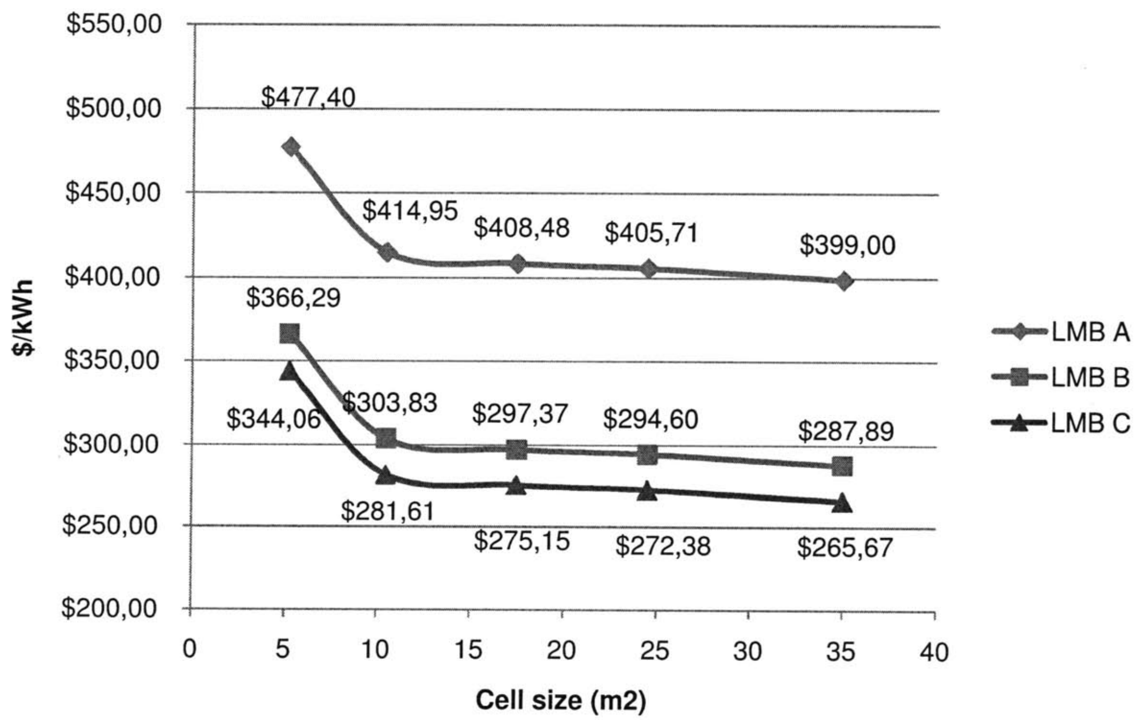


Figure 5-9 Effect of cell size in cell cost

It can be observed how the influence of the cell size in the cell cost decreases as the size of the cell increases. The reason for this happens to be that the distance between cells have been kept unchanged whereas the dimensions of the cell change, so that the ratio building area to cell surface area is higher for smaller cells than for bigger cells. This way, the costs of construction and civil works have a higher impact in smaller cells. Some further analysis could be made in order to find the best distribution for each cell size, but for this initial approximation the floor disposition is preferred to be kept unchanged.

Another consideration has also to be made. The cell current relates directly to the cell surface area, and it has already been mentioned that the cost of the power electronics are highly dependent on the rated current rather than on the rated power, so reducing the system total current will imply a higher cost per kW for the rectifier and the inverter, increasing even more the cost here estimated.

5.8.4 Cell voltage, current density and cell efficiency sensitivity

The technology here presented is still under research, and the final characteristics of the system in terms of cell voltage, current density and cell efficiency will have a great impact in the final cost of the system.

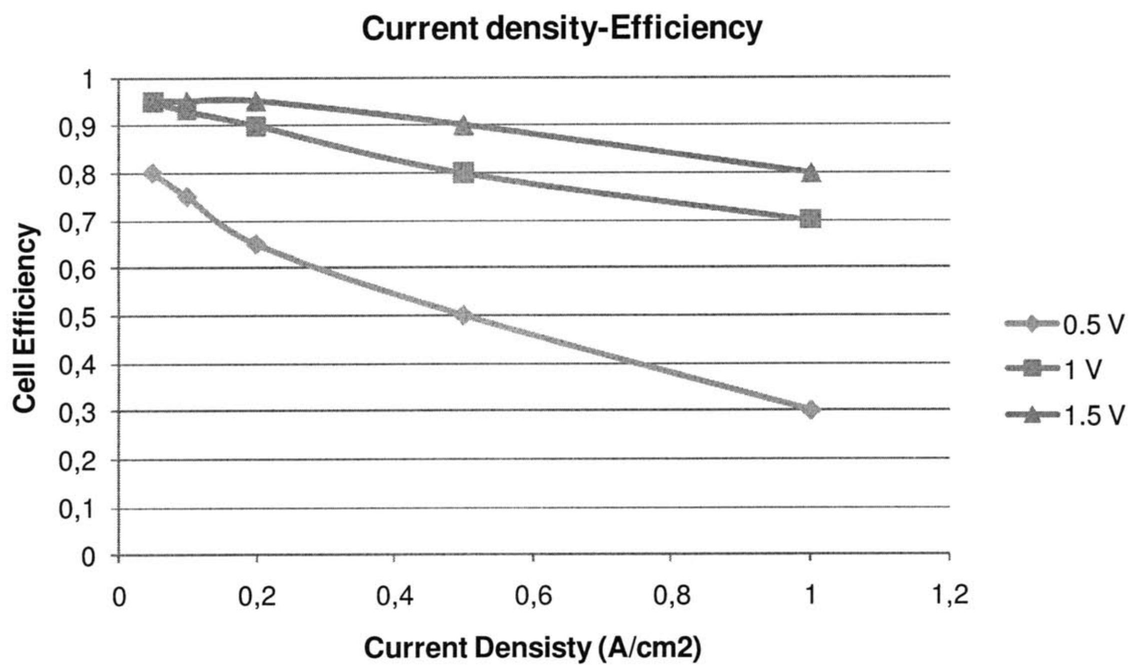


Figure 5-10 Cell efficiency for some cell voltages

The figure above shows the estimated relationship between current density and efficiency for different values of cell voltages. The cell technology is still under development, so the data displayed above are rough estimates of the possible behavior of the cell but they will help to give an idea of what to expect once the technology of the cell is fully developed.

The following graphs show the result of applying the previous data to the cost model of the Liquid Metal Batter

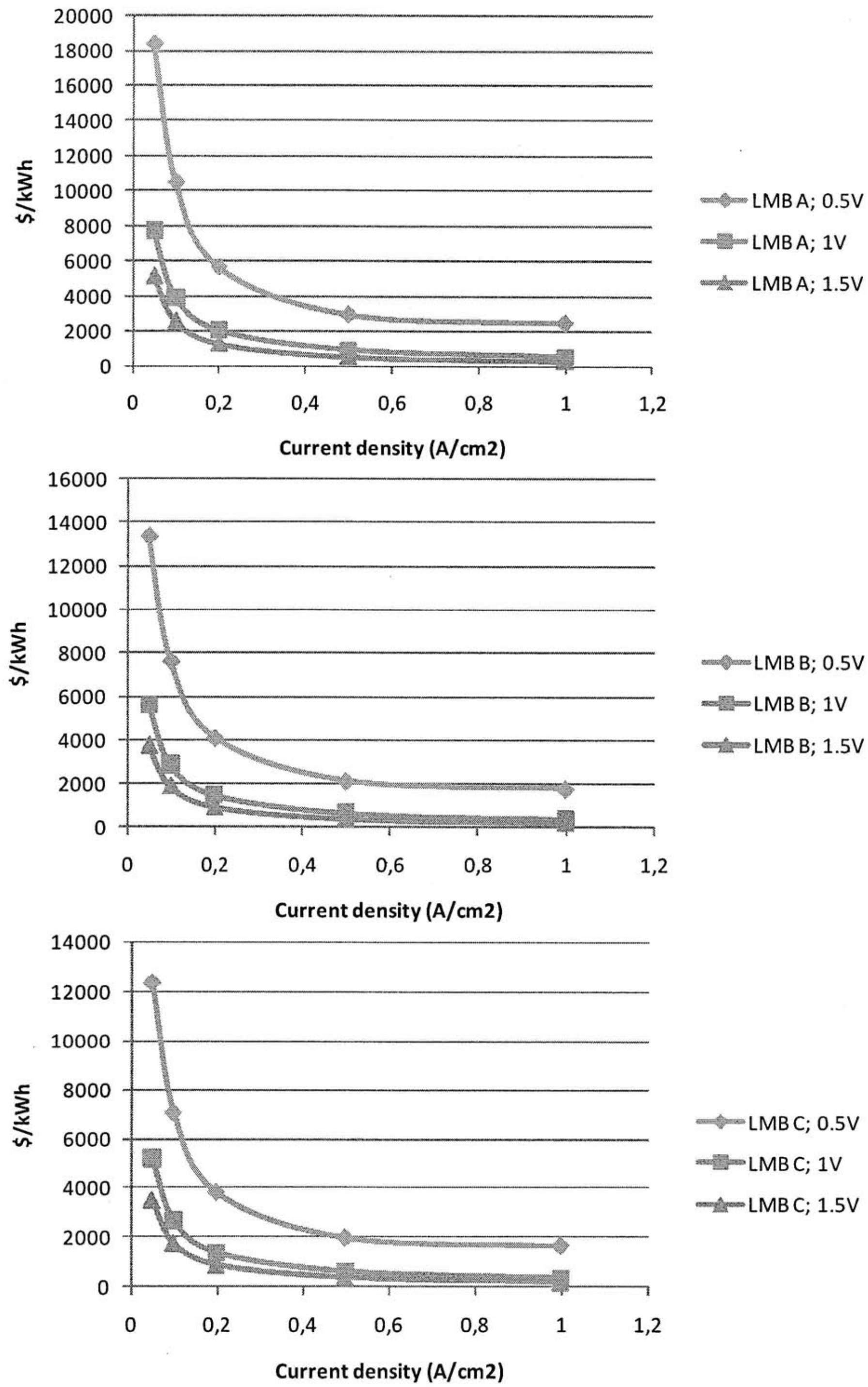


Figure 5-11 Cell cost for different voltages, current densities and efficiency

5.9 Summary

The following charts summarize the results already presented in the former sections. They have been divided by active material, in order to make an easier comparison.

LMB A

	Base Scenario	Scenario One	Scenario Two
$/kWh	408.26	363.82	332.21
% Building	14%	3%	8%
% PCS	21%	24%	21%
% Active Materials	41%	46%	41%
% Cell	24%	27%	24%

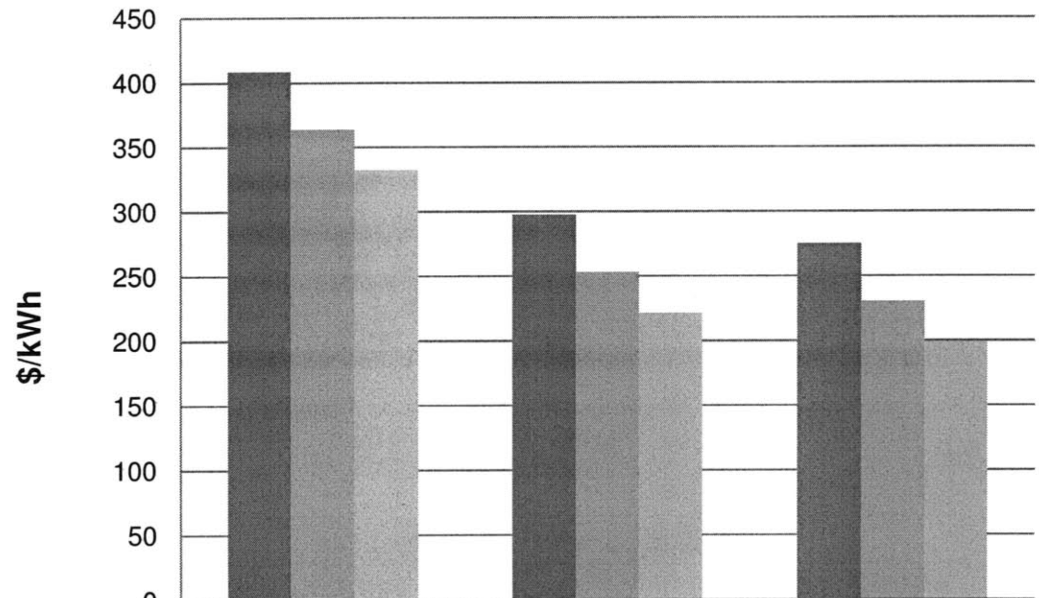
LMB B

	Base Scenario	Scenario One	Scenario Two
$/kWh	297.15	252.71	221.1
% Building	19%	4%	12%
% PCS	29%	35%	40%
% Active Materials	19%	22%	25%
% Cell	33%	35%	23%

LMB C

	Base Scenario	Scenario One	Scenario Two
$/kWh	274.93	230.49	198.88
% Building	20%	5%	14%
% PCS	32%	38%	44%
% Active Materials	12%	14%	17%
% Cell	36%	43%	25%

The following chart summarizes the cost estimations for the complete system in the three main scenarios analyzed (those related to energy applications). It has to be noted how the most profitable configuration is the one considered in Scenario Two, where eight cells are place in each of the pots, reducing the footprint to one half of the initial value.



	LMB A	LMB B	LMB C
Base Scenario	**408,26**	**297,15**	**274,93**
Scenarion One	**363,82**	**252,71**	**230,49**
Scenario Two	**332,21**	**221,1**	**198,88**

Figure 5-12 Complete comparison among scenarios

In this case, where the height of the cell is reduced to its minimum, the reduction in cost goes from a 19% in the case of LMB A to a 28% in the case of LMB C.

In Scenario One, we can see that reducing the total footprint of the system to one fifth of its initial value entails a reduction of 11% in the total cost of the system with the most expensive active materials (LMB A) while for the system with the less expensive ones, it implies a reduction of 16% of the total cost.

6

Chapter 6 Conclusions

6.1 Main conclusions

Aluminum reduction is one of the best known electrolytic industrial processes. Due to its characteristic high current density, it has been taken as a model for the development of the Liquid Metal Battery developed by Group Sadoway.

In order to get an estimate of the cost of this Energy Storage System, the capital costs of the Aluminum Smelting Industry has been analyzed.

It has been determined that the average investment in the aluminum smelter industry varies from $4,500 to $6,000 per installed ton, depending on location and size.

This investment has been deeply analyzed, in order to calculate the investment required by each of the subsystems that composes the smelter. There has been a special interest in breaking down the cost of the different elements within the reduction building in order to get the most accurate estimation as possible. The reduction cells used in the reduction process have been adapted in order to fit the requirements of the Energy Storage System.

Another element that has also been scrutinized has been the electrical substation, comprised by the transformers and rectifiers in charge of the power conditioning. The understanding of this system has helped estimate the cost of the power conversion system needed by the energy storage system.

With all these, the cost per kWh for three different types of Liquid Metal Batteries (based on different combinations of active materials) has been calculated, and is displayed in the next figure.

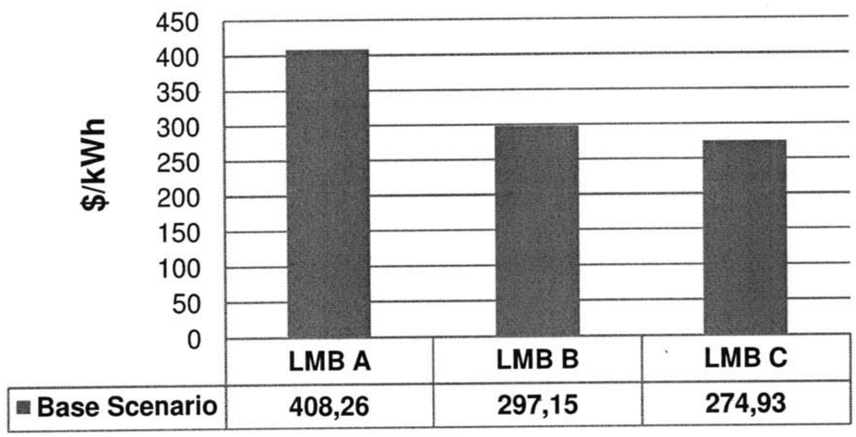


Figure 6-1 Base Scenario Summary

These values are useful in order to compare the proposed technology with its competitors. The following chart shows the current cost in $/kWh for most of the current energy storage technologies.

Technology	Current Cost ($/kWh)	10-yr Projected Cost ($/kWh)
Flooded Lead Acid Batteries	$150	$150
VRLA Batteries	$200	$200
NiCd Batteries	$600	$600
Ni-MH Batteries	$800	$350
Li-ion Batteries	$1,333	$780
NaS Batteries	$450	$350

Technology	Current Cost ($/kWh)	10-yr Projected Cost ($/kWh)
Zebra Na/NiCl Batteries	$800[14]	$150
Vanadium Redox Batteries	20kWh=$1,800/kWh 100kWh=$600/kWh	25 kWh= $1200/kWh 100 kWh=$500/kWh
Zn/Br Batteries	$500	$250/kWh plus $300/kW[15]
Low-speed Flywheels	$380	$300
High-speed Flywheels	$1,000	$800
Electrochemical Capacitors	$356/kW	$250/kW

Table 6-1 Energy Storage Systems Capital Cost (36)

A quick look through the table gives an idea about the position of the Liquid Metal Battery. Although it seems that there are some technologies with lower costs than the proposed system, it has to be noted that there are other parameters that need to be analyzed in order to determine which technology is the most suitable for the specific application.

The following graph gives a better idea in terms of comparison among systems. It can be seen where the Liquid Metal Battery is placed according to the cost estimations developed in this report (labeled as LMB (expected)). Its position is quite favorable against other systems such as NaS or Li-ion batteries. It can also be said that although Pumped Hydro and CAES are placed in a better position with respect to the LMB, these technologies have some limitations since they required some specific requirements for their installation that cannot most of the times be fulfilled.

[14] €600/kWh

[15] The battery system includes an integrated PCS; the PCS price will vary with the rated system output

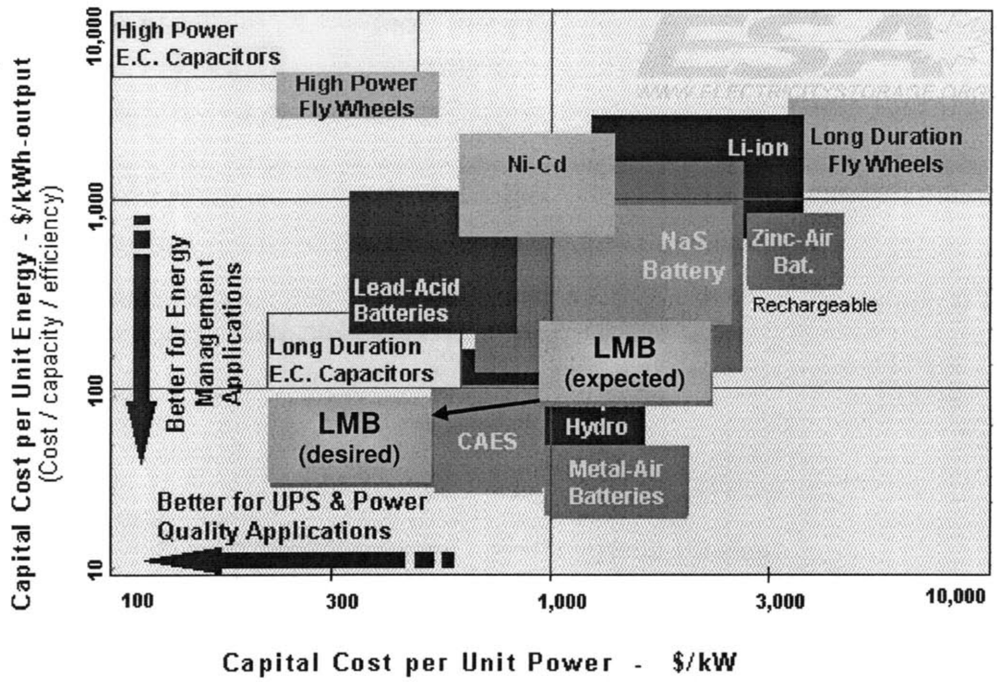


Figure 6-2 Capital Cost per Unit Power- per Unit Energy Comparison [Modified form (11)]

In any case, great effort needs to be made in order to reduce the PCS and BOP cost of the system so that the technology can be placed in the best favorable position of the chart (marked as LMB (desired)). If this position is achieved, the rest of advantages of the Liquid Metal Battery will help it succeed as the best Large Scale Energy Storage System.

6.2 Future work

It has been remarked through the whole report the difficulty of getting enough data to get a much more accurate estimation of the Power Conversion System.

Further effort could be made to get a more accurate configuration of the Power Conversion System, where the costs are thoroughly analyzed in order to get a better cost model for the Liquid Metal Battery.

Once the technology is completely developed, more accurate values can be obtained, since the relationship between cell voltage, current density and efficiency will be known.

Another area that can be analyzed is the possibility of retrofitting a shut down smelter. This way the smelter that is no longer operating could be refurbished and turned into an Energy Storage System. It could be interesting analyzing the cost of such a system since a reduction in building and cell technology cost can be expected.

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Annex A List of Future Smelters

Data extracted from (32)

Smelter	Investment (million $)	Capacity (tpy)	$/ton
Aluar -> Argentina	292	60000	4866.667
Aluar -> Argentina (expansions)	400	105000	3809.524
Alutrint -> Trinidad and Tobago	540	120000	4500
NFC -> China	775	120000	6458.333
Trinidad and Tobago	465	125000	3720
Aluar -> Argentina (expansions)	850	130000	6538.462
Rusal -> Irkutk	600	170000	3529.412
Aluar -> Argentina	650	180000	3611.111
Alcasa -> Venezuela	710	210000	3380.952
CVG -> Venezuela	685	240000	2854.167
Citi Group -> Egypt	800	270000	2962.963
Nalco -> Iran	1700	310000	5483.871
Rio Tinto BC Hydro -> Canada Kitimat Smelter	2500	400000	6250
India -> Ashapura	1500	500000	3000
Nalco -> Indonesia	3200	500000	6400
Qatalum -> Qatar	4600	609000	7553.366
Dubal -> Algeria	5000	700000	7142.857
Abu Dhabi -> al Ruwais	5000	700000	7142.857
Emal -> Saudi Arabia	5000	700000	7142.857
Rusal -> Russia	2000	750000	2666.667
Century Aluminum -> Democratic Republic of Congo	3000	800000	3750
Dubal -> Algeria	5400	900000	6000
Dubal -> Abu Dhabi (Emal)	8000	1400000	5714.286

Annex B List of Current Smelters

Smelter	Location	Investment (million $)	Capacity (tpy)	$/ton
VALE DO SUL ALUMINIO S.A. (VALESUL)	SANTA CRUZ BRAZIL	400	93000	4301.075
PECHINEY	DUNKIRK FRANCE	850	215000	3953.488
ALUMINERIE LAURALCO INC	DESCHAMBAULT, QUEBEC CANADA	840	235000	3574.468
MOZAMBIQUE ALUMINIUM CO. (MOZAL)	MAPUTO MOZAMBIQUE	1300	250000	5200
ALCAN SMELTERS & CHEMICAL LTD.	ALMA, QUEBEC CANADA	1600	375000	4266.667

Annex C Aluminum Smelter Investment Breakdown

Cost breakdown			Total cost	Cost per unit	
			$ 2.000.000.000,00		
EPC		**6,00%**	$ 120.000.000,00		
Civil and construction		**23,00%**	$ 460.000.000,00	$15.333,33	/m2
	Reduction building civil and construction	*44%*	*$ 201.560.834,91*	*$ 6.718,69*	*/m2*
	Utilities	*33%*	*$ 150.168.503,63*	*$ 5.005,62*	*/m2*
	General Services	*8%*	*$ 38.994.031,33*	*$ 1.299,80*	*/m2*
	Site and civil works	*15%*	*$ 69.276.630,13*	*$ 2.309,22*	*/m2*
Cells, Pot tending and Technology		**20,00%**	$ 400.000.000,00	$1.111.111,11	/cell
	Pot shells and linings, including lids and anodes jacking	*67,92%*	$ 271.676.300,58	$ 754.656,39	*/cell*
	Busbar and conductors	*20,04%*	$ 80.154.142,58	$ 222.650,40	*/cell*
	Cranes-Pot tending machine	*12,04%*	$ 48.169.556,84	$ 133.804,32	*/cell*
Alumina Conveying System		**15,00%**	$ 300.000.000,00		
Anode Plant		**30,00%**	$ 600.000.000,00		
Casting and dispatch		**2,00%**	$ 40.000.000,00		
Rectifier substation		**4,00%**	$ 80.000.000,00	$ 58,73	/kW
	Transformers	*36,00%*	*$ 28.800.000,00*	*$ 57,14*	*/kW*
	Rectifiers	*23,00%*	*$ 18.400.000,00*	*$ 36,51*	*/kW*
	Level 2 Scada	*1,00%*	*$ 800.000,00*		
	Plant Engineering PM	*16,00%*	*$ 12.800.000,00*	*$ 25,40*	*/kW*
	Construction	*8,00%*	*$ 6.400.000,00*	*$ 12,70*	*/kW*
	GIS with cables	*11,00%*	*$ 8.800.000,00*	*$ 17,46*	*/kW*
	Power factor correction	*5,00%*	*$ 4.000.000,00*	*$ 7,94*	*/kW*

Annex D LMB Base Scenario Cost Model

Building

		Price per m2	Total
Surface (m2)	30000	$ 6.718,69	$201.560.834,91

Cells

		Price per 'group'	Total	%
Number of groups	360	$754.656,39	$271.676.300,58	76,3%
Busbars and conductors	360	$222.650,40	$80.154.142,58	22,5%
Current collectors/ cell separators	2160	$2.047,50	$4.422.600,00	1,2%

Battery active materials

	kWh	$/kWh	Total
LMB A	4032000	$150	$604.800.000
LMB B	4032000	$50	$201.600.000
LMB C	4032000	$ 30	$120.960.000

Power electronics

	kW	$/kW	Total	%
Transformer	504000	$ 57,14	$28.800.000,00	9,0%
Rectifier	504000	$36,51	$18.400.000,00	5,8%
Inverter	504000	$520,00	$262.080.000,00	82,2%
Switchboard	504000	$ 17,46	$8.800.000,00	2,8%
Control System	1	$800.000,00	$800.000,00	0,3%
			$ 318.880.000,00	100,0%

Results

LMB A

		$/kW	$/kWh	%
Building	$201.560.834,91	$444,36	$55,54	13,6%
Cell	$356.253.043,16	$785,39	$ 98,17	24,0%
Active Materials	$604.800.000	$1.333,33	$166,67	40,8%
PCS	$318.880.000,00	$703,00	$87,87	21,5%
Total	**$1.481.493.878,07**	**$3.266,08**	**$408,26**	

LMB B

		$/kW	$/kWh	%
Building	$201.560.834,91	$444,36	$55,54	18,7%
Cell	$356.253.043,16	$785,39	$98,17	33,0%
Active Materials	$201.600.000	$444,44	$55,56	18,7%
PCS	$318.880.000,00	$703,00	$87,87	29,6%
Total	**$1.078.293.878,07**	**$2.377,19**	**$ 297,15**	

LMB C

		$/kW	$/kWh	%
Building	$201.560.834,91	$444,36	$ 55,54	20,2%
Cell	$356.253.043,16	$ 785,39	$98,17	35,7%
Active Materials	$120.960.000	$266,67	$33,33	12,1%
PCS	$ 318.880.000,00	$ 703,00	$87,87	32,0%
Total	**$997.653.878,07**	**$2.199,41**	**$274,93**	

Annex E LMB Scenario One Cost Model

Building

		Price per m2	Total	
Surface (m2)	6000	$ 6.718,69	$40.312.166,98	

Cells

		Price per 'group'	Total	%
Number of groups	360	$754.656,39	$271.676.300,58	76,3%
Busbars and conductors	360	$222.650,40	$80.154.142,58	22,5%
Current collectors/ cell separators	2160	$2.047,50	$4.422.600,00	1,2%

Battery active materials

	kWh	$/kWh	Total
LMB A	4032000	$150	$604.800.000
LMB B	4032000	$50	$201.600.000
LMB C	4032000	$30	$ 120.960.000

Power electronics

	kW	$/kW	Total	%
Transformer	504000	$ 57,14	$ 28.800.000,00	9,0%
Rectifier	504000	$36,51	$18.400.000,00	5,8%
Inverter	504000	$520,00	$262.080.000,00	82,2%
Switchboard	504000	$17,46	$8.800.000,00	2,8%
Control System	1	$800.000,00	$ 800.000,00	0,3%

Results

LMB A

		$/kW	$/kWh	%
Building	$40,312,166.98	$88.87	$ 11.11	3.1%
Cell	$356,253,043.16	$ 785.39	$ 98.17	27.0%
Active Materials	$604,800,000	$1,333.33	$166.67	45.8%
PCS	$318,880,000.00	$703.00	$87.87	24.2%
Total	**$1,320,245,210.14**	**$2,910.59**	**$363.82**	

LMB B

		$/kW	$/kWh	%
Building	$ 40,312,166.98	$ 88.87	$ 11.11	4.4%
Cell	$356,253,043.16	$785.39	$98.17	38.8%
Active Materials	$201,600,000	$ 444.44	$ 55.56	22.0%
PCS	$ 318,880,000.00	$703.00	$87.87	34.8%
Total	**$917,045,210.14**	**$2,021.70**	**$252.71**	

LMB C

		$/kW	$/kWh	%
Building	$40.312.166,98	$ 88.87	$11.11	4.8%
Cell	$356,253,043.16	$ 785.39	$98.17	42.6%
Active Materials	$120.960.000	$266.67	$ 33.33	14.5%
PCS	$ 318.880.000,00	$ 703.00	$ 87.87	38.1%
Total	**$917,045,210.14**	**$2,021.70**	**$252.71**	

Annex F LMB Scenario Two Cost Model

Building

		Price per m2	Total
Surface (m2)	15000	$6.718,69	$100.780.417,46

Cells

		Price per 'group'	Total	%
Number of groups	180	$ 754.656,39	$ 135.838.150,29	75,0%
Busbars and conductors	180	$222.650,40	$40.077.071,29	22,1%
Current collectors/cell separators	2520	$2.047,50	$5.159.700,00	2,8%

Battery active materials

	kWh	$/kWh	Total
LMB A	4032000	$ 150	$ 604.800.000
LMB B	4032000	$50	$201.600.000
LMB C	4032000	$ 30	$ 120.960.000

Power electronics

	kW	$/kW	Total	%
Transformer	504000	$ 57,14	$28.800.000,00	9,0%
Rectifier	504000	$36,51	$ 18.400.000,00	5,8%
Inverter	504000	$520,00	$262.080.000,00	82,2%
Switchboard	504000	$ 17,46	$8.800.000,00	2,8%
Control System	1	$800.000,00	$800.000,00	0,3%

Results

LMB A

		$/kW	$/kWh	%
Building	$ 100.780.417,46	$222,18	$27,77	8,4%
Cell	$181.074.921,58	$399,20	$49,90	15,0%
Active Materials	$604.800.000	$ 1.333,33	$166,67	50,2%
PCS	$ 318.880.000,00	$ 703,00	$87,87	26,5%
Total	**$1.205.535.339,04**	**$2.657,71**	**$332,21**	

LMB B

		$/kW	$/kWh	%
Building	$100.780.417,46	$222,18	$ 27,77	12,6%
Cell	$181.074.921,58	$399,20	$ 49,90	22,6%
Active Materials	$201.600.000	$444,44	$55,56	25,1%
PCS	$318.880.000,00	$703,00	$87,87	39,7%
Total	**$802.335.339,04**	**$ 1.768,82**	**$ 221,10**	

LMB C

		$/kW	$/kWh	%
Building	$100.780.417,46	$222,18	$27,77	14,0%
Cell	$181.074.921,58	$399,20	$ 49,90	25,1%
Active Materials	$120.960.000	$266,67	$ 33,33	16,8%
PCS	$ 318.880.000,00	$703,00	$87,87	44,2%
Total	**$ 721.695.339,04**	**$1.591,04**	**$198,88**	