Potential economic and environmental advantages of lithium-ion battery manufacturing using geothermal energy in Iceland

Pai-Chun Tao

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by

Pai-Chun Tao

Thesis

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Thesis submitted to the School of Science and Engineering
at Reykjavík University in partial fulfillment
of the requirements for the degree of
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Abstract

The lithium-ion battery is one of the most critical technologies for energy storage in many recent and emerging applications. However, the cost of lithium-ion batteries limits their penetration in the public market. Energy input is a significant cost driver for lithium batteries due to both the electrical and thermal energy required in the production process. The drying process requires 45~57% of the energy consumption of the production process according to our model. In Iceland, it is possible to use geothermal steam as a thermal resource in the drying process. The most feasible type of dryer and heating method for lithium batteries would be a tray dryer (batch) using a conduction heating method under vacuum operation. Replacing conventional heat sources with heat from geothermal steam in Iceland, we can lower the energy cost to 0.009USD/Ah from 0.054USD/Ah based on average European energy prices. The energy expenditure after 15 years operation could be close to 1.03% of total expenditure using this renewable resource, down from 7~11% in other European countries. According to our profitability model, the internal rate of return of this project will increase from 9%~11% in other European countries to 27% by replacing the energy source. The impact on carbon emissions amounts to 393.4-215.1g/Ah lower releases of CO_2 per year, which is only 3-5 % of original carbon emission compared to traditional energy sources in other countries.

摘要

在近來許多新興能源應用上，鋰電池是一項非常重要的能源儲存科技；然而，鋰電池較高的成本卻局限了它在大眾市場的占有率。由於在生產過程中電能與熱能的需求使能源成本在鋰電池中成為顯著的因素。根據我們的模型，乾燥過程大約需要耗去總生產耗能中的45~57%能源；而在冰島我們有機會利用地熱蒸汽於乾燥製程中的熱源，調查結果中顯示最適合鋰電池的乾燥機類型與加熱模式是真空傳導式托盤乾燥機。當我們在冰島使用地熱蒸汽取代傳統熱源時，可將能源成本從歐洲平均能源成本0.054(美金/度)降低至0.009(美金/度)。在十五年的營運之後，再生能源的利用將讓能源支出佔總支出的比例從歐洲其它國家的7~11%降至在冰島的1.03%。根據我們的利益率模型，藉由能源的替代，此案之內部收益率將會從歐洲其它國家的9~11%成長到27%。至於在碳排放的影響上，它僅僅排放了其它使用傳統能源國家3-5%的二氧化碳排放量，降低了393.4-215.1 克/安培。

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1. Introduction

1.1 Motivation of this thesis

The exponential growth in the use of portable electronic devices and electric vehicles has created enormous interest in inexpensive, compact, light-weight batteries offering high energy density. The lithium-ion battery is one of the most appealing technologies to satisfy this need. It is estimated that the global market for lithium-ion batteries could grow from $877 million in 2010 to $8 billion by 2015 (Pike Research , 2010). However, the cost of lithium-ion batteries limits their penetration in the global market. Energy is a significant cost driver for lithium batteries as both electrical and thermal energy is required in the raw materials processing and battery manufacturing and assembly. Iceland offers a number of potential avenues for cost and carbon emissions reductions in the manufacturing process, due to readily available medium grade thermal energy from geothermal or industrial sources, access to inexpensive renewable electricity, and a skilled workforce. The purpose of this thesis is to quantify the economic advantages and carbon emission reductions to be gained by siting a lithium iron phosphate ($LiFePO_4$) factory in Iceland close to geothermal heat sources, versus sites in other locations where fossil sources of energy must be used. Furthermore, we will also present the sensitivity of profitability to energy cost.

1.2 Methodology of research

The project consists of three main tasks: 1) Collection of relevant data and information. 2) Estimation of energy consumption at various steps in the production process and 3) Assessment of profitability and impact on carbon emissions. Firstly, the literature review, including interview data, provides us information to draw a complete production process map of the lithium iron phosphate battery manufacturing process. Unfortunately, the detailed energy consumption data from each step in lithium battery production is not readily available from factories due to confidentiality reasons in this competitive market. Consequently, we build a theoretical energy consumption model for drying process based on the thermal properties and moisture content of materials in the batteries, basic physical formulas, and industrial experience. There are some uncertainties existing in this model, such as energy efficiency, heat loss, and other assumptions. The result of this energy consumption model is therefore not an accurate value from an actual factory, but should be realistic none the less. In reality, it could be lower or higher depending on individual equipment design. In terms of the profitability assessment, there are some common standards of estimating the profit of an investment, for example, net present value (NPV) and the internal rate of return (IRR). Consequently, we build a comprehensive profitability assessment model of building a new lithium iron battery factory in Iceland. Most cost data are obtained directly from suppliers or the publicly available information. In the model, we make several financial assumptions, such as rate of debt, interest rate based on conditions in Iceland. The profitability calculation and Monte Carlo analysis are performed by Microsoft Excel plug in with @Risk5.7.

1.3 Structure of thesis

This thesis consists of six chapters and appendix at the end:

Chapter 2: Contains the basic knowledge of lithium ion battery technology, lithium metal extraction, and lithium oxide synthesis to help us understand how Li-battery function in real world and some energy related issue in this industry.

Chapter 3: Address how energy cost in Iceland can be optimized. Firstly, the production process map will be present as text and figures. Secondly, we deduce the energy consumption from drying process by the theoretical model. Finally, we find out the alternative drying methods and equipments for the battery factory in Iceland.

Chapter 4: Covers background information of Iceland energy market, available energy resource, and carbon footprint associated with most resources. Base on this, it is demonstrated that Iceland has an appealing investment environment for lithium battery industry.

Chapter 5: In this chapter, we perform a feasibility assessment study of building a lithium ion battery factory in Iceland. From this, we will know how energy cost effect the entire cost and the potential financial profitability of this investment.

Chapter 6: Sums up the conclusions from the thesis and points out interesting paths to explore in future work.

2. Literature reviewing of related technologies

In this research we investigate the production cost of lithium ion battery with a special focus on the cost contribution associated with energy consumption. Firstly, we would sort out the basic theory and key components of lithium ion batteries in order to understand how does it work in reality. In addition, extraction of lithium metal and synthesis of lithium powder for cathode are also energy intensive business. Consequently, we will also introduce the basic production procedure in those industries. Although we will not look into detailed energy data of those procedures, it's beneficial for us to have a more comprehensive view of entire supply chain.

2.1 Lithium ion battery technology

2.1.1 Basic concept and theory

Rechargeable lithium batteries involved a reversible insertion/extraction of lithium ions (guest species) into/from a host matrix (electrode material), called lithium insertion compound, during the discharge/charge process. The lithium insertion/extraction process occurring with a flow of ions through the electrolyte is accompanied by the reduction/oxidation reaction of the host matrix combined with a flow of electrons through the external circuit. The name of lithium-ion battery is usually determined by cathode material, for example, lithium iron phosphate, and lithium cobalt battery.

Electrochemical Reaction

In the case of lithium iron phosphate batteries ($LiFePO_4$), lithium iron phosphate ($LiFePO_4$) is the cathode, Li_xC_6 is the anode, and the electrolyte is a non-aqueous solution. The $LiFePO_4$ has an olivine structure. During discharge, the lithium ions are inserted into the van der waals gap between the olivine structure and the charge balance is maintained by a reduction of the Fe^{2+} ions to Fe^{3+}. The insertion/extraction reaction of the lithium ions is shown below: $LiFe(II)PO_4 \leftrightarrow Fe(III)PO_4 + Li^+ + e^-$. During charge, exactly the reverse process involving the extraction of lithium from the van der Waals gap and oxidation of Fe^{3+} to Fe^{2+} occurs. Figure 2.1 shows the illustration of the charge /discharge process in lithium-ion cell.

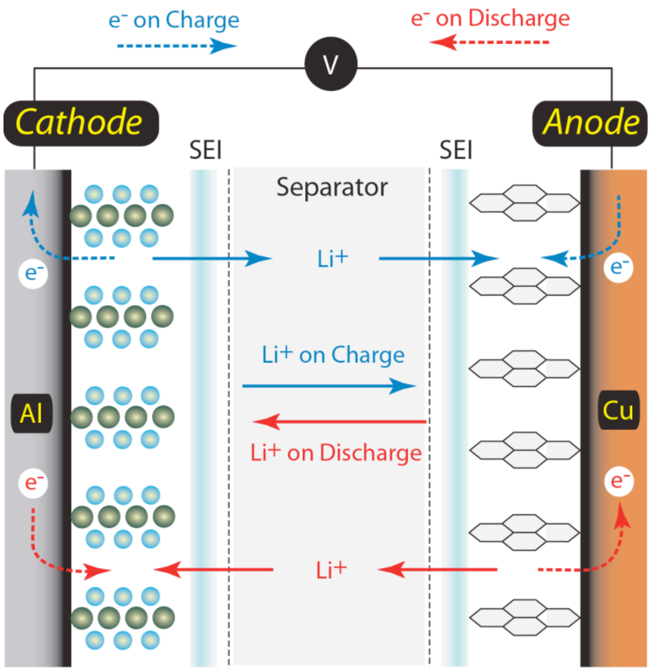


Figure 2.1 Charge/discharge process in lithium ion cell (Landi, 2009)

Battery Voltage

The open-circuit voltage V_{oc} of a lithium cell is given by the difference in the lithium chemical potential between cathode ($\mu_{Li(c)}$) and the anode ($\mu_{Li(a)}$) as(Gholam-Abbas Nazri, 2009):

$$V_{oc} = (\mu_{Li(c)}-\mu_{Li(a)}) / F \qquad \text{(Eq-1)}$$

Where F is the Faraday constant. The cell voltage V_{oc} is determined by the energies involved in both the electron transfer and Li^+ transfer. While the energy involved in electron transfer is related to the work functions of the cathode and anode, that involved in Li^+ transfer is determined by the crystal structure and coordination geometry of the site into from which Li^+ are inserted extracted. Figure 2.2 shows the various kinds of cathode and anode material and their associated chemical potentials. In the public market, the average standard voltage of $LiFePO_4$ battery in the industry is 3.2V, which is lower than 3.8V of Li_xCoO_2 and $Li_xMn_2O_4$ battery. In theory, higher voltage could carry more energy by the same current, but it would also cause some degradation of other components during operation time. Consequently, lower voltage could extent the cycle life of battery in some way.

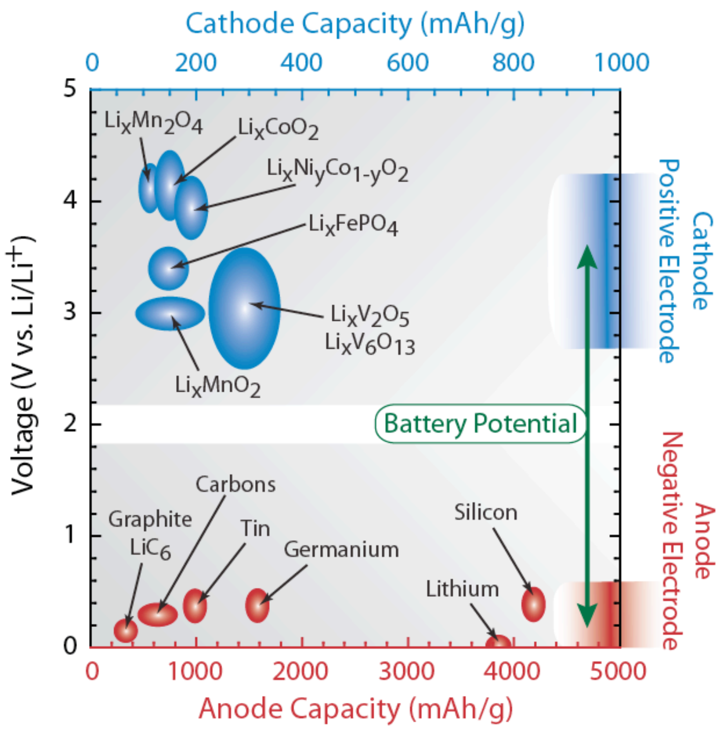


Figure 2.2 Potential differences between cathode and anode materials(Landi, 2009)

Specific energy and power

The specific energy and power are the critical factors that decide the application of various batteries, especially on the laptop, mobile phone, and other portable devices. In general, people pursue the lightest battery with highest specific power and energy. However, it is constrained by the chemical composition and density of raw material. In Figure 2.2, you can see the Lithium-ion battery provide very high theoretical specific energy (150 Wh/kg) or specific power because of this lowest density of material. But, in reality, the specific would be lower than this number, since producers have to add some other material to increase the conductivity of the electrode. Additionally, the manufacturers could produce batteries with various specific power and energy by controlling the thickness of powder on the electrode. Thicker powder on the same area of electrode could increase the energy capacity of battery. In contract, the battery with thinner thickness of powder would provide higher specific power. It would be suitable for the Hybrid electric vehicle.

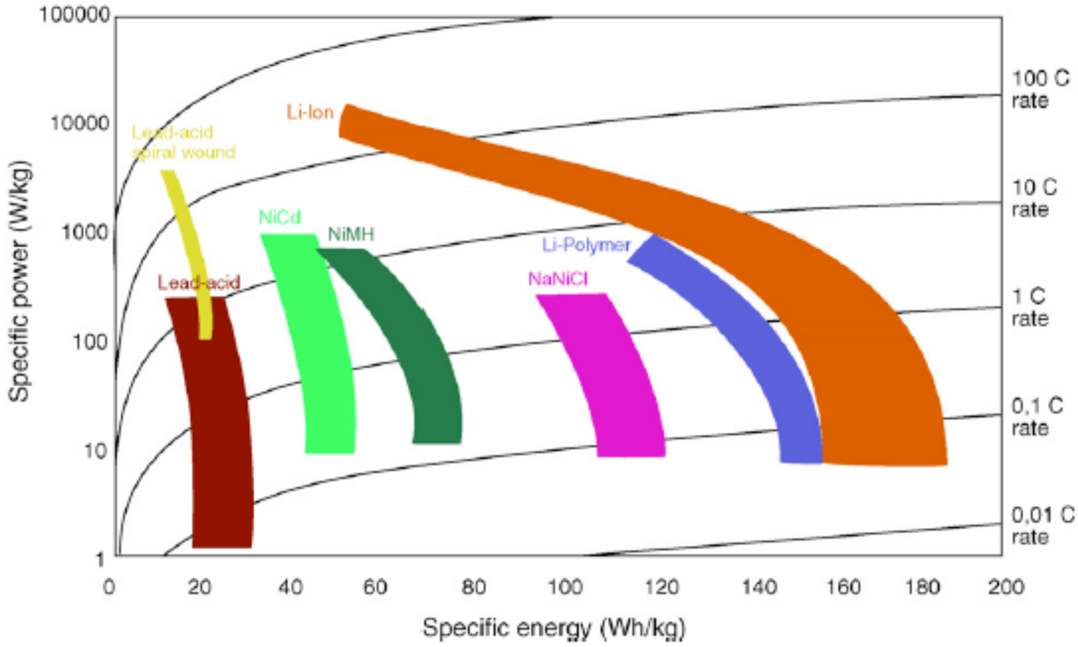


Figure 2.3 Specific power and specific energy of various types of battery(Bossche, Vergels, & Mierlo, 2005)

Cycle life and Performance

Cycle life of battery is a complicated issue. It is associated with many issues, like the chemical composition, structure of material, operation temperature, and how the battery is used. Due to the olivine crystal structure, $LiFePO_4$ has generally longer cycle life compare to other battery types. Its lattice volume only decreases by 2.59% during charge. Figure 2.4 shows cycle life achieved by SAFT for different depths of discharge(Kalhammer & Kopf, 2007). For example, if discharged consistently to 40% DOD(Depth of discharge), the battery under test will yield about 12,000 cycles. Basically, the number of cycles would decrease with the increase of depth of discharge. However, through some new nano-technology, likes A123 system claims their $LiFePO_4$ battery could achieve 7000 complete discharge (100% DoD)(A123 System, 2010). Even when cycle at 10C discharge rate, their cells deliver in excess of 1,000 full depth of discharge cycle. Besides, this stability of battery could help the development of fast charging significantly.

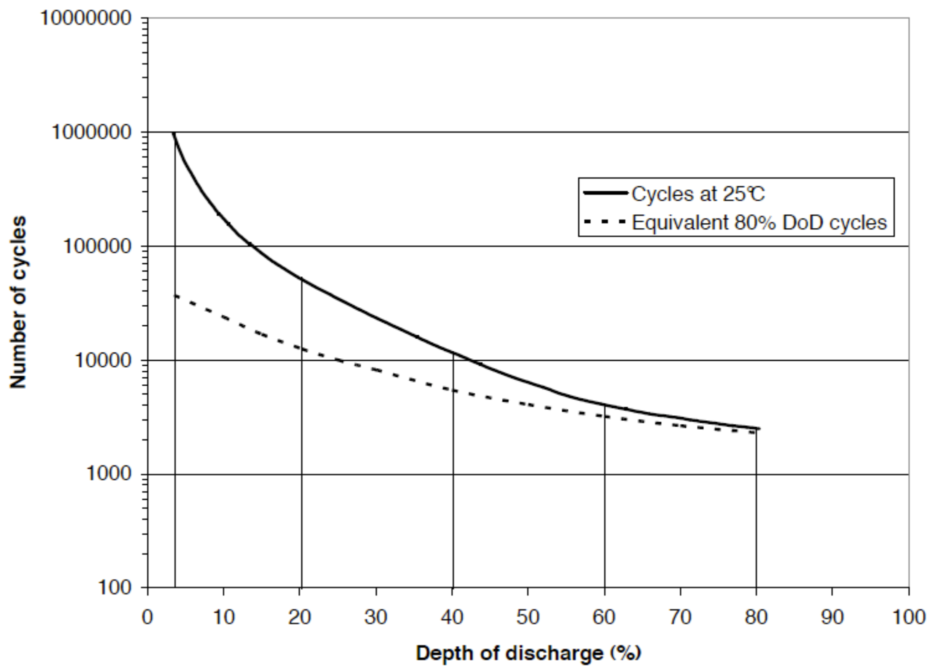


Figure 2.4 Correlation between depth of discharge and number of cycles(Kalhammer & Kopf, 2007)

2.1.2 Battery Components

There are two main types of battery cells to date, cylindrical and prismatic cell as you can see as below. It is cheaper to produce cylindrical cell with roll structure compare to prismatic cell. However, the prismatic cell could offer more compact structure and save more space in the battery packs. It could increase the energy capacity of battery packs. Although they have different shapes of cell, they both contain the same main components in the cells, which we will describe in greater detail in the following section.

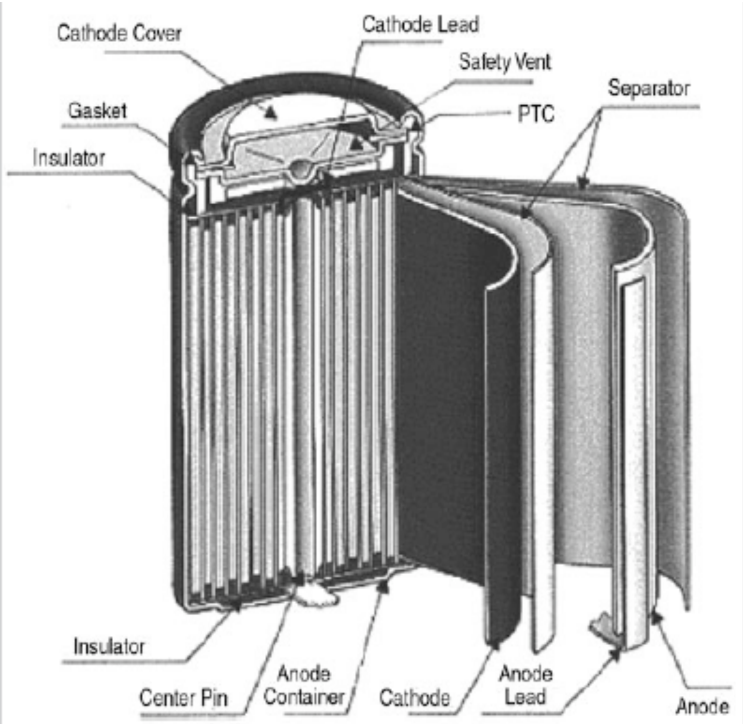


Figure 2.5 Schematic diagram of cylindrical type of battery(Argonne National Laboratory, 2000)

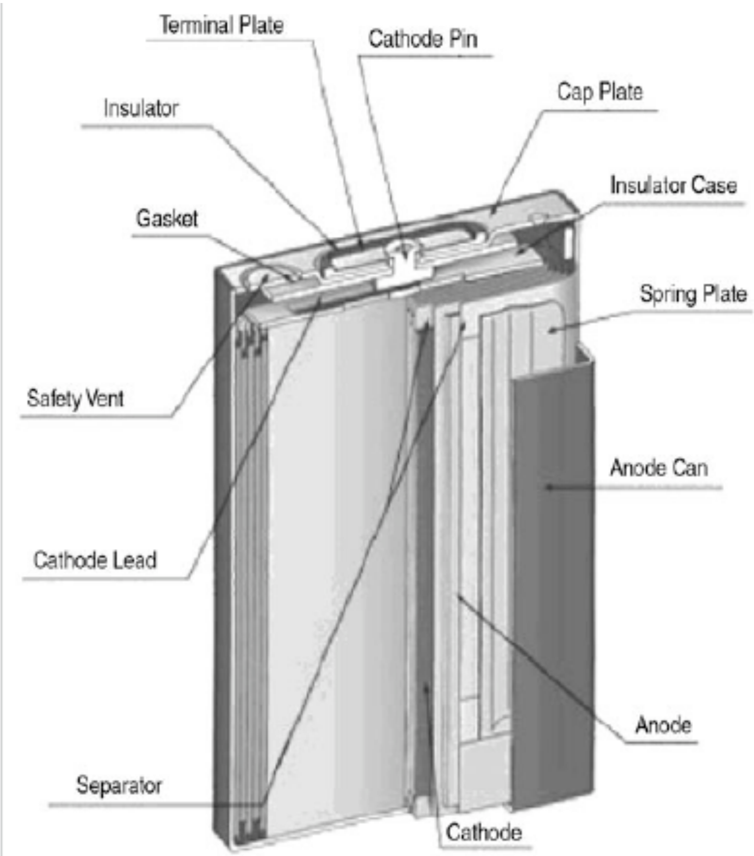


Figure 2.6 Schematic diagram of prismatic type of battery

Cathode electrode

The cathode electrode consists of current collector (20μm thick Al), and the cathode material mixed with slurry spread onto foil. The cathode electrode is one of the key components in the battery pack. It dominates around 48.8% of the total raw material cost (Argonne National Laboratory, 2000). More Importantly, it affects the energy capacity, voltage, cycle life, safety and other things. There are many researches that focus on how to improve cathode material running throughout the world. In lithium ion battery, lithium cobalt and nickel oxide with layered structure, lithium manganese with spinel structure could be used on cathode electrode. The lithium cobalt released by Sony on 1990 is the most common commercially used battery in electric devices due to its high energy density. But, its high price of raw material, instability and toxic features provoked the incentives for using other powder materials. Hence, there are some transition metal oxide powders developed by adding other element in the synthesis. In 1996, the professor at University of Texas at Austin, John B. Goodenough and coworkers identified lithium iron phosphate ($LiFePO_4$) and other phosphate-olivines (lithium metal phosphates with olivine structure) as cathode materials. This discovery is recognised as the breakthrough technology in this field because its stable olivine crystal structure could provider longer cycle life and satisfy higher safety standard. Moreover, the price of iron is much cheaper than rare metal, such as cobalt and manganese.

Table 2.1 Comparison of various cathode materials

Cathode Material	Structure	Average Voltage	Gravimetric Capacity
$LiCoO_2$	Layer	3.7 V	140 mA·h/g
$LiMn_2O_4$	Spinel	4.0 V	100 mA·h/g
$LiNiO_2$	Layer	3.5 V	180 mA·h/g
$LiFePO_4$	Olivine	3.3 V	150 mA·h/g
Li_2FePO_4F	Olivine	3.6 V	115 mA·h/g
$LiCo_{1/3}Ni_{1/3}Mn_{1/3}O$	layer/spinel	3.6 V	159 mA·h/g
$Li(Li_aNi_xMn_yCo_z)O_2$	layer/spinel	4.2 V	220 mA·h/g

Anode electrode

The anode electrode is usually made of graphite and is, coated on thin copper foil. In the case of graphite anode electrode, a single lithium ion can be inserted into each hexagon in the graphite's molecular structure. The theoretical capacity of graphite is 372mAh/g. However, this is still poor compared with charging density of lithium (3,862mAh/g). For this reason, some researches are trying to increase the capacity by using novel carbon, materials alloys, and other intermetallic compounds. The best carbons in current research intercalate 2.5 Li ions and achieve capacities as high as 750 mAh/g(Argonne National Laboratory, 2000). Carbon-coated copper-tin alloys could provide 460 mAh/g and stable cyclic performance ever after 40 cycles(Sheng Liu, 2008). Silicon has an extremely high capacity of 4199mAh/g, corresponding with a composition of Si_5Li_{22}(Daniel, 2009). Additionally, a $Li_4Ti_5O_{12}$ lithium cell discharged at C/12 delivered 155mAh/g(K.Zaghib, 1999). However, cycling behaviour is poor, and capacity fading not yet understood. Note that both of their average voltage of Silicon (0.5~1V) and $Li_4Ti_5O_{12}$ (1.5V) are higher than graphite. It would affect the cell potential of battery.

Electrolyte

The main task of the electrolyte in lithium ion battery is to continuously carry lithium from anode to cathode during charge/discharge. The basic requirements of a suitable electrolyte are high ionic conductivity, low melting and high boiling points, chemical and electrochemical stability and safety. Liquid electrolyte consists of lithium salts, such as LiPF6, Li [PF_3 $(C_2F_5)_3$], or $LiBC_4O_8$ in organic solvents, such as ethylene carbonate(EC), dimethyl carbonate(DMC), and diethyl carbonate(DEC).

The general liquid electrolyte is a 1 molar solution of a lithium salt in an organic solvent(Argonne National Laboratory, 2000). Above the 1M concentration, there is significant salt precipitation at low temperatures. Normally, below 0.4M Salt concentration a marked decrease in conductivity of electrolyte is observed and considered not to be practical(Gholam-Abbas Nazri, 2009). The main safety concern of organic solvent is that it would be decomposed under high voltage operation and its flammability. Another kind of electrolyte in lithium battery is a solid polymer electrolyte (SPEs) frequently applied in mobile, and laptop devices. It offers several advantages, including enhanced safety (no liquid to spill), lighter weight, and design flexibility (no rigid cell can is required). However, their higher internal resistance limit their performance and lifetime. Additionally, they show very poor low-temperature performance because the lithium mobility in the solid is greatly reduced at low temperatures(Daniel, 2009).

Separator

In liquid electrolyte batteries, separators are placed between cathode and anode in order to prevent physical contact. Meanwhile, the lithium ions should be able to pass through the separator, but electronic flow. The basic requirements of a suitable separator are sufficient porosity (typically, 40%(S.S.Zhang, 2004)), chemical stability, mechanical strength to resist the assembly process, and appropriate melting point for safety concern. The way they insure the safety of cell is that they would shutdown the battery by melting themselves when the battery is overheated. As an alternative, the shutdown function could be obtained by multilayer design of the separator, in which at least one layer melts to close up the pores below the thermal runaway temperature and the other layer provides mechanical strength to prevent physical contact of the electrodes. Mostly, they are made of microporous polyolefin (PE), polyolefin (PO) membrane.

Cell packaging

The purpose of cell case is to keep the battery stable and in constant shape under operation. They are now generally made of aluminium, which is light and cheap. The problem of using plastic material is that it could be dissolved by organic electrolytes. But, polymer lithium batteries using solid SPEs don't need cell cases and could be made in a variety of shapes.

2.1.3 Best solution to date and future

To conclude, the layered $LiMO_2$(M=Co and Ni), spinel $LiMn_2O_4$, and olivine $LiFePO_4$ containing lithium have emerged as the leading cathode candidates in the last ten years. Although the $LiFePO_4$ has lower voltage and power density compare to $LiCoO_2$, the cheaper and non-toxic raw material (Fe) and more stable olivine structure cause $LiFePO_4$ to become the most promising insertion compound material. The key barrier to commercialization was its intrinsically low electrical conductivity of $LiFePO_4$. This problem, however, was then overcome partly by reducing the particle size and effectively coating the $LiFePO_4$ particles with conductive materials such as carbon, and partly by employing the doping approaches developed by Yet-Ming

Chiang and his coworkers at MIT using cations of materials. The future challenge of lithium ions batteries is to develop simple oxide cathodes without other element such as P in which at least one lithium ion per transition metal ion could be reversibly extracted/inserted to give close to 300 mAh/g while keeping the materials cost and toxicity low. Such cathodes can double the energy density compared to the present level. Another possibility of increasing the capacity anode perhaps is focusing on amorphous materials and metal nitrides, borides, and carbides with significant covalent character. In addition to energy capacity, safety concern is a critical issue in the future applications such as electric vehicles. The cathodes with a lower voltage (3 to 4 V), but with an increased capacity are desirable for future application. Such cathodes would also be attractive for polymer batteries from a stability point of view.

2.2 Lithium metal extraction

In this project, although our main focus is to quantify the advantage of producing lithium ion battery packs in Iceland, we will also look at the opportunity of bringing other upstream industries in this field. In the case of lithium iron phosphate battery, the cost of raw materials plays significant part of overall cost of lithium battery. According to Matti Nuutinen's research(Nuutinen, 2007) of Chinese battery factory, the cost of raw materials play 67% of the total cost. Among the various materials, cathode active material ($LiFePo_4$) dominates 48% of the total material cost(Argonne National Laboratory, 2000). Besides, cathode material is the core technology of lithium ion battery. Through the literature review, we found out the lithium metal electrolysis extraction process and $LiFePO_4$ powder hydrothermal synthesis are both very energy intensive procedures. Normally, the energy consumption of electrolysis of LiCl into Li metal is 30~35 kWh/ kg-Li(Garrett, 2004). This characteristic gave Iceland excellent opportunity to fit into this supply chain of lithium oxide powder.

2.2.1 Overview of Lithium extraction process

Lithium is a comparative rare element, although it is found in many rocks and some brine, but always in very low concentration. If the concentration of lithium is not high enough, it will increase the cost of processing products. Therefore, there are only few commercial valuable mines and brines in the world based on recent technology. Almost 70% of world economic Lithium deposits are found in one small location on the Earth-the Lithium Triangle where the borders of Chile, Bolivia and Argentia meet (Meridian Internation Research, 2008). However, the most significant cost driver for lithium metal is coming from the extraction process, since extremely active lithium element usually appears as lithium carbonate in the brine. The following primary lithium metal production process could help us to understand why it might be a suitable business in Iceland.

The extraction of lithium metal from lithium carbonate involves into two main phases.

1) Conversion of lithium carbonate into lithium chloride.
2) Electrolysis of lithium chloride.

According to Donald's "Handbook of lithium"(Garrett, 2004), the lithium carbonate will be heat up and mixed with hydrochloric acid (usually, 31%HCL) in the agitated reactor.

$$Li_2CO_{3\ (s)} + 2HCl_{\ (aq)} \dashrightarrow 2LiCl_{\ (aq)} + H_2O_{\ (aq)} + CO_{2\ (g)} \qquad \text{(Eq-2)}$$

The carbon dioxide that is formed is vented from the top of the reactor. A small amount of barium chloride is then added to precipitate any sulfate. After filtering, the solution is evaporated to saleable 40% LiCl liquid product. To produce dry LiCl powder, since the solution's boiling point and solubility are so high, it must be concentrated by direct contact with flue gas. The solid lithium chloride finally formed in the bottom of tower with proper size (usually below 8 mesh), and packaged in air-tight containers.

After first step, the electrolysis of molten pure and dry lithium chloride-potassium chloride (45%LiCl; 55% KCl) is the way to produce lithium metal. The purpose of adding potassium chloride is to decrease the melting point from 614 °C to approximate 420 °C depends on the proportion of KCl. The basic steel vessel has exterior ceramic insulation, and steel rod on the bottom as a cathode. The anode is constructed of graphite, which slowly sloughs-off. The vessel might be heated up by gas firing between ceramic insulation and vessel's interior steel wall. The lithium metal accumulates at the surface of the wall and is poured into ingots. Meanwhile, chloride gas generated by reaction has to be routed away carefully. Typically, the electrolysis process is usually operated with a cell voltage of 6.7~7.5V, the typical cell current would be in the range of 30~60 kA. It consumes 30~35 kWh of electricity energy and 6.2~6.4kg LiCl to produce one kilogram lithium metal with 20~40% energy efficiency.

$$\text{Cathode: } Li^{+} + e^{-} \rightarrow Li_{\text{metal}}$$

$$\text{Anode: } Cl^{-} \rightarrow \tfrac{1}{2} Cl_2 + e^{-}$$

$$\text{Total: } 2LiCl \rightarrow 2Li + Cl_2$$

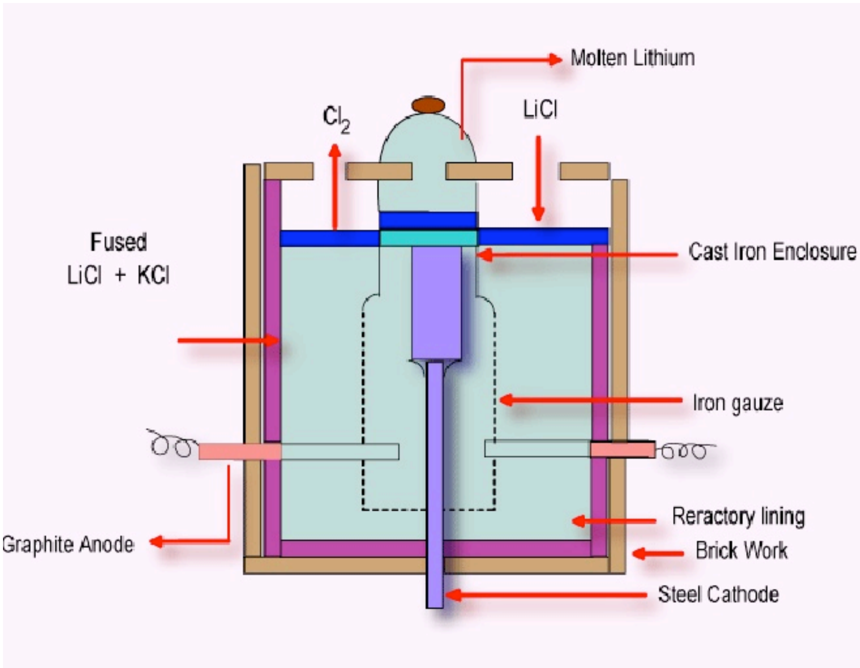


Figure 2.7 Schematic structure of vessel

In Iceland, the small amount of lithium element(8ppm) is contained in geothermal brines at Reykanes field(David Kadko, 2007). Additionally, twelve lava eruption samples from Hekla volcano area show the concentration of Lithium could achieve 37.2 ppm(Jan A. Schuessler, 2009). Although those numbers so far are not high enough to become economical brines providing lithium metal, it might have potential to be utilized along with the development of technology and more field investigation. At this moment, the energy intensive step and the need of potassium chloride used to lower the melting point have turn this business become suitable in Iceland. It not only could be used as the source of lithium iron powder, but also as an alloying element for aluminium is currently in bulk in Iceland. Besides, if the producers consume 35kWh electricity to produce 1 kg lithium metal, it means that energy cost accounts around 6~7% of overall cost based on the electricity price at 0.07$USD/kWh and 40$USD/kg lithium. From this, the production of lithium is an energy intensive business and apparently emits a large amount of carbon dioxide directly and indirectly by using energy from fossil fuel. However, in Lithium battery industry, only 4.7kg lithium metal would be used in 30kWh size Li-battery on average according to Argonne National Laboratory's research in 2009. Through our calculation, it means only 0.017kWh electricity is consumed to produce 1 Ah Li-battery. It is only 3% of the energy, which is used in battery production (0.54kWh/1Ah battery). From this point of view, to locate a lithium metal extraction factory in Iceland only can slightly reduce the carbon emission of the final product, lithium-ion battery.

2.3 Hydrothermal synthesis of lithium iron phosphate powders

To date, there are many approaches that have been developed to synthesize the promising lithium iron phosphate powders, such as microwave process, spray pyrolysis, precipitation method and hydrothermal process. The point is which method could produce cathode powders with fine size and stable electrochemical performance cheaply. According to Dragana Jugovic's research(Dragana Jugovic, 2009), it shows most of all approaches need high temperature from 300°C to 900°C. However, in 2006, M. Stanley Whittingham's research group successfully found $LiFePO_4$ could be synthesized by a new hydrothermal method under lower temperature (around 175°C)(Whittingham, 2006). It could exclude the high temperature step and increase the opportunity of direct using of geothermal steam in Iceland. Therefore, we would focus on this low temperature hydrothermal synthesis method in this part.

The $LiFePO_4$ was prepared by hydrothermal reaction in a Parr reactor. The starting materials were $FeSO_4 \cdot 7H_2O$(98% Fisher), H_3PO_4 (85 wt% solution Fisher), LiOH (98% Aldrich). The molar ration of the Li: Fe: P was 3:1:1, and typical concentration of $FeSO_4$ was 22 g/l of water(Whittingham, 2006). Initially, the $LiFePO_4$ prepared by hydrothermal synthesis under 120 °C only has 100 mAh/g capacity due to some lithium/iron disorder with around 7% iron on the lithium sites(Dragana Jugovic, 2009). But later on, by modifying the synthesis conditions, came to optimal hydrothermal parameters for obtaining electrochemically active $LiFePO_4$. It was found that the temperature of synthesis must exceed 175 °C to minimize iron disorder and obtain a material with correct lattice parameters and volume. Furthermore, reductants, such as ascorbic acid or sugar, prevent the formation of surface ferric films. In Whittingham's experiment, the concentration of sugar or ascorbic is 1.3g/liter(Whittingham, 2006). Lastly, the autoclave was sealed and heated at 150-220 °C for 5 hr. Precipitates were collected by suction filtration and dried at 60 °C for 3 hr in the vacuum oven. The enthalpy of formation of $LiFePO_4$ from $FePO_4$ and Li is 37.84 kJ/mole(Jiajun Chen, 2008).

3. Energy cost optimization of Li-ion battery production

One of the factors may make Iceland a feasible location for a battery production is because that we can utilize electricity and geothermal steam at a relatively reasonable price. Therefore, to quantify the fraction of electric energy that could be replaced by geothermal steam is the main goal in this chapter. In general, the best way to answer this question is to collect the energy consumption data from factories in operation. Unfortunately, the detailed energy consumption data from each step in lithium battery production is not readily available from factories due to confidentiality reasons in this competitive market. Besides, most of battery producers have not done this investigation in their own factories according to one general manager of Taiwanese lithium battery firm. Consequently, in this project, the first step is to understand whole production process through literature review and interviews with people from battery companies and draw a complete production process map. Then, we develop our own model to estimate how much thermal resource is necessary in each process step. In other word, it could help us to find out the new energy supply structure (the percentage of electricity and geothermal resource) in a new hypothetic battery factory in Iceland. Additionally, the technical feasibility of applying geothermal heat in lithium ion battery production has never been done before. For this reason, we will also investigate the theoretical feasibility of using geothermal drying in battery production and do a equipment survey on the recent market.

3.1 Brief overview of lithium iron battery production

The different factories have different approaches and design of equipments to produce their battery pack based on their raw material and application of the battery. Although there are few differences between different processes, the basic principle of procedure would be similar. In general, the production process of lithium iron battery starts from buying various raw materials and components from suppliers. The first step is to coat the anode and cathode powders mixed with solvent on the foils respectively and dry it in the vacuum oven. Then, the dried disks are cut into suitable sizes and compressed thinner by automatic machines. At this stage, the individual electrode is completed and ready for assembly. The second part is to assemble the various components, such as the separators, internal circuit, anodes and cathode altogether. In this step, the electrodes would be stacked and clamped first and put into a metal packing case. After core drying process again, producers would inject the electrolyte into the cell and seal it completely. Since the electrodes are very sensitive to moisture, those processes are usually operated in a dry room, which controls the humidity and keep it within an acceptable range. In principle, the battery pack is externally ready to sell at this stage. However, most of the producers would test their products a few times in order to insure its performance and collect the data before shipping it to consumers. In the following part, the detailed description of production process would be present.

3.2 Detailed Description of each stage

In this sub-chapter, the production process is described as given in some reference articles, which we found online, the documents we got from cooperative companies and also the interview file with few persons from lithium iron battery companies. This procedure does not focus on any specific lithium ion battery factory, instead it is a general process focusing on energy consumption in each stage. In figure 3.1 and figure 3.2, we can see the whole process divided into two parts, the preparation of electrodes and cell assembly.

Part 1: Preparation of Electrodes

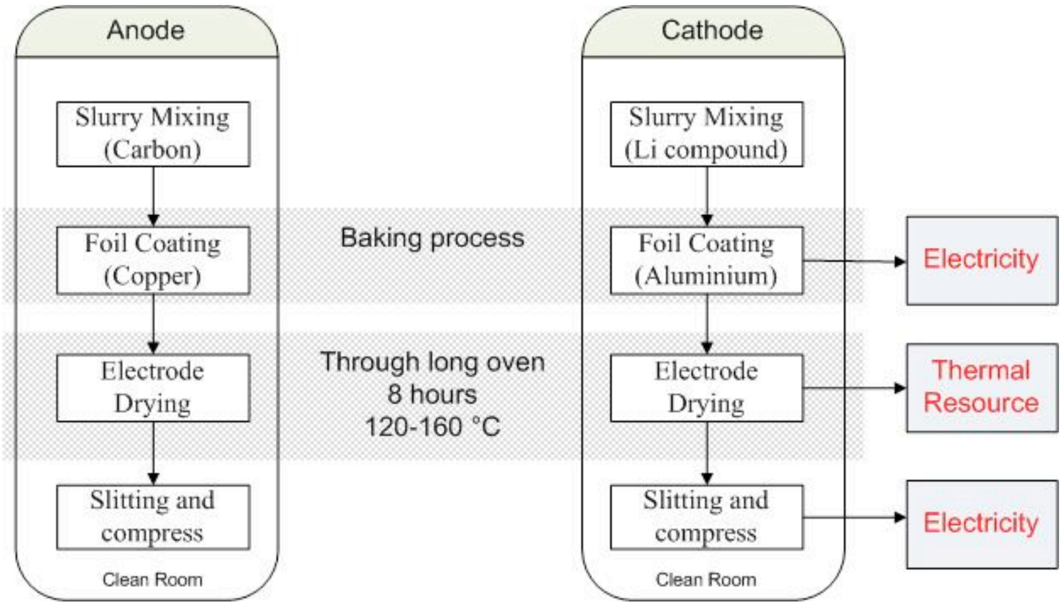


Figure 3.1 Production process map of first part

Slurry mixing process

In general, the factories get anode, and cathode powder from other powder suppliers. However, there are some companies producing their own powder. Most powder has been dried before shipping to buyers, but the battery companies should with benefit dry it again in order to insure the quality of their product. The anode material is usually made of carbon and the cathode material is a form of lithium compounds. Both of them are delivered to factory in the form of black powder and it is difficult to distinguish them by untrained eye. Therefore, they usually mix it with ethanol, distilled water and solvent binder separately in different rooms. For the cathode, the cathode active material, conductive agent (carbon black), binder (PVDF), and solvent (NPM) were approximately mixed at a rate of weight of 10:1:1:5.5 under high purity nitrogen atmosphere for 1 hr(Masatoshi Majima, 2001). For the anode, the natural graphite with a mean particle size of 12 μm was used as an anode active material. The anode active material, binder, and solvent are mixed at a rate of weight of 10:2:10(Masatoshi Majima, 2001).

Coating slurry on foils

The thin copper and aluminium foils are delivered on large reels with 20μm thickness, such as 1600 meters length and 500 mm wide(Nuutinen, Transferring production of Li-ion battery facto ry from China to Finl, 2007). The producers will spread the slurry, which prepared in the last step onto the both sides of foils as it passes into the coating machine. Since the energy storage capacity of cathode material and anode material are different, they should have specific proportion to each other. The thickness of the active material is around 200~250μm (for high energy cell). It will be determined by the application of the cells. For example, the thicker active materials are usually used on the pure battery electric vehicle, which need higher energy capacity battery. On the contrary, the batteries made for the hybrid vehicles will have thinner active material on the foil that could be released very fast in a short time to provide higher power. The machine would control the thickness of cathode and anode material by the gap between the knife edge and foil.

Electrode Drying

From the coating device, the coated foils are fed into a long drying oven to bake the material onto the foils. In the Chinese factory, this process takes around 8 hours at 120 °C to 160 °C and doesn't require any employee's intervention(Nuutinen, Transferring production of Li-ion battery facto ry from China to Finl, 2007). This step would reduce the thickness by 25% to 40%(Argonne National Laboratory, 2000). The main purpose of this step is to remove the moisture in the electrode because the active material is very sensitive to water.

Slitting and compressing

The coated foils are subsequently fed into the slitting machine to cut it into right size for various sizes of electrodes. Then, the machine would press the foils as thin as possible in order to put more foils in one battery pack and to make sure the thickness is more uniform. Due to those two steps are simple to reconcile, the better idea is to move these devices into a single step in a row.

Part 2: Cell Assembly

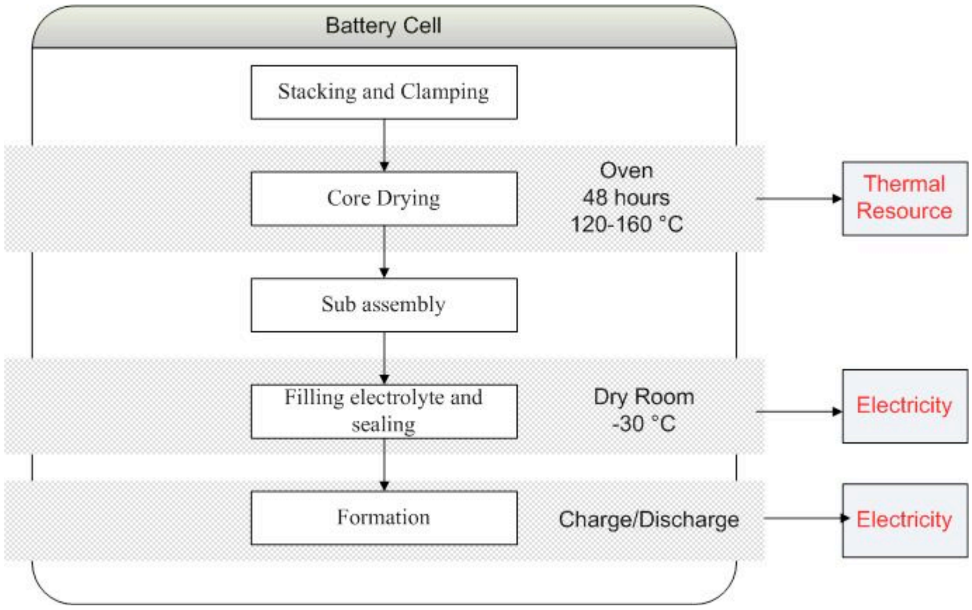


Figure 3.2 Production process map of second part

Stacking and Clamping (For prismatic cell)

In prismatic cell, the design uses a stacked electrode structure in order to optimize the use of space. The separator maybe cut into the same size as the electrode but more likely it is applied in a long strip wound in zigzag fashion between alternate electrodes in the stack. It's showed in Figure 3.2. However, it has the disadvantage that it uses multiple electrode plates, which need a clamping mechanism to connect all anodes together and similar mechanism for the cathodes. This process could be done by human or machines. But the automatic process could increase the quality of battery pack.

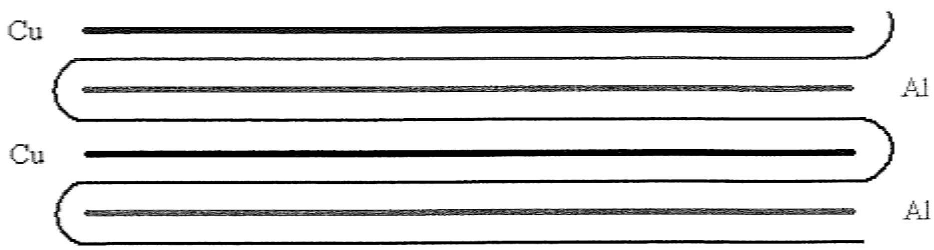


Figure 3.2 Long strip wound in zigzag fashion(Nuutinen, Transferring production of Li-ion battery facto ry from China to Finl, 2007)

Core drying

At this stage, the battery cells are inserted into the core drying machines. The purpose of this step is to remove the moisture from electrodes completely. It is the most energy intensive step in the whole process. In general, the manufactures are supposed to dry it as soon as they can by increasing the temperature in the oven. Unfortunately, the melting point of binder (PVDF) is around 170°C, therefore, they have to dry it in vacuum oven below 170°C. However, they could lower the pressure in the oven to decrease the boiling point of water, and solvent in order to shorten the drying process. In the end, the moisture content rate in the electrodes would be down to 2%.

Sub assembly (Attach the terminals, vents, and safety device)

In this stage, they need to connect the safety devices and, terminals post which are made of aluminum and copper. Due to the corrosion problem and the price of raw material, they use aluminum more often instead of copper. Then, the can is sealed in a laser welding or heating process, leaving an opening for injecting the electrolyte into the can. Those processes are supposed to be done in the dry room, which control the moisture in the air carefully.

Filling electrolyte and sealing

The following step is to fill the electrolyte into cell and seal it. This must be carried out in a “dry room” at very low temperature, because the non-aqueous electrolyte would react with water. Moisture will cause the electrolyte to decompose with the emission of toxic gases.

Formation

Once the whole cells are completed, they have to go through the charge/ discharge test one time. Instead of using constant voltage, the charging process starts with lower voltage, which builds up gradually in order to create the SEI (solid electrolyte interface) on the anode. This is a passivation layer, which is essential for moderating the charging process under normal use in the future. Meanwhile, the measurement equipments also record the performance of batteries, such as capacity and impedance. It could help them to manage the quality control.

3.3 Energy consumption of lithium ion battery production

Energy consumption in lithium iron battery production is not openly available information from this emerging industry. It's difficult to get the energy consumption data from battery companies directly. Lifecycle analysis of lithium iron battery by Mats Zackrisson and Lars Avellán in 2010 claims that the total energy consumption corresponds to 11.7 kWh electricity and 8.8 kWh of thermal energy from natural gas per kg lithium-ion battery (Zackrisson, Zackrisson, & Orlenius, 2010). This corresponds to an energy consumption for 1Ah battery of approximately 0.68kWh, assuming that one kg lithium-ion provides 30Ah capacity of battery. In addition to it, we also get the energy consumption data from Matti Nuutinen, who has done one research on Chinese lithium iron battery factory and works for European Batteries Oy. In this report, it shows that 5000kW electricity power is required to produce 80MAh battery per year. It means the energy consumption of 1Ah battery is approximate 0.54kWh. Based on this source, the energy consumption could be range from 0.54 to 0.68 kWh/Ah according to our investigation.

3.4 Energy consumption model of a vacuum dryer

Through production analysis, the approximately energy consumption figure has been already addressed in the previous text. But, we don't know the precise energy consumption of each step in the entire production process. In this project, we are planning to replace the energy resource for the drying process. Hence, it is necessary to know the energy consumption of the vacuum dryer, if we want to compare the capital and operation cost of different equipment. Ideally, the energy consumption data from the operating factories would be the best. However, most of the companies we have contacted did not measure the energy consumption of their dryer. Also, they are not willing to release this internal information. For this reason, we have to build an own calculation model based on available data. It is not a perfect, but an acceptable solution to figure out the approximate energy consumption of drying process. Obviously, there would be some uncertainties in the calculation, such as the heat loss, and actual energy efficiency. We would have to make some assumptions according to the industrial experience or laboratory result. The more detail information about the dryer and feedstock we can get the more precise result we can extract from the model.

In the following part, we introduce how we build this model and how the energy consumption is calculated.

The thermal properties of components

The first step of building energy consumption model of drying is to collect the weight percentage and thermal properties of component materials, such as the specific heat capacity, boiling point and evaporation energy. In Mats Zackrisson's research, it provide us the clear information about the weight precentage in one kilogram lithium iron phosphate battery(Mats Zackrisson, 2010). For other thermal properties, we have to get the data from different accademic papers or books. Table 3.1 shows the relevant properties of each material in the lithium iron battery. For some properties, the number will be effected by the pressure and temperature. We will discuss how to deal with that in the calculation part.

Table 3.1 Physical properties of component materials

Information of 1 kg lithium iron battery component material			
Cathode Composition	Weight (g)	Heat capacity	Others
$LiFePO_4$	422 gram	Heat capacity: 0.9 J/g-K[1]	
Al foil	19 gram	Heat capacity (25°C) 0.89 J/g-K [4]	Melting point: 660.3°C [6]
Carbon black	27 gram	Heat capacity (25°C): 0.71 J/g-K [4]	Melting point: 3500°C [6]
Binder (PVDF)	28 gram	Heat capacity: 1.9J/g-K[2]	Melting point: 170 °C [2]

1 Mats Zackrisson, Life cycle assessment of lithium-ion batteries for plug-in hybrid electric vehicles, 2010

2 Dr. Michael Eastman, Smart Sensors Based On Piezoelectric PVDF ,2010

3 Taminco CO, N-Methylpyrrolidone Electronic grade Technical Data Sheet

4 Heat capacity, Wikipedia, http://en.wikipedia.org/wiki/Heat_capacity

5 She Haung Wu and Yang-Ting Lai, The effects of the moisture content of LiFePO4/C cathode and the addition of VC, The electrochemical Society, 2007.

NMP solvent	65~70 solid-content (67%) Initial: 244.2 gram Outlet moisture: 10g	Heat capacity: 1.76 J/g-K [3]	Boiling point (1atm): 202°C Heat of vaporization, 20°C: 550.5 kJ/g [3]
Anode Composition	Weight (g)	Heat capacity	Others
Graphite	169 gram	Heat capacity (25°C): 0.71 J/g-K [4]	Melting point: 3500°C [4]
Cu foil	46 gram	Heat capacity (25°C): 0.385 J/g-K [4]	Melting point: 1084.6°C [4]
NMP solvent	65~70 solid-content (67%) Initial: 116.2 g Outlet: 4.8g	Heat capacity: 1.76 J/g-K [3]	Boiling point (1atm): 202°C Heat of vaporization, 20°C: 550.5 kJ/g[3]
Total moisture (Cathode and anode)	Initial: 4.5g [5] Outlet: 0.5g	Heat capacity (25°C): 4.18 J/g-K Heat capacity (100°C, steam): 2.08 [4]	Evaporation energy: 2270 kJ/g) [5]

Energy consumption calculation

The result of this model shows how much thermal energy we need to remove the moisture and NMP from the electrodes. It is accompanied with the increasing temperature of other materials and some heat lost to environmental. The thermal energy consumption of drying process calculation could be divided into two parts. (1) The energy for increasing the temperature of all component materials. (2) The energy for evaporating the moisture and NMP away from the feedstock. Through the thermal properties and some basic physical formulas, the theoretical results are obtained for both parts respectively. Subsequently, the empirical energy efficiency of vacuum dryer is taken into account to get the more realistic data.

Part1: Energy consumption for increasing the temperature of materials

Initially, the vacuum dryer is heated up to 120°C from room temperature at 20°C. After the feedstock is placed in the dryer, all the materials are gradually heated up. As you can see in the Figure 3.3, since the wet bulb temperature water would be reduced to 48°C, the moisture will only be heated up to 48°C and start to be evaporated. After that, the steam will be removed by vacuum pump outside of dryer.

On the other hand, the rest of material will keep increasing the temperature by the thermal resource from vacuum dryer.

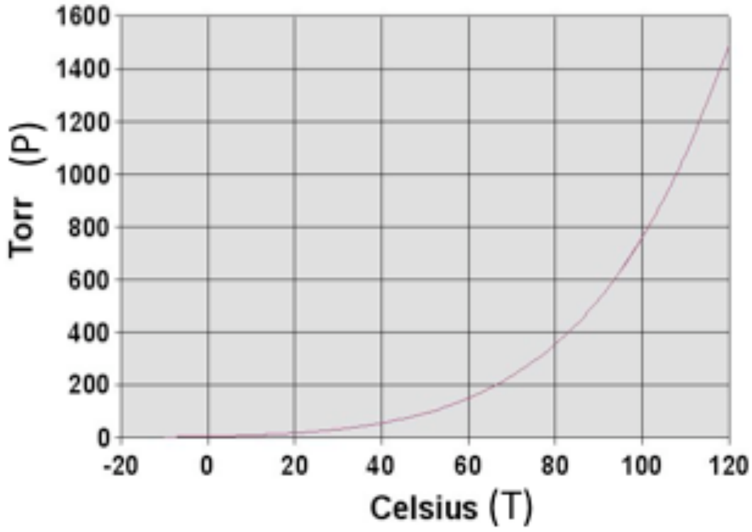


Figure 3.3 Boiling point of water with different pressure

By using Eq-3, we can get the energy consumption for increasing the temperature of all materials. As can be seen in table 3.2, the overall energy consumption of increasing temperature would be 128.6kJ/kg. It is a relative small part of the entire energy consumption.

$$\Delta Q = \Delta T * C * W \qquad (Eq\text{-}3)$$

ΔQ: Energy consumption (kJ)

ΔT: Temperature change (°C)

C: specific heat capacity (kJ/g)

W: weight of material (g)

Table 3.2 Result of part1 calculation

Energy consumption of increasing the temperature of 1 kg battery materials				
Cathode material	weight(g)	heat capacity(J/g-K)	ΔT	Energy consumption(J)
$LiFePO_4$ powder	422	0.9	100	37980
Al foil	19	0.89	100	1691
Carbon black	27	0.71	100	1917
Binder (PVDF)	28	1.9	100	5320
NMP slolvent	244.2	1.76	100	42979.2

Moisture (initial)	2.25	4.18	28	263.34
Total				90150.54
Anode material	weight(g)	heat capacity(J/g-K)	ΔT	Energy consumption(J)
Graphite	169	0.71	100	11999
Cu foil	46	0.385	100	1771
Binder (PVDF)	21	1.9	100	3990
NMP solvent	116.2	1.76	100	20451.2
Moisture (initial)	2.25	4.18	28	263.34
Total				38474.54
Overall consumption				128625.08

Part2: Energy consumption of evaporation

The second part is the energy consumption of evaporation. It actually dominates the energy consumption of drying process. Especially, the evaporation of NMP solvent consumes a lot thermal resource. In table 3.3, it shows the overall energy consumption of evaporation is 19984.1 kJ/kg. The key factors in this calculation are the initial weight and outlet weight of moisture because the heat of evaporation of water is relative bigger compare to other number.

$$\Delta Q = (W_{inital} - W_{outlet}) * \Delta H \qquad (Eq\text{-}4)$$

ΔQ: Energy consumption (kJ)

ΔH: Heat of evaporation (kJ/g)

W: weight of material (g)

Table 3.3 Result of part2 calculation

Evaporation energy				
Cathode	Weight (initial)	Weight (outlet)	Evaporation energy (J/g)	Energy consumption (J)
NMP solvent	244.2	10	550.5	128927.1
Moisture	2.25	0.25	2270	3972.5
Total				132899.6

Anode	Weight (initial)	Weight (outlet)	Evaporation energy	Energy consumption (J)
NMP solvent	116.2	4.8	550.5	61325.7
Moisture	2.25	0.25	2270	3972.5
Total				65298.2
Overall consumption				1998419.8

Total theoretically energy consumption of drying process:

19981.4kJ/kg(Evaporation) +128.6kJ/kg(Temperature increase) = 20110 kJ/kg

= 5.58 kWh/kg

Besides, 1 kg of raw material is approximately used to produce 30Ah $LiFePO_4$ battery.

5.58 kWh/kg / 30Ah = 0.186 kWh/Ah

In fact, the energy efficiency is not 100%. Based on the literature we assume that the energy efficiency of the vacuum dryer is 0.6 according to the Handbook of Industrial Drying (Mujumdar, 2006). In this case, the practical energy consumption would be 0.186/0.6 = 0.31 kWh/Ah. As a consequence the energy required is approximately 0.31 kWh thermal to dry 1Ah of lithium iron phosphate battery. This number doesn't include the electricity for vacuum machines and drying rooms, which are also part of drying system. It only focuses on the thermal resource that could be replaced by geothermal steam. According to the energy consumption data in previous research, the whole energy consumption of producing 1Ah lithium battery would be from 0.54~0.68 kWh. It means that the thermal resource in the drying process amounts to 53~57% of the energy consumption of the whole process. When we want to calculate the energy cost in the later chapter, it would be the actual requirement of alternative thermal resource, such as, geothermal steam.

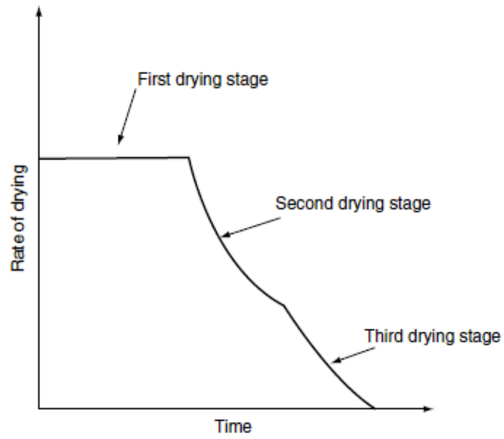
3.5 Drying process options in battery industry

Drying commonly describes the process of thermally removing volatile substances (moisture) to yield a solid product(Mujumdar, 2006). In this case, the main targeted materials are moisture and organic solvent (NMP) that are trapped in the cathode or anode paste. The oven would provide thermal energy to products continuously by convection, conduction, or radiation in order to remove the targeted materials from the batteries. Originally, the battery manufactures apply the vacuum batch oven using electricity as a thermal resource in the drying process. The reason for using vacuum oven is that the priority of time saving in the production process. Drying is the bottleneck process of entire procedure and it also plays a significant part of capital cost. According to our cost survey of equipment, it accounts 14% of total production line cost.

Meanwhile, there are some considerations have to take into account, if we want to apply a new drying equipment using other thermal resource into the production line. For example, the physical form and chemical characteristics of products will both affect the selection of drying method. Before going into the detail of different drying methods, we should look at the typical checklist of selection of industrial dryers as you can see in Table 3.4.

Table 3.4 Basic information of feedstock

Typical Checklist for selection of industrial dryers	
Physical form of feed	Paste on the solid foils
Average throughput	kg per batch (dry/wet)
Fuel choices	Electricity Oil Gas Geothermal steam
Inlet-outlet moisture content	Inlet moisture: 0.45% Outlet moisture: 500ppm
Heat sensitivity	Melting point: Binder (PVDF) 170°C Al Foil: 660.3 °C Cu Foil: 1084.6 °C

<table>
<tr><td>Drying time</td><td>

Dry curves
Effect of process variables</td></tr>
<tr><td>Special requirement</td><td>Material of construction:
Corrosion: None
Toxicity: NMP potentially cause genetic problem
Non-aqueous solution: NMP solvent
Flash point of NMP is 91 °C
Fire hazard: low
Color/texture/aroma</td></tr>
<tr><td>Footprint of drying system</td><td>Space availability for dryer and ancillaries: No limit</td></tr>
</table>

3.5.1 Heating methods

Convection

Convection is possible the most common drying method, especially for particle, sheer-form, or pasty solid. The dried material will be exposed to the hot flowing air carrying the thermal resource. When the hot air contact with surface, the heat will evaporate and carry away the moisture trapped from the products. This is a very old and traditional way of using geothermal steam in many products. For instance, Agency for the Assessment and Applied Technology (BPPT) in Indonesia have already designed the specific equipment and applied the geothermal drying on beans, or other agriculture product(Sumotarto, 2007). Figure 4.4 shows the simple design of geothermal dryer designed by BPPT. It seems an decent way to utilize geothermal steam to heat up the flowing air directly in the drying machine. In addition, the simple design can make this equipment usually more economical than other kind of dryers. However, the biggest problem in this case is the requirement of lower pressure in the dryer in order to lower the boiling points of moisture and NMP. In this situation, it makes no sense to employ the convection mode of drying in the equipment under very low pressure. Consequently, as long as we consider the vacuum environmental as the first priority, we have to find another choice.

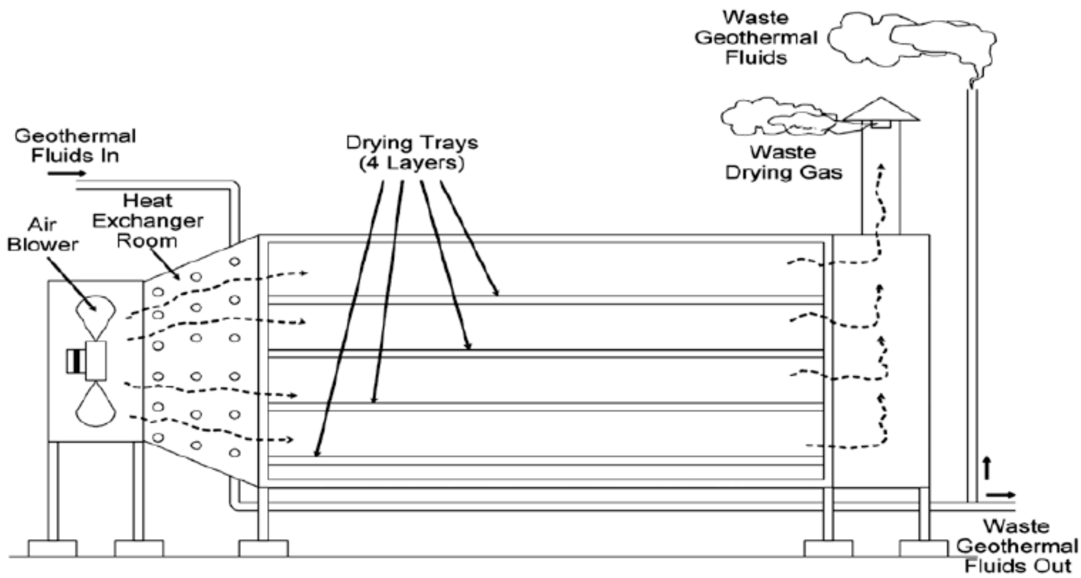


Figure 3.4 Schematic diagram of convection geothermal dryer (Sumotarto, 2007)

Conduction

Generally, conduction dryers are more appropriate for thin products or for very wet solids. In this case, the electrode is a thin piece of foil with wet active materials on top of it. This form of feedstock has more volume of contact heated surface with the heating trays. As you can see in Figure 3.5, heat for evaporation is supplied through the heated surfaces placed within the dryers. When the feedstock was placed on the heated trays, the evaporated moisture is carried away by vacuum operation or flowing gas. Since the binder (PVDF) is heat-sensitive material (low boiling point), manufacturer can't heat the dryers higher than 160°C. Instead of using higher temperature, the vacuum operation is another approach to accelerate this step. The lower internal pressure will reduce the boiling point of moisture and NMP. Besides, the thermal efficiency of conduction dryers tends to be higher than convection dryers, because the thermal waste air from convection will lose a certain amount of heat to environment. On the other hand, if the insulation of conduction dryer performs perfectly, the waste heat could be controlled deliberately.

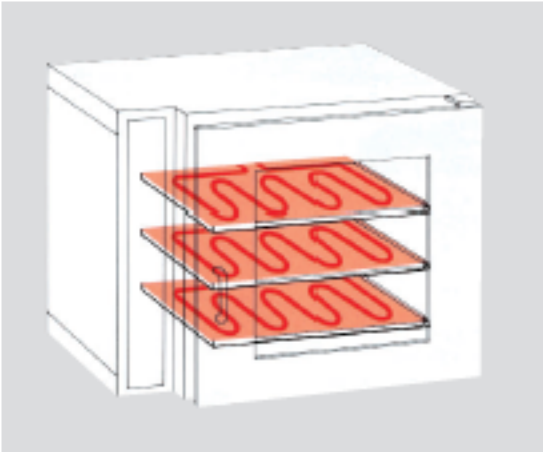


Figure 3.5 Schematic diagram of conduction dryer

Radiation

Various heat resources with temperature above absolute zero would emit radiation to environment. In the term of drying, infrared radiation is often used in dry coating, thin sheets, and films. Although most moist materials are poor conductors of 50-60Hz current, the impedance falls dramatically at RF; such radiation can be used to heat the solid volumetrically, thus reducing internal resistance to heat transfer(Mujumdar, 2006). Energy is partly absorbed by the water molecules; as the production gets drier less energy is used. Normally, its capital and operation cost are both higher than other drying modes, thus this technique is usually only applied on the high unit value products or for final correction of moisture profile wherein only small quantities of hard-to –get moisture are removed. In this case, the combined mode drying with conduction is considerable. Although this might make the design of dryer more complex, it could be able to accelerate the procedure.

3.5.2 Selection the type of dryers

The most widely used dryer is the recirculation type truck and tray compartment dryer. Usually, the type of dryer is determined by the feedstock's form and duration of drying. The feedstock in this case is solid electrodes with paste on the top of it. As we can see in the Figure 3.6, the suitable type of dryer for formed solid and conduction mode are tray dryer (batch). Moreover, due to the requirement of vacuum insulation, it is difficult to apply the tray dryer (continuous) in the production line.

Nature of Feed	Liquids			Cakes		Free-Flowing Solids					Formed Solids
	Solution	Slurry	Pastes	Centrifuge	Filter	Powder	Granule	Fragile Crystal	Pellet	Fiber	
Convection Dryers											
Belt conveyer dryer							×	×	×	×	×
Flash dryer				×	×	×	×			×	
Fluid bed dryer	×	×		×	×	×	×		×		
Rotary dryer				×	×	×	×		×	×	
Spray dryer	×	×	×								
Tray dryer (batch)				×	×	×	×	×	×	×	×
Tray dryer (continuous)				×	×	×	×	×	×	×	
Conduction Dryers											
Drum dryer	×	×	×								
Steam jacket rotary dryer				×	×	×	×		×	×	
Steam tube rotary dryer				×	×	×	×		×	×	
Tray dryer (batch)				×	×	×	×	×	×	×	×
Tray dryer (continuous)				×	×	×	×	×	×	×	

Figure 3.6 Suitable dryers for various types of feedstock (Mujumdar, 2006)

On the aspect of duration of drying, the typical drying time of electrodes is more than 8 hours depend on the moisture content and drying temperature. In some situation, it even needs more than 48 hours. As you can see in Figure 3.7, the most suitable dryer for solid with more than 8 hours residence time within dryer is tray dryer (batch).

Solids' Exposures to Heat Conditions

Dryers	Typical Residence Time Within Dryer				
	0–10 (s)	10–30 (s)	5–10 (min)	10–60 (min)	1–6 (h)
Convection					
Belt conveyor dryer				×	
Flash dryer	×				
Fluid bed dryer				×	
Rotary dryer				×	
Spray dryer		×			
Tray dryer (batch)					×
Tray dryer (continuous)				×	
Conduction					
Drum dryer		×			
Steam jacket rotary dryer				×	
Steam tube rotary dryer				×	
Tray dryer (batch)					×
Tray dryer (continuous)				×	

Figure 3.7 Dryer's selection versus feedstock form (Mujumdar, 2006)

3.5.3 Energy resource for heating

Electricity

Electricity is the most commonly used energy form for drying in industrial application. The dryer could be heated by electricity directly in short time. It is also very flexible and convenient to use it. In addition, the energy efficiency of converting the electricity to thermal resource is very high. It could be able to heat up the product to extremely high temperature; for instance, the industrial electric arc furnace could be heat up to 2000°C. In developed countries, the supply of electricity is usually very stable and safe. However, the electricity is usually more expensive compare to other energy resource. Besides, it also causes some pollution problems and emit amount of carbon dioxide emission, if it was produced by coal power plant. Consequently, although the electricity is a very easy used resource to date, the escalating price of electricity and environmental concern would increase the user's burden in the near future.

Oil and Nature gas

As you can see in Figure 3.8, another option of energy resource is to burn oil or natural gas. Most commonly, the adiabatic combustion temperatures for oil are around 2,150 °C for oil and 2,000 °C for natural gas. It could be used to heat up the flowing nature air for or working fluid injected into the hollow shelves. In the conduction dryer, as the heated working fluid pass through the tube inside the trays, it will heat up the tray by conduction. The temperature of working fluid could be controlled by the mass flow of hot and cold medium. The gas dryers of today use a hot surface ignitor to light the gas compared to the old pilot light days so safety in that regard is not an issue. In the term of cost, the gas dryer has higher capital cost and lower operation cost compare to electric dryer. The energy consumption of gas dryer is half less than electric dryer. But, burning oil and nature gas would also cause the pollution problem. Moreover, the price of oil and nature is fluctuant and many countries don't have enough domestic oil or nature gas resource. Thus, it seems like an economical solution, but it comes with some risks.

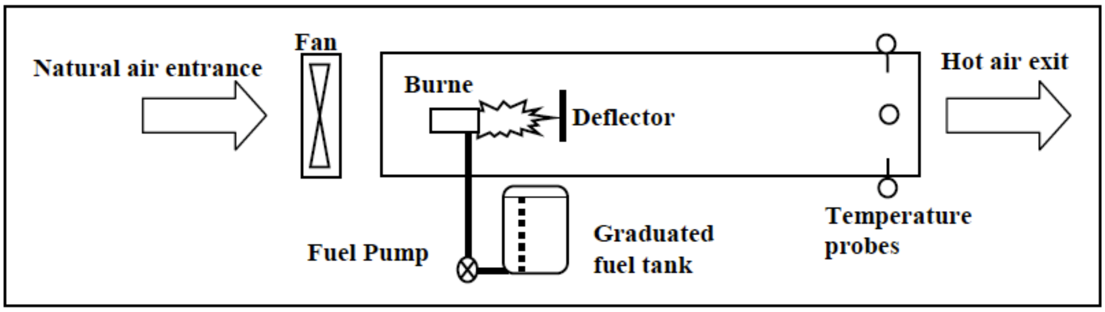


Figure 3.8 Schematic diagram of gas dryer (Diego Ricardo, 2008)

Geothermal steam

The approaches of using geothermal steam could be divided into two categories. In normal convection dryers, the users could pump the hot geothermal steam into the heat exchangers in order to heat up the nature air or any working fluid. Then, the heated air would be blown through into the dryer to carry the moisture away from feedstock. However, if the users need to run the vacuum operation, they should to blow the geothermal steam into the tubes inside the tray directly. The heat would be transfer from geothermal steam to metal tube and then dried products eventually. The main advantages of using geothermal steam are more economical and environmental friendly. The price of geothermal steam could be economically attractive, when they get it from geothermal power plant. Through amount of data and experience, the stable supply of steam is not an issue in some specific location in countries, such as Iceland, Indonesia, and Japan. The possible temperature range of geothermal steam is from 90°C to 300°C depending on the properties of resource. In this case, we need to keep the inside temperature of dryer at around 120°C. In theory, it is feasible temperature to apply geothermal resource into lithium battery drying. However, one problem is that corrosive materials contained in the geothermal steam might cause damage to the equipments. But, if we extract the steam from separators in geothermal power plant in this case, most of deleterious material would be removed with liquid phase.

Ideal dry mode in Iceland

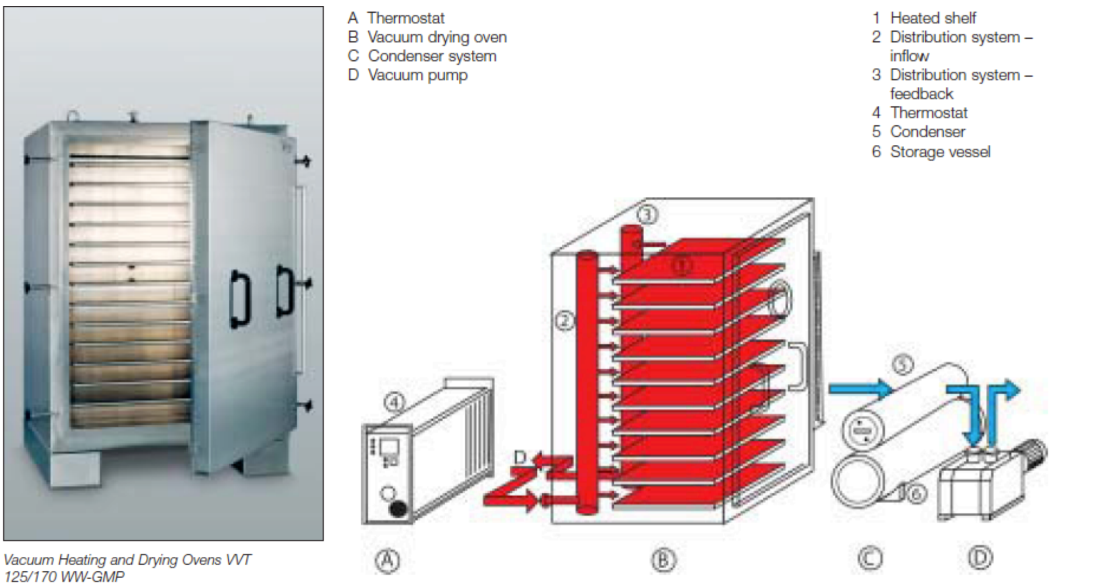
According to those considerations as above, the ideal type of dryer and heating method for lithium batteries would be tray dryer (batch) using conduction heating method under vacuum operation. On the aspect of thermal resource, we would suggest to use the economical geothermal steam at 9 bars, and 173°C as main thermal resource in Iceland. The high temperature geothermal steam from geothermal power plant is available in many places in Iceland. Through the thermostat's control, the geothermal steam will keep the internal temperature of oven at 120°C, which is the target temperature for drying. In addition to the conduction, it also could be combined with radiation heating method in order to accelerate the drying rate in the final period. In terms of the chemical character of geothermal steam, most of corrosive particles are condensed into the liquid phase at 9 bars. Consequently, we should be able to use the geothermal steam in dryers directly with the regular maintenance. However, in the aspect of economical situation, it needs to be planed deliberately and probably sign a long-term contract with the power company to insure the supply and price. As long as we can make sure the stable supply of geothermal steam, this should be more economical competitive and environmental friendly solution. We will discuss the price of geothermal steam in the financial chapter.

3.6 Drying equipments survey

Nowadays, geothermal drying technique is applied on many different kinds of food and agricultural product. However, no one really has applied the geothermal drying technique on lithium battery production process under vacuum operation before. It is more convenient to find a suitable dryer on the market instead of designing a new dryer from scratch. Therefore, we will do an equipment survey in order to find out few suitable vacuum dryers for this project. Drying technology is extensively used in many industrial applications, thus there are various types of drying equipments existing on the market to date. As we discuss in previous section, tray vacuum dryer using with conduction heating mode is our ideal solution in this case. We can treat geothermal energy as one type of thermal resource providing heat resource to any types of working fluid, like oil or water through heat exchanger. Consequently, we will introduce few suitable vacuum dryer we found on the market in the following part.

Votsch's vacuum dryer

The main components of this dryer are drying oven with shelves, thermostat, vacuum pump and, condenser. All components of the drying oven itself are of stainless steel with material class 1.4571 as these may come into contact with the products. The external housing and reinforcements are made of stainless steel with the material class 1.4301.The range of applications is quiet wide, from pharmaceutical industry, food processing industry, Electrical product, Aerospace industry, and chemical industry, even you can state your special requirement to them. They offer four heating solution, electrical, heating medium, infrared radiation, and Microwave. The first two processes are based on the principle of contact heating. This means that the heat is conducted from the heat medium through contact areas to the products. In this case, we will use a heat medium as a heating mode. The difference from the electrical version is that the heat transfer medium flows through channels and then fills the entire cavity of the shelves. A separate thermostat controls the temperature of heat medium is pumped in a cycle through the individual shelves. With steam heating version a special valve is responsible for controlling amount of steam. There are two safety devices, pressure-relief valve and temperature limiter. As usually, this vacuum dryer provides some common advantages such as the lower drying temperature, higher drying rate, no oxidation process, no turbulence, no skin-forming. The key difference of this dryer is flexible heating mode. Another detailed data will be attached in the Appendix 8.



Vacuum Heating and Drying Ovens VVT 125/170 WW-GMP

Figure 3.9 Picture and schematic figure of Votch's vacuum dryer (Weiss Gallenkamp, 2010)

BOC Edward Stoke vacuum shelf dryer model 438

The BOC Edward Stokes vacuum shelf dryer design has pioneered safe, rapid and even batch drying of delicate materials under vacuum at low temperature and without agitation or oxidation. It is made of carbon steel or stainless steel. One of the key design features of Stoke vacuum dryer is the shelf heating connection and manifold system. The shelves are constructed and inspected for maximum steam working pressure of 50 psig and are suitably baffled for efficient heating or cooling using water, oil or steam. Another detailed data will also be attached in the Appendix 8.

Table 3.5 Comparison of two brand vacuum dryers

Brand	Votch	BOC Edward
Series	VVT 85/170	Stoke vacuum self dryer model 438 F
Nominal temperature	200	N/A
Volume (liter)	1515	804
No. of shelves (standard) Available surface (standard) m^2	10 8	12 6.68
External dimensions	Width: 1080 mm Height: 2000 mm Depth: 1430 mm	Width: 1028mm Height: 2171mm Depth: 1968mm
Temperature distribution on the shelves	+4	N/A
Heating capacity Heating capacity with max. no of shelves	20 kw 32	500 Btu/hr/ft2
Heating mode	Electrical: 200~400°C Warm water: 95~140°C Thermal oil: 200~250°C Steam: according to steam pressure Microwave Infrared radiation	Electrical Warm water Thermal oil Steam
Ultimate vacuum	$1*10^{-2}$ mbar	4 psig
Weight (kg)	1900	1667

4. Background information of Iceland

Despite its name, Iceland has a relatively mild climate for its northerly location at a latitude from 63°24’ to 66°33’N and longitude from 13°30’ to 24°32’W due to the warm ocean current passing. The mean annual temperature in the capital, Reykjavík, is -1.5°C on January and 10.3°C on July. It is located in the North Atlantic, about 3 hours by air from major cities in Western Europe and 5-6 hours from the East Coast of the USA. Shipping distances are 3-4 days to Europe and 7-8 days to the North American east coast(Invest in Iceland Agency, 2010). Consequently, its location makes it a good place for American and European market. It has a population of 319,368 and a total area of 103,000 km^2. (Statistic Iceland, 2010). Approximately 38% of the population live in the capital, Reykjavík, and 63% in the capital and neighbouring communities. With 22% of its population aged 15 and below, and 12% aged 65 or above, Iceland has the youngest population in Europe. The official written and spoken language is Icelandic. English is widely used as second language. Studying both languages and also Danish is a mandatory part of the compulsory school curriculum. The high-level educated human resource is an important asset. In addition to those, there are a number of important factor that must be considered before we need to know tons of information for making a big investment in other country. In this chapter, we will only focus on energy resource and environmental issue. It is the key advantage of building a lithium ion battery factory in Iceland. The financial assessment will be discussed in the next chapter.

4.1 Available energy resources in Iceland

In Iceland, the profiles energy production is very different from most other countries. Due to rich natural resource, almost 99% of electricity was generated by renewable energy with lower carbon emission in Iceland (Orkustofnun, 2009). Besides, the energy supply is very stable and economically attractive for the energy intensive industry. For example, there are many aluminium smelters have been built in Iceland due to the lower energy price. In this case, we plan to apply geothermal resource into the drying process to replace electricity consumed by drying equipments. The rest of the energy consumption would be supplied by cheaper and clean renewable electric energy. Consequently, we should insure the characteristic and the sufficient supply of those energy resources in Iceland could meet this new demand.

Geothermal Resource

Geothermal energy is a power extracted from heat stored in the earth. The heat is constantly produced due to the decay of radioactive material and storage in the earth mantle and core. Iceland is located on the boundary of North American and Eurasian tectonic plates, also called Mid-Altantic ridge. The strong volcanic activity in this area brings an excellent opportunity of utilizing geothermal energy in Iceland because of those two main following reasons. First, the active magma at relative shallow depth provides heat resource to rock. Usually, the geothermal gradient is 35°C/km in normal location, but it could be up to 200°C/km in some location in Iceland (Ármannsson, CO_2 emission from Geothermal Plants, 2003). Secondly, the activities create series of fault and fractures, which could be the channels for circulating water and provides permeability in the geothermal system. Consequently, as you can see in Figure 4.1, there are around 30 high temperature fields located within the active volcanic zone running through Iceland from south-west to north-ease, and the low temperature field can be found all over Iceland.

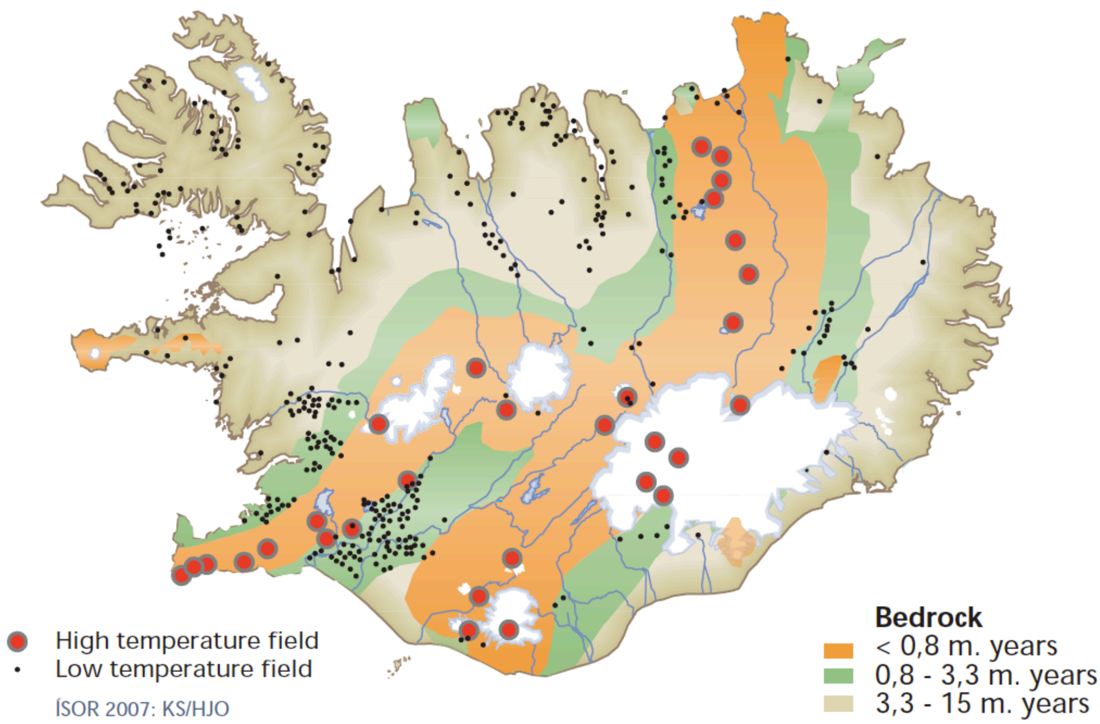


Figure 4.1 Location of the geothermal area in Iceland

Geothermal energy is extensively used in many applications in Iceland for many years, for example, electricity generation, district heating, and swimming pools. From 1930, Icelanders started to use geothermal water to heat their houses in Reykjavik. To date, the total geothermal energy has been up to 39PJ in Iceland (Orkustofnun, 2009). This abundant natural resource brings great benefit to economical development in the past 80 years. In terms of industrial use, the first case was a diatomic plant at Myvatan near Namafjall high temperature geothermal field. The annual steam consumption is about 270 thousand tonnes at 10 bar absolute pressure for drying. Another case is a seaweed processing plant at Reykholar, which uses geothermal water at 107°C for drying (Gunnlaugsson & Ragnarsson, 2001). Those experiences could provide us practical cost data of equipments and technological advices of utilizing geothermal resource. For this hypothetic battery factory in Iceland, we estimate that we need total 10 MW power supply, including office, heating system, and drying equipment. As you can see in chapter 4, energy consumption of drying process amounts to around 50% of total energy consumption. It means we require more than 5MW geothermal resource to meet our energy demand for drying. One of the solutions is to drill our own production well of geothermal steam with 150~180°C and build a lithium battery plant close to it. In this situation, it will increase the initial investment and risk significantly. But, we don't need to pay the cost of steam after operation. In addition, the location of battery factory could be more flexible. However, there are many existing geothermal power plant under operation in Iceland, like Nesjavellir Geothermal Power Station (120MW), Krafla Power Station (60MW), Hellisheið Power Station (213MW), and so on. Actually, they have extra waste geothermal water or steam from separator. The battery companies might be able to get it very cheaply by signing a long-term contrast with the energy company. The detailed cost information would be discussed in chapter 6. Obviously, it seems like a good deal for mutual benefit, thus it is very likely that they build a partnership. However, the distance between geothermal power plant and battery factory will be limited, if they want to use the waste heat from power plant. Although they can build a pipeline to transport heat resource, it will increase the initial and operation cost. In Figure 4.2 and Table 4.1, you can see the location and basic information of main geothermal power stations. Among the items, the road distance between ports and new battery factory would affect the transportation cost.

Table 4.1 Information of geothermal power stations in Iceland

Power Plant	Capacity	Road distance to ports	Owner
Nesjavellir Power Station	120 MW	30km to Reykjavik port	Orkuveita Reykjavíkur.
Krafla Power Station	60 MW	100km to Akureyi	Landsvirkjun
Svartsengi Power Station	76 MW	36km to Hafnarfjordur	HS Orka
Reykjanes Power Station	100 MW	2km to Helgurih	HS Orka

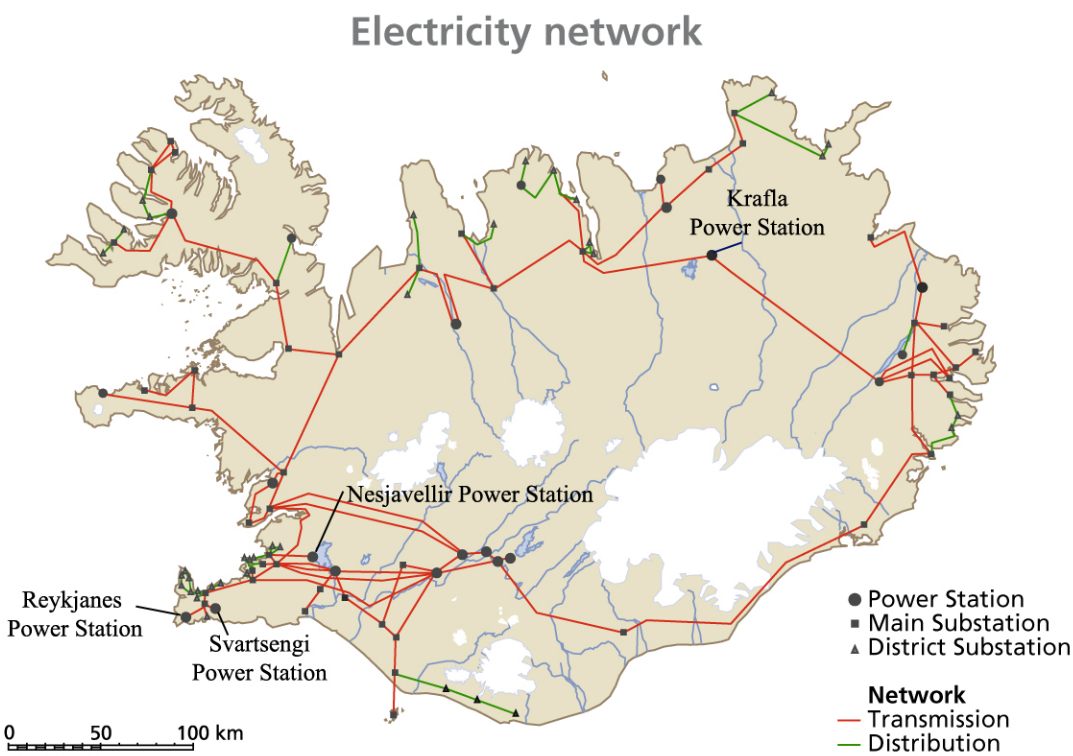


Figure 4.2 Electricity network and main geothermal power stations in Iceland

Method of Utilizing geothermal steam or water from power plant

In general, if we plan to get the geothermal steam from the power plant, we can choice to pump the steam or liquid from separators. In figure 4.3, you can see there are two different separators with high pressure and low pressure in the reference case of Krafla power plant, which is a double flash design. There is usually a tube could transfer the extra steam to existing exhaust stack in order to maintain the stability of separator. Thus, we can get the wasted steam from this tube directly and transport it to battery factory by pipeline. In Iceland, geothermal power plants are typically operated at 9~12 bar, but some wells in the Reykjanes field deliver higher pressure up to 18 bar. For this project, we plan to use geothermal steam at 9 bar, and 175 ˚C as thermal resource. The transmission system of geothermal steam is well known knowledge in Iceland, since it is not an issue here.

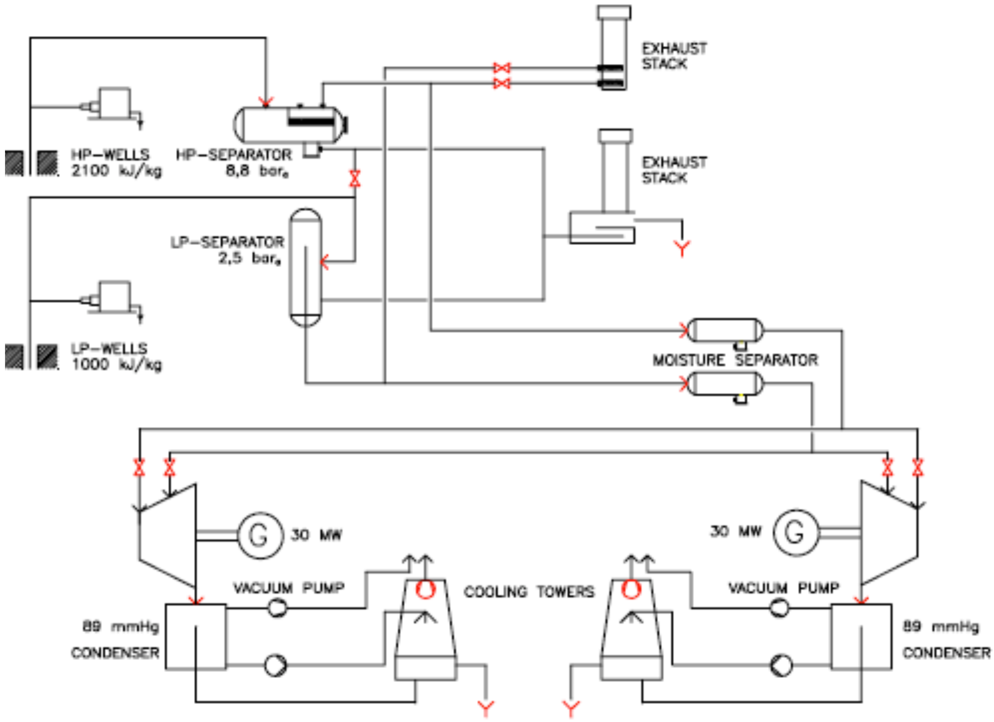


Figure 4.3 Schematic design of Krafla Power Station (120MW)

Electricity and fossil fuel supply in Iceland

In addition to geothermal energy, stable supply of electricity and fossil fuel is also an important consideration for industrial development. Lacking of sufficient energy supply would constrain the production capacity of battery plant based on the same fixed cost. For example, the Thundersky's lithium battery factory can't operate 24 hrs a day because of insufficient energy supply in Shenzhen(Nuutinen, Transferring production of Li-ion battery factory from China to Finland, 2007). In this case, the total amount of power demand of battery plant is 10 MW. In Iceland, the total installed electricity capacity is 2363MW and 2574MW in 2007 and 2008, respectively. There are some ongoing projects of new hydro and geothermal power plants in Iceland. For instance, Orkuveita Reykjavíkur has had plans to develop a new geothermal power plant in HverahliÅL, Bitra and are extending the capacity of existing power plant in HellisheiÅL area, it's totally expected to provide 380MW more capacity by 2015(Orkuveita Reykjavikur, 2010). Since it is a small and independent energy market, energy supply is tightly matched to energy consumption. Although increasing 10MW electricity demand should not be a difficult challenge, it is better the battery companies could make a purchase agreement with local energy provider in order to insure the energy supply and competitive price.

4.2 Carbon footprint of electricity in Iceland

"Carbon footprint" is total amount greenhouse gas (GHG) emissions caused directly and indirectly by an individual, organisation, event or product, and is expressed as a carbon dioxide equivalent(Carbon trust, 2010). As you can see in Table 4.2, it shows that hydropower and geothermal contribute almost 100% electricity production. The range in CO_2 emissions from high-temperature geothermal fields used for electricity production is variable, but much lower than that for fossil fuels. Bertani and Thain (2002) reported on emissions from 85 geothermal plants currently operating in 11 countries and found a weighted average of CO_2 emissions of 122 g/kWh, which compares fairly well with the value of 91 g/kWh reported for the USA plants by Bloomfield(World Energy Council, 2010). On the other side, the average carbon footprint of electricity from hydropower is 4 g of CO_2 per kWh according to World energy council. According to Landsvirkjun's report, the average direct carbon emission from geothermal and hydro power plant in Iceland is 96 and 5 g of CO_2 per kWh, respectively(Landsvirkjun, 2008). If we calculate the average carbon emission based on the percentage, the average carbon emission from Landsvirkjun's electricity would be 23.5 g of CO_2 per kWh.

Table 4.2 Electricity production data in Iceland(Orkustofnun, 2009)

	2008		2007	
	GWh	%	Gwh	%
Hydro	12,427	75,5	8,394	70,1
Geothermal	4038	24,5	3,579	29,9
Fuel	3	0	3	0
Total	16,468	100	11,976	100

Though Landsvirkjun only take the carbon emission during operation into account, Figure 4.4 shows that this amount of carbon emission of electricity is so much lower than the CO_2 emission from coal and natural gas plant.

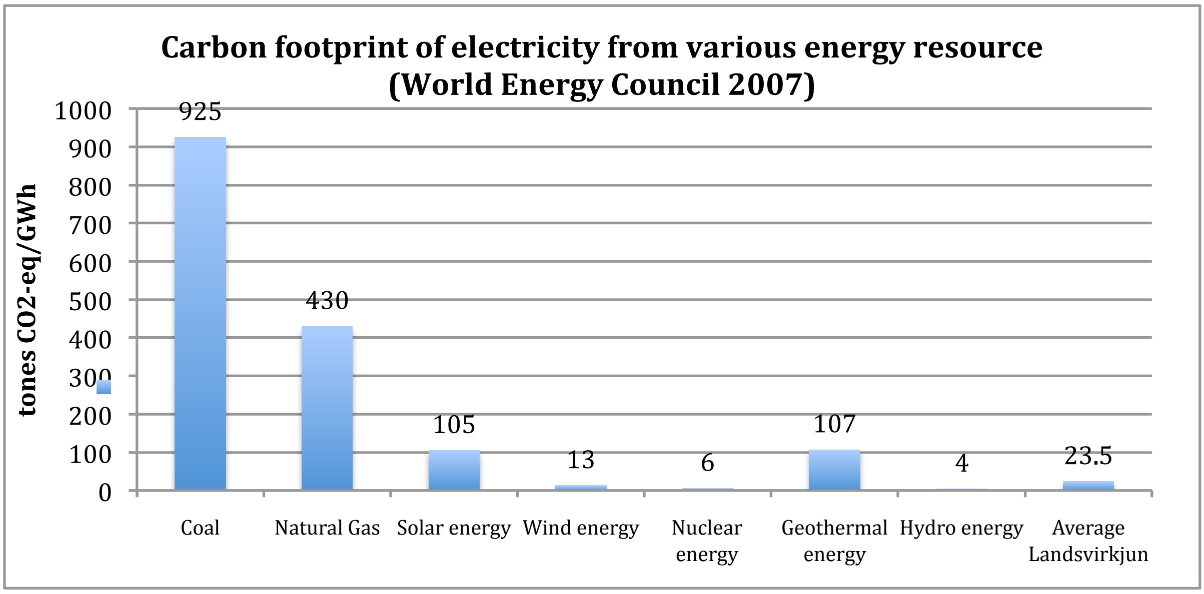


Figure 4.4 Average Carbon emission of Landsvirkjun's power plant compare to other energy resource across the world (World Energy Council, 2010)

In Table 4.3, we can see the energy structure of each country has different feature. Based on that, we can calculate their average emission from electricity generation. If we build a lithium ion battery with 10MW power need in other country, it will emit 36247~64771 tons of CO_2 per year depend on the country's energy structure. In Iceland, approximate 50% of energy consumption is still electricity, which emits 23.5 g/KWh CO_2 on average. The rest of energy consumption will be replaced by geothermal steam, which emit 18g/KWh CO_2. Thus, the total CO_2 emission in Iceland would be around 1818 tons of CO_2 per year. The impact on carbon emissions amounts to 393.4-215.1g/Ah lower releases of CO_2 per year, which is only 2-5 % of original carbon emission compared to traditional energy sources in other countries. In addition, we have to put it in mind that most of carbon dioxide emits naturally from geothermal area in Iceland. The emission from geothermal plants is already part of CO_2 cycle, no new CO_2 is being produced as is in the case of fossil fuel(Ármannsson, CO2 emission from Geothermal Plants , 2003).

Table 4.3 Electricity production structures of various countries and CO_2 emission comparison

Various Resource	Average CO_2 emission (g/kwh)	Estonia	China	USA	Germany	Japan
Renewable	50	1.6%	0.4%	2.8%	11.6%	2.7%
Oil	400	0.3%	0.6%	1.3%	1.4%	12.8%
Gas	430	6.6%	0.9%	20.9%	13.7%	26.1%
Nuclear	6	0.0%	1.9%	19.2%	23.3%	23.8%
Hydro	4	0.3%	16.9%	6.4%	4.2%	7.7%
Coal	925	91.2%	79%	49%	45.6%	26.6%
Total		100%	100%	100%	100%	100%
Average CO_2 emission from electricity (g/kwh)		873.9	738.9	552.1	494.2	413.51
Total emission for 87.66 GWh (tons)		76606	64771	48402	43321.5	36247.4
CO_2 emission in Iceland (tons)		1818	1818	1818	1818	1818
Reduction emission (tons)		74778	62953.9	46584.3	41503.5	34426.4

5. Financial feasibility assessment of Li –ion battery factory in Iceland

Although we have confirmed the feasibility of geothermal drying in this project in the previous chapters, we still have to consider many other local economical factors, such as salary, land price, and transportation cost when we plan a new investment project. In financial world, there are some common methods of estimating the profit of an investment, for example, the project's net present value and internal rate of return. For this reason, we build a comprehensive profitability assessment model to calculate the net present value and internal rate of return based on the current cost data on the market and some assumptions. In this case, we use Microsoft Excel to develop many different spreadsheets for cost analysis, investment, operation, cash flow, and profitability in this model. And then, we will enter the cost data and assumptions into this model. Each of spreadsheet contains the relevant information and result of calculation to present the financial situation for specific purpose during all operation years. Through this model, we can gain the main results, like NPV, IRR, ROI and graph of this project and then we will discuss how does it go in the all period. The detailed information of this model will be displayed in Appendix 1. In the end, we will perform the sensitivity analysis and Monte Carlo simulation on this project in order to find out the most influential factors and the risk of this project. Besides, because the factories will buy the raw material and equipments from suppliers at similar price, we assume most of the significant cost drive will be the same. For this reason, we will be able to apply this model to Germany, Finland, and Estonia individually by changing the energy price and salary in each country. From the result, we can simply compare how energy price affects the result of this investment in different countries, although it is not a very precise assessment for other countries.

In this model, we mostly investigate into the real market to get the recent data such as, raw material price, interest rate, and exchange rate. But, we still make some assumptions, such as capital structure and discount rate to complete our model based on our experience. In table 5.1, it shows the main numbers and resource, which we used in this model based on our research. In the following section, we will provide more detailed information of each number.

Table 5.1 Main assumptions in this model

Item	Number	Resource
Exchange Rate of ISK	Euro: 155.17_11/24/10 USD: 111_11/24/10	Central bank of Iceland
Corporate tax	18%	Invest in Iceland Agency
Interest rate on loan	12%	Landsbanki
Sales price	1.44 (USD/Ah), with 3% annual decreasing trend	Price survey on market
Raw material price	0.67 (USD/Ah), with 2.75% annual decreasing trend	From many supplier
Capital structure	Equity: 30% Loan: 70%	Assumption
Initial investment	9612 million ISK	From many supplier
Salary in different countries	Iceland: 238,000 ISK/mon Germany: 301,000ISK/mon Finland: 310,000 ISK/mon Estonia: 69,750ISK/mon, with 10% annual increase rate	Iceland: Iceland Statistic Germany: Statistisches Bundesamt Deutschland Finalnd: International Average Salary Income Database Estonia: Estonica.org
Energy price	Iceland: 3.7 ISK/KWh (6 years contract) Germany: 13.02ISK/KWh Finland: 8.52ISK/KWh Estonia: 6.82ISK/KWh	Iceland: Landsvirkjun Other countries: Europe's Energy protal
Discount Rage	15%	Assumption

5.1 Financial and economical environment

As we know, many European countries have incentive policies relative to green business, such as electric vehicle, and solar power. It makes Europe a main market in the early stage for lithium ion battery. As a member of European Economic Area, Iceland implements the same basic liberal business philosophy as the European Union. Consequently, Iceland is an ideal springboard for tariff-free access to the major EU market area. In terms of tax system, the Icelandic tax system is relatively simple and effective. The emphasis has been to simplify it further, reduce tax rates, broaden the tax base and conclude more double taxation conventions, which will increase the competitiveness of Icelandic corporations and attract foreign investors. The corporate income tax in Iceland is 18%, which is one of the lowest ranks in OECD member countries (Invest in Iceland Agency, 2010). However, the collapse of banking system and economical crisis in 2008 result a very unstable environment for investors. Many economical indexes still showed the bad economical situation in Iceland after crisis. For example, the annual economical growth rate is -6.8% and unemployment rate exceed 9% in 2009 (Statistic Iceland, 2010). However, the economical growth rate is expected to be 2.6% in 2010 and 2.8% in 2011. The inflation of Iceland fallen back to 3% in 2010. The positive number of net balance of trade is a sign of growing economy.

Currency issue

The official currency unit of Iceland is Krona(ISK) instead of Euro. The exchange rate of Krona is determined on the interbank market for foreign exchange. In Figure 5.1, the exchange was keeping floating around 80 ISK/Euro before crisis. After global economical crisis and collapse of three main banks, ISK plummeted sharply in the end of 2008. Although it brought the huge effect on the value of foreign debt, it will also benefit the exporting business. Moreover, it causes very high inflation in Iceland, which was 12.4% and 12% in 2008 and 2009, respectively. Hence, the government was forced to put monetary restriction on their currency market in order to mitigate the damage. This action did stop depreciating of ISK, but exchange rate of ISK is still not very stable. It was floating between 145 ISK/Euro to 180 ISK/Euro during 2008 and 2009. In this case, we use 155.17 ISK/Euro (24/11/10) as our exchange rate in the model (Central bank of Iceland, 2010).

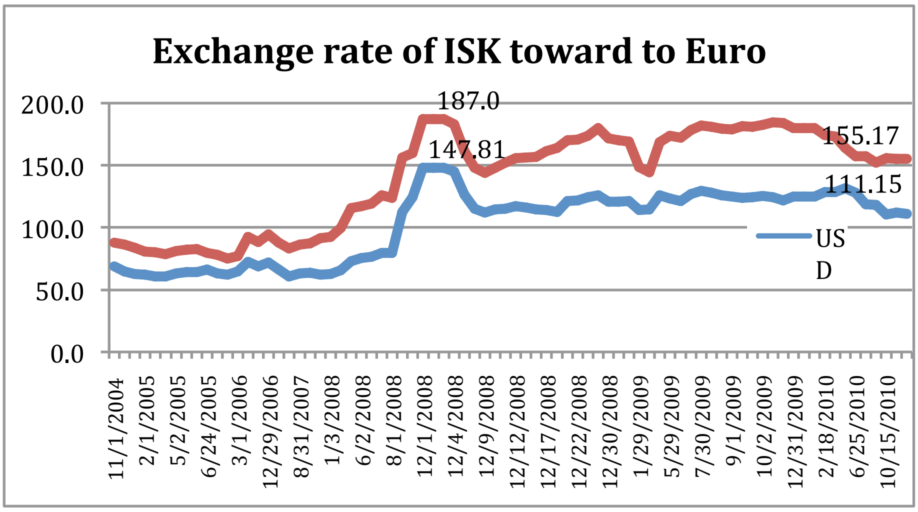


Figure 5.1 History of exchange rate of ISK (Central bank of Iceland, 2010).

Cost of raising capital

There are two general ways of raising capital. (1) Debt from bank. (2) Equity. In this model, we decide to use 30% of equity and 70% of debt as our capital structure. In terms of debt, the main cost of debt is the determined by the interest rate. There is no exact number on this issue, especially for a new category investment. Normally, each bank will announce their prime rate for loan every period of time based on central bank's interest rate and many other factors. And then, they will add the risk premium, which will increase with the risk of individual investment. Recently, Lanksbanki's highest prime rate is 5.6% without risk premium. Their index-loan and non-index interest rate is 10.3% and 12.25%, respectively (Landsbanki, 2010). But, the interest rate is always negotiable and affected by many factors. In this case, we will use 12% as our initial interest rate in the calculation. But, we will try different interest rate in the sensitivity analysis. Besides, it's also possible to get grant from government because it is an emerging and green business. For instance, an American lithium battery company, A123 System, got $249 million from Department of Energy in 2009 for their new battery factory.

5.2 Cost analysis

5.2.1 Initial investment

Cost of construction the factory

There are few methods of assessing the cost budget of construction the factory we can find online or in the civil engineering textbooks. However, they might be not very close to the practical situation in Iceland, hence we consulted, who works for one civil engineering company in Iceland. After discussion, he made an assessment of construction factory in Iceland with 20000m^2 based on our requirement. It includes the cost of construction, electrical system, heating system, design, project management, licence fee, and so on. Value Add Tax (VAT) has been taken into account in the assessment. In table 5.2, it lists the cost of various work items in this project with VAT. Detailed information will be showed in Appendix 4.

Table 5.2 Cost of construction factory in Iceland (Magnússon, 2010).

Work items	Price		Total
Site and earthwork	10500	kr/m^2	210000000
Structual	51500	kr/m^2	1030000000
Utilities and heating	18300	kr/m^2	366000000
Ventilating	15200	kr/m^2	304000000
Interior finish	29500	kr/m^2	590000000
Electrical	19500	kr/m^2	390000000
Exterior finish	39300	kr/m^2	786000000
Site improvements			105000000
Unforeseen cost and change orders (10%)			367600000
CONTRACTORS EXPENSE with VAT			4148600000
Design, project supervision, project management			518575000
License fees, connection fees and assessments			20000000
Other costs such as printing, advertising, etc.			4348150
GENERAL COST with VAT			542923150
TOTAL COST with VAT			4691523150

As you can see, the total cost of whole project is around 4.7 billion kr (Magnússon, 2010). Since we will build the factory in four stages from 2012, the total cost will be split into four parts.

Cost of Production lines

The cost of production line includes all the machines from coating machine, calender, slitters, automatic stacker, sealing machine, vacuum dryer, and so on. It's very complex question to look at the cost of the each equipment, when we try to estimate the cost of whole production line. Moreover, different type of lithium battery cell would need different equipments in some steps, such as assembly and winding. According to Matti's report on Thundersky's factory, the cost of installation one entire production line is 5 million Euros. Their final product is similar to ours, so the cost should be similar. The list of their equipments would be showed in Appendix. In addition to this information, we also have contacted one Chinese seller, LinYi Gelon New Battery Materials Co.Ltd, who can provide entire production line equipment for lithium iron phosphate battery. They design the whole entire production equipments based on our need and give us the estimation cost of it. In this case, we will produce prismatic type of lithium iron phosphate cell with 10~30Ah capacity. One production line could be able to produce 10000 cells per day. If we operate the factory 24 days a month and 18 hours a day, the annual production capacity is 21MAh per line. In their assessment, the production line is divided into few different work items as you see in table 5.3. Each work items consists of various equipments, which will be showed in Appendix 2. Besides, training and technical support cost is included in the calculation. Total cost of each production line is 33 million RMB, which is equal to 556.7 million in ISK according to their assessment. In this case, we assume the price of new type of dryers has similar price as well as electrical dryers based our price survey. Besides, the cost of dryers is only 14% of production lines. The small amount of difference in equipment price does not affect the overall cost of production significantly. Following the development plan, investors will increase the numbers of production line year by year. Finally, the total cost of production lines would amount to 4.5 billion ISK by 2015.

Table 5.3 Cost of lithium iron battery production line with 21MAh/yr capacity

Work items	Cost
Cathode production	6452000
Anode production	5952000
Assembling	9792000
Formation/ Grading	6571000
Pack	100000

Power system	1010000
Testing equipment planning	783000
Conventional testing	115000
High and low temperature test	300000
Training and technical support costs	2000000
Total cost	33,075,000(RMB)

Other Cost

Certainly, there is other initial cost not included in the building and production line cost. For instance, the company have to purchase some office facility, information system for operation, and pay the cost of creating a firm and administration fee. In this case, we use 5% of production line cost and construction building cost as other cost.

Table 5.4 Summary of initial investment

	2012	2013	2014	2015
Install Production lines on this year	1	3	2	2
Incremental capacity	10 MAh	60MAh	40MAh	40MAh
Cost of production lines	556.7	1670.3	1113.5	1113.5
Incremental Area of factory	10000	4000	3000	3000
Cost of construction factory (MISK)	2000	900	900	900
Other cost	127.83	128.51	100.6	100.6
Total cost of each year	2684.6	2698.8	2114.2	2114.2

5.2.2 Fixed cost

Maintain Cost

According to Matti's report, maintain cost in lithium battery industry is usually 10% of the price of equipment (Nuutinen, Transfering produciton of Li-ion battery factory from China to Finland, 2007). We will also use 10% of the price of production lines in this model.

Salary cost

Of Iceland's population of 317,593 on December 1, 2009, the labour force totaled

180,900. Unemployment was 7.2% in 2009 (Invest in Iceland Agency, 2010). According to Statistics Iceland, we can find out the average salary of various kinds of profession in Iceland in 2009. By international comparison, wages and wage cost in Iceland are very competitive relative to most Western countries. In manufacturing, they are less than half those in Germany, for example. Indirect wage cost is relatively low in Iceland at 35-40% (including vacation and sickness provisions, payroll taxes and contribution to a pension fund). The operation personnel are determined by the production capacity of factory and different types of equipment. Usually, high-energy cell will need less labour force for the same amount of battery. We estimate the number of workers we need in this case based on few previous research. In ANL's report (Argonne National Laboratory, 2000), each production line need 19~26 workers per shift for whole process. In this case, there will be two shifts and 8 production lines in the final stage. The total number of workers and annual salary cost will be showed in Table 5.5. After 2015, we assume we will hire the same amount of employees.

Table 5.5 Annual salary analysis of 160MAh/annual battery plant

	Mean salary (KISK/Mon)	2012	2013	2014	2015
Number of production lines		1	4	6	8
CEO	1000	1	1	1	1
CTO and CFO Managers	676	2	2	3	3
Senior Engineer	557	3	6	9	9
Associate Engineer	415	3	9	12	12
Clerk	310	3	6	8	10
General, machine workers	238	40	160	240	320
Total number of employee		52	184	273	355
Total salary cost per year		221.4	559.2	1018	1293

Land Rental

In this project, we will build the whole factory step by step. In the first year, we need to rent 10000m^2 for office facilities area and two production lines. After that, we will need to rent 4000m^2 area more for installing another two production lines.

Consequently, the rental will be increased to 411.84MISK in 2015 and keep the same in the next twelve years.

Table 5.6 Rental for land

Land cost data	2012	2013	2014	2015
Rental area (m^2)	10000	14000	18000	22000
Annual unit rental price (kr/m^2)	18720	18720	18720	18720
Total rental (MISK)	187.2	262.08	336.96	411.84

Research & Development cost

In the aspect of research and development, we decide that the company will invest 200MISK in the first three years, and then spend 8% of profit after tax on R&D on each year. It will bring some burden to their budget in the early stage, but it is necessary in every industry in order to improve their products and production efficiency.

5.2.3 Variable cost

Energy cost

In Iceland, electricity market was almost dominated by Landsvirkjun. Total electricity production in Iceland was 16,839 GWh (Statistic Iceland, 2010).Landsvirkjun's electricity sales amounted to 12,546 GWh in 2009 (Landssvirkjun, 2009).Their market share was approximately up to 73%. Other private energy companies usually keep their price of electricity confidential. Consequently, we will use the price of electricity from Landsvirkjun as our assumption. Currently, Landsvirkjun provides so-called wholesale contracts, which can be valid for one, three, seven or twelve years. Moreover from the beginning of 2006 the company also provides so-called base load contracts valid from 6 and up to 12 years. In this case, it's most like the lithium battery companies sign a base load contract with Landsvirkjun for at least 6 years in the beginning. According to their website, the price of electricity is around 3.7 ISK/kWh, if they sign 6 years base load contract. After replacing the drying equipment, we only need 0.23KWh electric energy to produce 1Ah Li battery. Therefore, the electric energy cost is 0.851ISK/Ah in Iceland. In practice, the price could be even lower as they negotiate longer contract with Landsvirkjun.

Another energy resource we might need in this case is industrial steam. Normally, the steam generated from coal cost 7.3 USD/ton (Invest in Iceland Agency, 2010). In

Iceland, the power company Hitaveita Sudumesja offered 20 barg steam at 4USD/ton and 6 barg at 3 USD/ton from 1995 (Invest in Iceland Agency, 2010). In addition, the diatomite plant at Myvatn that was in operation until 2004 paid 1 USD/ton. In Iceland, geothermal power plants are typically operated at 10~ 12 bar, but some wells in the Reykjanes field deliver higher pressure up to 18 bar. This pressure is high enough for the vacuum drying using steam as heating medium. In this case, we assume that we will use 9 bar geothermal steam in drying process. According to our calculation, we need around 0.522 kg steam to dry 1Ah battery. If we can get the steam at 3 USD/ton, it cost 0.17 ISK to dry 1Ah lithium ion battery. In summary, the total variable energy cost including electricity and geothermal steam in Iceland is 1.04 ISK/Ah.

Raw material

The total price of raw material is contributed by many different raw materials. According to the ANL's cost analysis in 2000, we can find out the unit price and quantity of various raw materials in one cell. Importantly, we can also know the cathode, electrolyte, graphite and separator are the main issues of cost. Since the recent price might be different from the old one, we will check out the new unit price for main costly material and sum up the new price of whole raw material based on the recent public market.

		High-Energy Cell			High-Power Cell		
Material	Price ($/kg)	Quantity (g)	Cost/cell ($)	%	Quantity (g)	Cost/cell ($)	%
Cathode	55	1,408.6	77.47	48.8	64.8	3.56	28.2
Separator	180	60.5	10.89	6.9	16.4	2.95	23.3
Electrolyte	60	618	37.08	23.4	44	2.64	20.9
Graphite	30	563.6	16.91	10.7	12.7	0.38	3.0
Can and vent		291	3.20	2.0	70	0.77	6.1
Binder	45	162.6	7.32	4.6	8.8	0.40	3.1
Copper	15	151.9	2.28	1.4	41.6	0.62	4.9
Aluminum	20	63	1.26	0.8	19.4	0.39	3.1
Carbon	20	46.4	0.93	0.6	2.2	0.04	0.3
Other	20	67.1	1.34	0.8	44.8	0.90	7.1
Total		3,432.7	158.68	100.0	324.7	12.66	100.0

Figure 5.2 Argonne National Laboratory's lithium battery cost analysis (Argonne National Laboratory, 2000)

In regard to cathode material, it is the most expensive part in the cell. In ANL's report, they use lithium cobalt as cathode material. Lower cost materials could drive further cost reductions. For example, onereview showed that moving to iron-phosphate can reduce cathode costs from 50% to 10% of the total material cost While there is no international price, the current domestic price in China is ranging from $23810 USD to $24600 per ton according to the vice president of China S Group. This depends on the raw material prices for lithium iron phosphate, which relies on lithium, iron ore and phosphate prices. In addition to cathode, we also have done a price enquiry for separators, electrolyte, and graphite. In Table 5.7, it shows the current price of the main material in the 10 Ah cell. The total price of one 10 Ah cell is 6.72 $USD based on our own enquiry and detailed information of quotation will be showed in Appendix5-7. Since it is just the primary enquiry to sellers, the wholesale price might be cheaper after negotiation. According to Matti's research, the total raw material price is around 0.4 Euro/Ah in Finland. In this model, we will use 0.67 USD/Ah as our average raw material cost. According to BTAP's research (Battery Technology Advisory Panel), they predict the material costs will decrease by 40% over the next 20 years, a rate of 2.5% per yeark (Kromer & Heywood, 2007). Consequently, we will reduce the cost of our raw material 2.5% per year in the model.

Table 5.7 Current cost of raw material in 10 Ah cell

Material	Unit price	Quantity (g)	$Cost/ cell	%	Data Source
Cathode	23.8US$/kg	64.8	1.54	22.9%	China Sun Group
Separator	85 US$ /kg	16.4	1.39	20.7%	Linyi Gelon New battery material Co.,Ltd
Electrolyte	35 US$/kg	44	1.54	22.9%	Beijing Chuangya Hengye New materials Technology Co.,
Graphite	9 US$ /kg (FOB)	12.7	0.11	1.7%	Kimwan Special carbon &Graphite Group
Can and vent	0.5 US$/ piece	70	0.5	7.43%	ANL's report
Binder	40 US$/kg	8.8	0.35	5.23%	ANL's report
Copper	8.254 US$/kg	41.6	0.34	5.11%	London metal exchange
Aluminum	2.241 US$/kg	19.4	0.04	0.65%	London metal exchange
Other	20	44.8	0.89	13.32%	

Total		322.5	6.72$USD	100.00%

Marketing, transportation, and R&D cost

After manufacturing the products, there are other expenditures, like the transportation cost and marketing cost, before delivering the products to clients. According to Anderson's research (Anderson, 2009), the marketing cost and transportation cost is around $15 /kWh and $25/kWh, respectively. In this model, we make use the same number as our assumption for marketing cost and transportation.

5.2.4 Sale price

The range of sale price of lithium iron battery is extensive depend on the quality of battery. The retail price of cell from world famous brand, like A123 system, or K-2 could up to 4.9 US$/Ah on the website (Batteryspace, 2010). And, the retail price of cell from Chinese battery company, such as Thundersky could down to 1.5 US$/Ah (Electric motorsport EV part, 2010). Usually, this kind of cell doesn't include battery manage system and test guarantee. In the wholesale market, the firm notes the average lithium-ion cell price in 2009 has been $650 per kwh, but claims automakers are already seeing bids for $450 per kwh from battery companies for delivery contracts in the 2011/2012 timeframe (GM motor, 2010). Consequently, we will use very $450 per Ah as our assumption, which is a relative conservative number. Several factors can drive lithium-ion battery price reductions. These include increasing production volumes, transitioning to low-cost alternative materials, improved manufacturing processes, and reducing external control circuitry. As you can see in Figure 5.3, both the Battery Technology Advisory Panel (BTAP) and Argonne National Labs (ANL) published high-volume cost projections for high-energy lithium-ion batteries (Kromer & Heywood, 2007). Their predicted price of lithium ion battery will be $224/kwh and $270/kwh in 20 years, respectively. Based on this trend, we will set the sale price of the product will decrease 3% each year. Therefore, the price at 2017 will be around $287.1/KWh in this model.

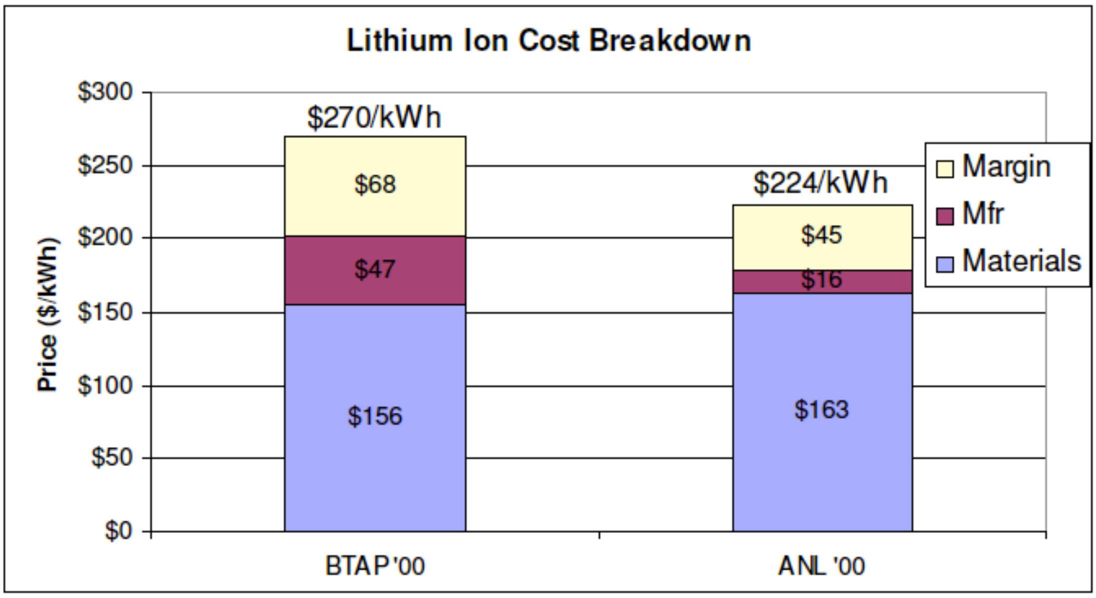


Figure 5.3 Projection of price from BTAP and ANL (Kromer & Heywood, 2007)

5.3 Main results of model

5.3.1 Net present value and internal rate of return

Net present value is a common tool for firm to evaluate an investment project. With negative value of NPV usually means this investment can't bring more value to the company. In this project, the NPV for total capital with 15% discount rate is 5075 million ISK after 15 years operation time. And, NPV for equity with 15% discount rate is 5517 million ISK. As you can see in Figure 5.4, the value of NPV for total capital and equity both take 9 and 8 years turn to positive, respectively. From the point view of NPV, it seems a reasonably profitable business in Iceland. But, if we move the factory to other countries in Europe with similar situation, the accumulated net present value might turn to negative due to much higher price of industrial electricity. In Table 5.8, it shows the electricity price for other countries in Europe and European average price. We pick up Germany, Finland, and Estonia and change the energy price and average salary in this model individually. Although the other cost assumption might be slightly different in every country, we can simply compare how energy price effects net present value. Figure 5.4 shows that NPV fall down to -2681 MISK in Germany and -251 in Finland, respectively. Due to the lower salary and decent energy price in Estonia, it results the similar net present value as Iceland.

However, the discount rate is a critical factor for calculating NPV. The discount rate was affected by the interest rate of loan and the return rate of equity after tax. As the expected return rate of equity get higher, the discount rate would be increased and NPV will go down at the same time. In this case, we use 15% as discount rate because this is a new and risk business lack of history data and experience.

Table 5.8 Industrial electricity prices in Europe (Europe's energy portal, 2010)

Nation	**Price(€/KWh)**		
Italy	€ 0.1	Sweden	€ 0.0602
Netherlands	€ 0.0925	Finland	€ 0.0559
Denmark	€ 0.089	France	€ 0.0519
Germany	€ 0.0848	Romania	€ 0.0595
United Kingdom	€ 0.0837	Estonia	€ 0.0449
Average Price in Europe	0.72 (€/kwh)		

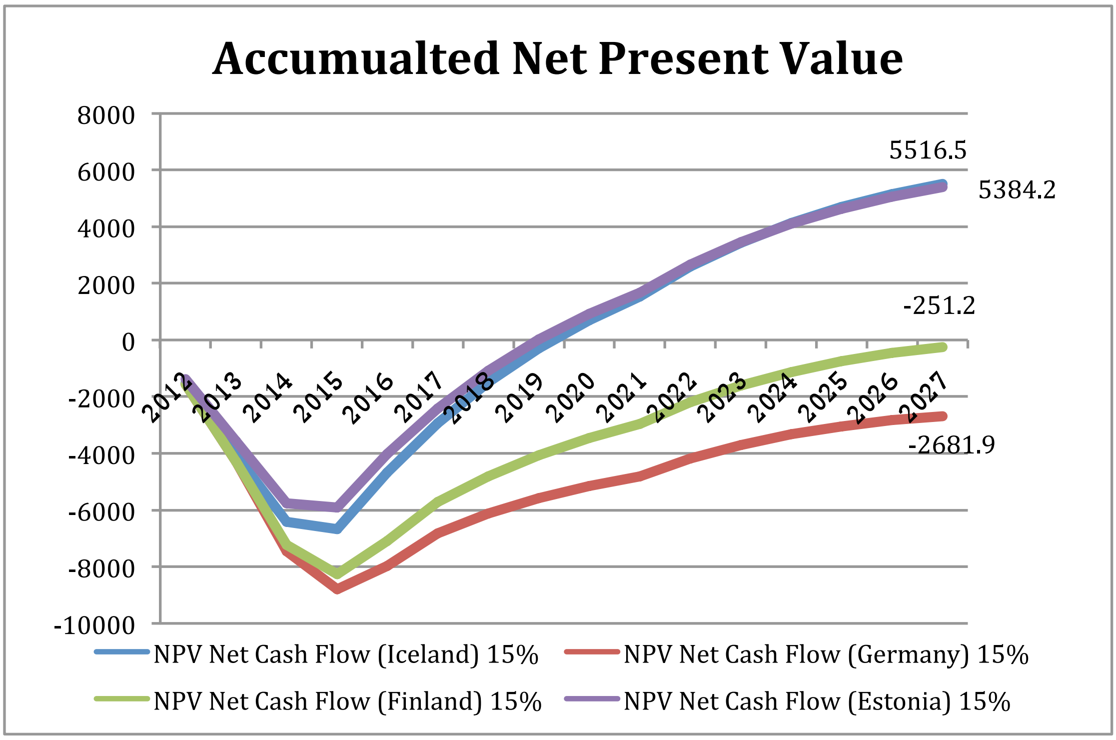


Figure 5.4 NPV of total cash flow and net cash flow with 15% discount rate

In terms of internal rate of return, it is used in capital budgeting to measure and compare the profitability of the investment. The higher a project's internal rate of return, the more desirable it is to undertake the project. In figure 5.5, it shows that the internal return rate of equity in Iceland is 27%. On the other side, the internal return rate of equity in Germany and Finland fall to 9% and 14, respectively. In Estonia, internal rate of return is also 27% because lower salary offset the impact of higher energy price. Although there is some risk and uncertainty in this project, NPV and IRR present a much higher value in Iceland compare to Germany and Finland with higher energy price and similar salary. From this point of view, we can say energy price significantly affects the result of this investment according to our model. However, salary is still an important cost driver in this business at the same time.

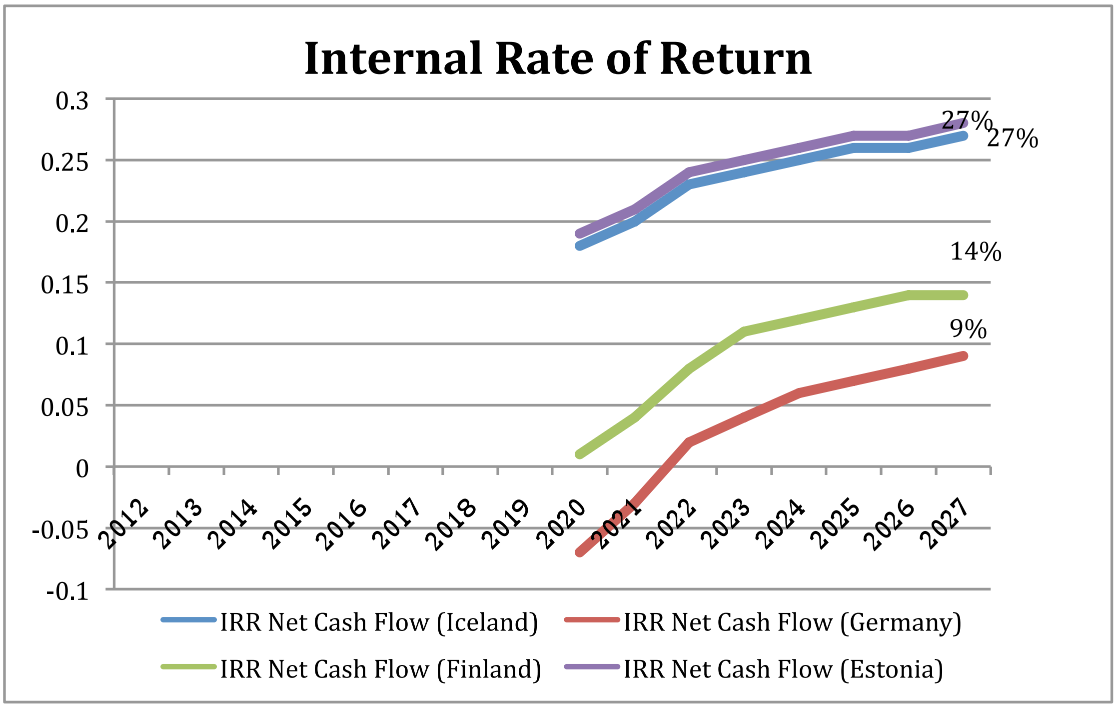


Figure 5.5 Internal rate of return of this project

5.3.2 Net cash flow and cash flow before tax

In the fist three years, the firm's initial investment and construction period result negative net cash flow, especially on 2014. For this reason, we have to prepare 4500 millions ISK as working capital, otherwise the firm will go bankrupt. After 2015, the firm start to generate huge amount of revenue from the sales of products. As you can see in Figure 5.6, the cash flow was increased with the incremental production capacity till 2016. However, after the production capacity hit the peak in 2016, the decreasing unit profit cause less cash flow in the next 10 years. Obviously, this firm's ability of generating cash is not as strong as before, but they don't need to pay extra financial cost, like interest and repayment of loan after 2012. In a word, this project could bring stable 3000 million ISK of cash flow from 2016.

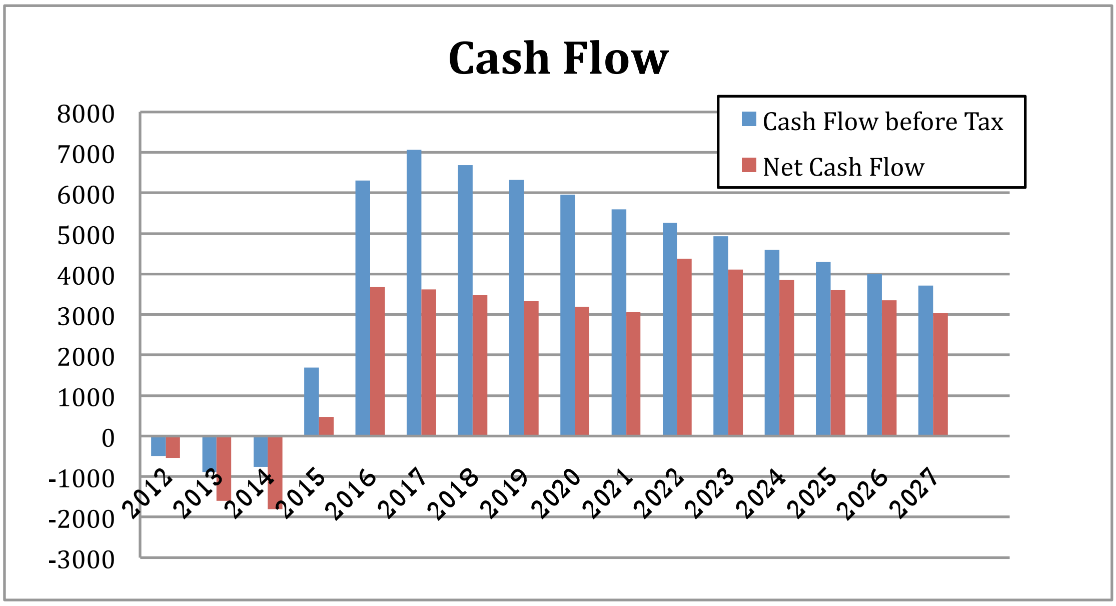


Figure 5.6 Cash flow before tax and net cash flow of this project

5.3.3 Finance indicators

Return on investment (ROI) and return on equity (ROE)

Those number measures the rate of return on the ownership interest (shareholders' equity) of the common stock owners or whole investment. It shows firm's efficiency of generating profits from every unit of shareholder's equity or whole investment. In Figure 5.7, you can see there is a clear peak of ROI on 2016 due to the full capacity operation of factory and lower capital situation. After that, ROI went down with the increasing accumulated capital. Meanwhile, ROI is relative stable because the big amount of debt as denominator.

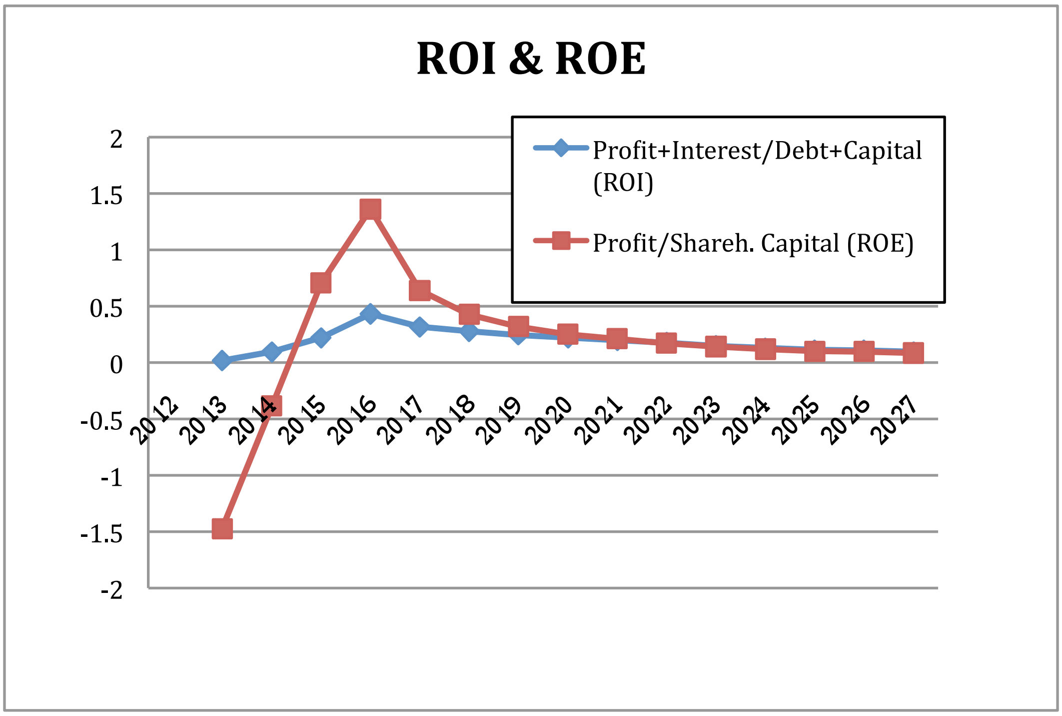


Figure 5.7 Return on investment and return on equity of this project

Current Ratios

The current ratio is a financial ratio that measures whether or not a firm has enough resources to pay its debts over the next 12 months. It compares a firm's current assets to its current liabilities. In Figure 5.8, you can see the current is extremely high because of lower liabilities. It is because they haven't started to pay the repayment, tax, and dividend in the first three years and the lower sales number. In the following year, the current ratios back to a stable increasing trend, since more and more asset was collected. As a whole, the firm's current ratios never lower than 1, and the lowest point is 1.29 of liquid current ratio on 2015. From this point of view, this company seems to have a good ability to pay back their debts.

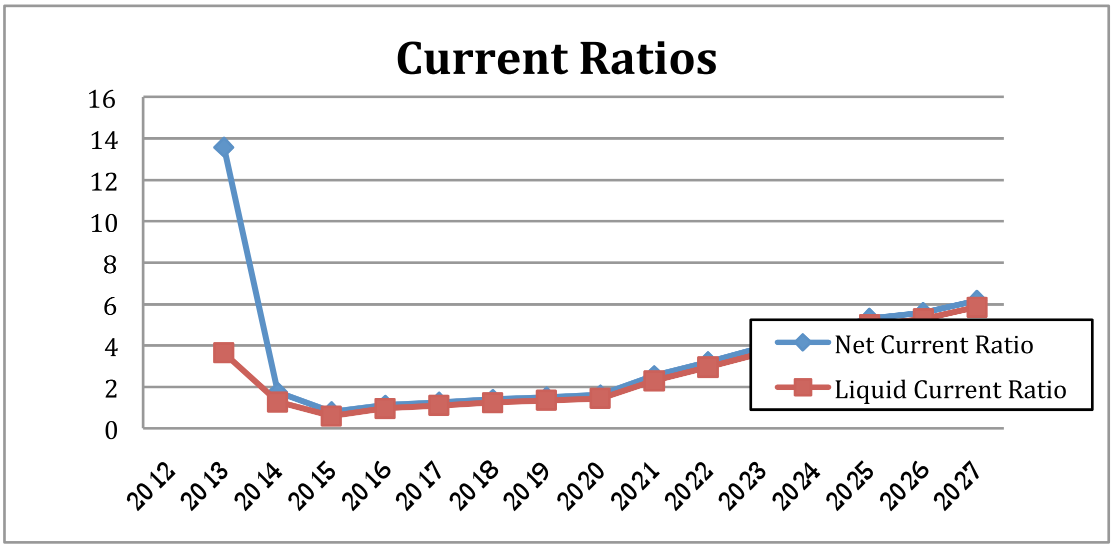


Figure 5.8 Current ratios of this project

Allocation of funds

In Figure 5.9, it shows clearly how this company allocates their fund during operation. In the beginning, they have very limited fund for paying back interest and loan management fee. After that, the repayment play important role of their allocation from 2016 to 2022. However, they should be able to collect more cash movement in the last couple of years. In reality, they might invest this big amount of cash into other projects or increase their production capacity.

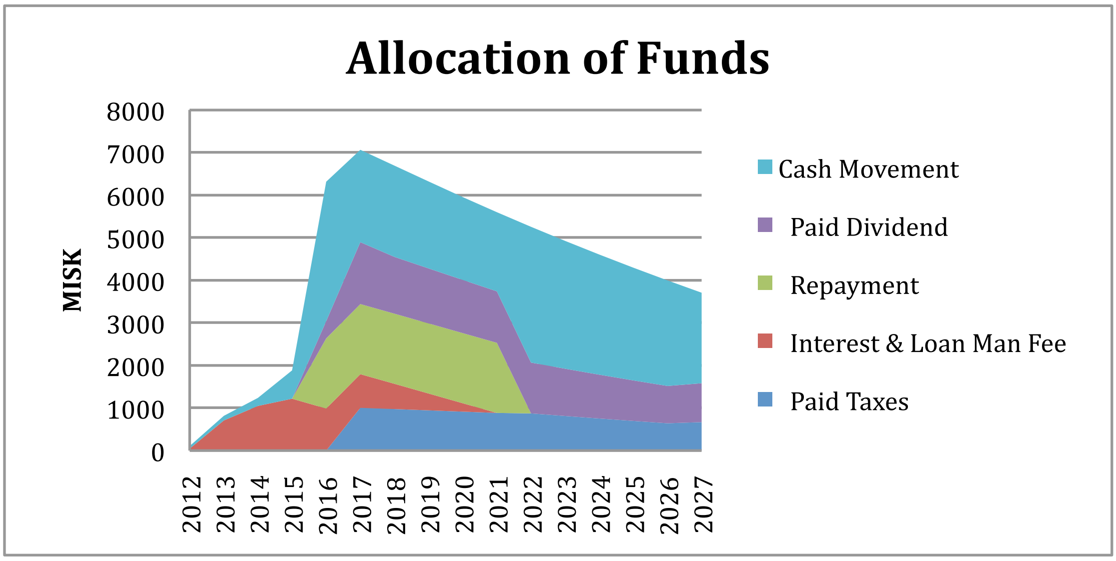


Figure 5.9 Allocation of funds in this project

Total expenditure of the project

In Figure 5.10, we sum up raw material cost, energy cost, salary cost, and many other costs separately over 15 years of operation in Iceland. The biggest part of expenditure is the cost of raw material, since it amounts to 67% of total expenditure. Importantly, the energy cost only cost 1% of total expenditure, which is a very low percentage compare to other European counties according to our model. In flowing figures, we can see that the percentage of energy cost climb to 8% and 11 % in Finland and Germany. In Estonia, the energy cost still amount 7% of total expenditure.

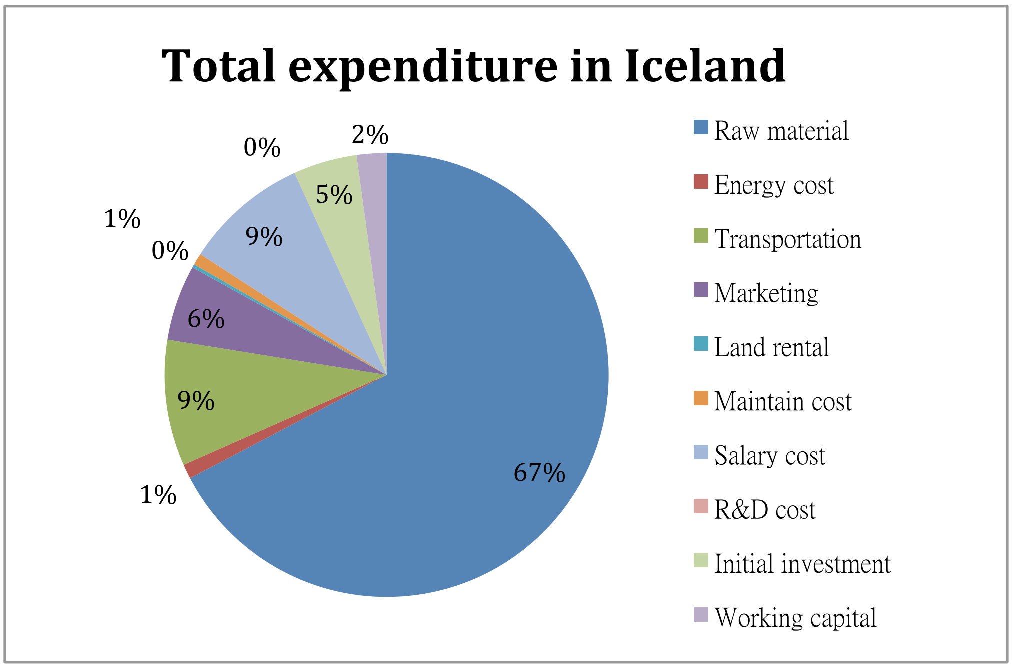


Figure 5.10 Total expenditure in Iceland after 15 years operation

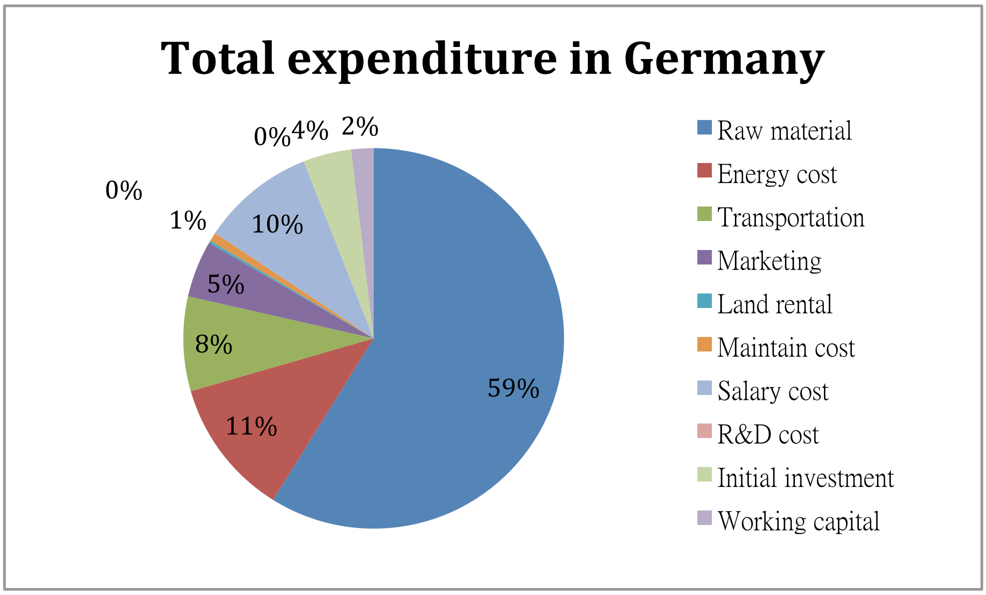


Figure 5.11 Total expenditure in Germany after 15 years operation

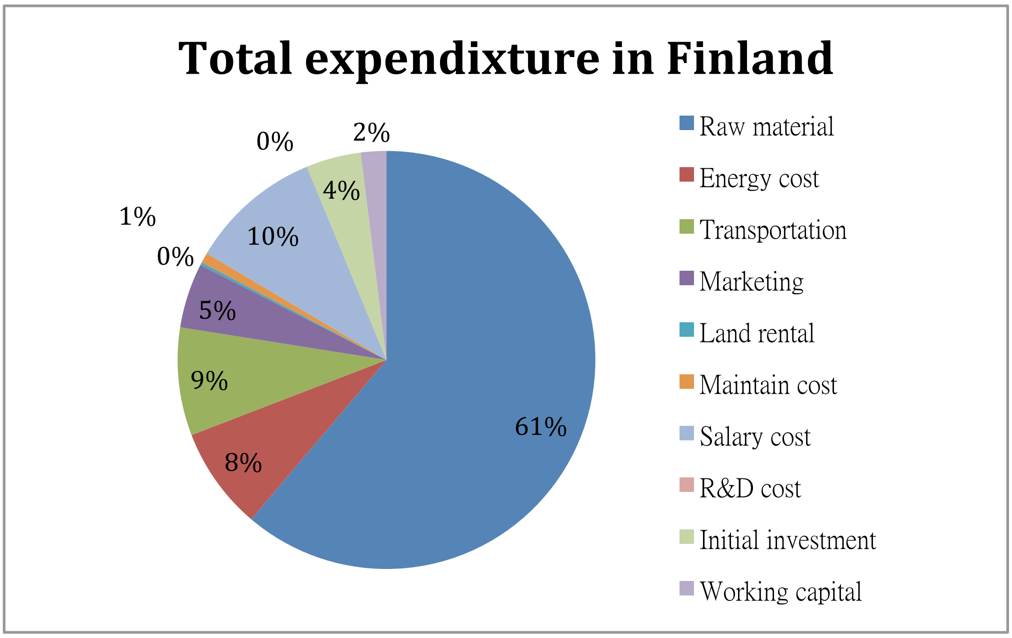


Figure 5.12 Total expenditure in Finland after 15 years operation

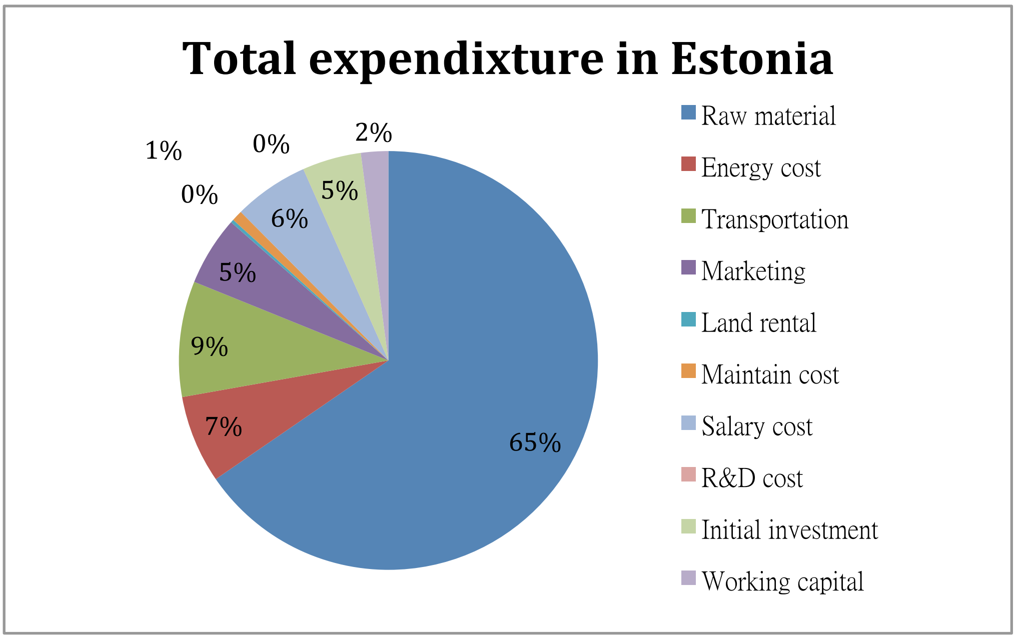


Figure 5.13 Total expenditure in Estonia after 15 years operation

5.4 Sensitivity analysis

5.4.1 Impact analysis

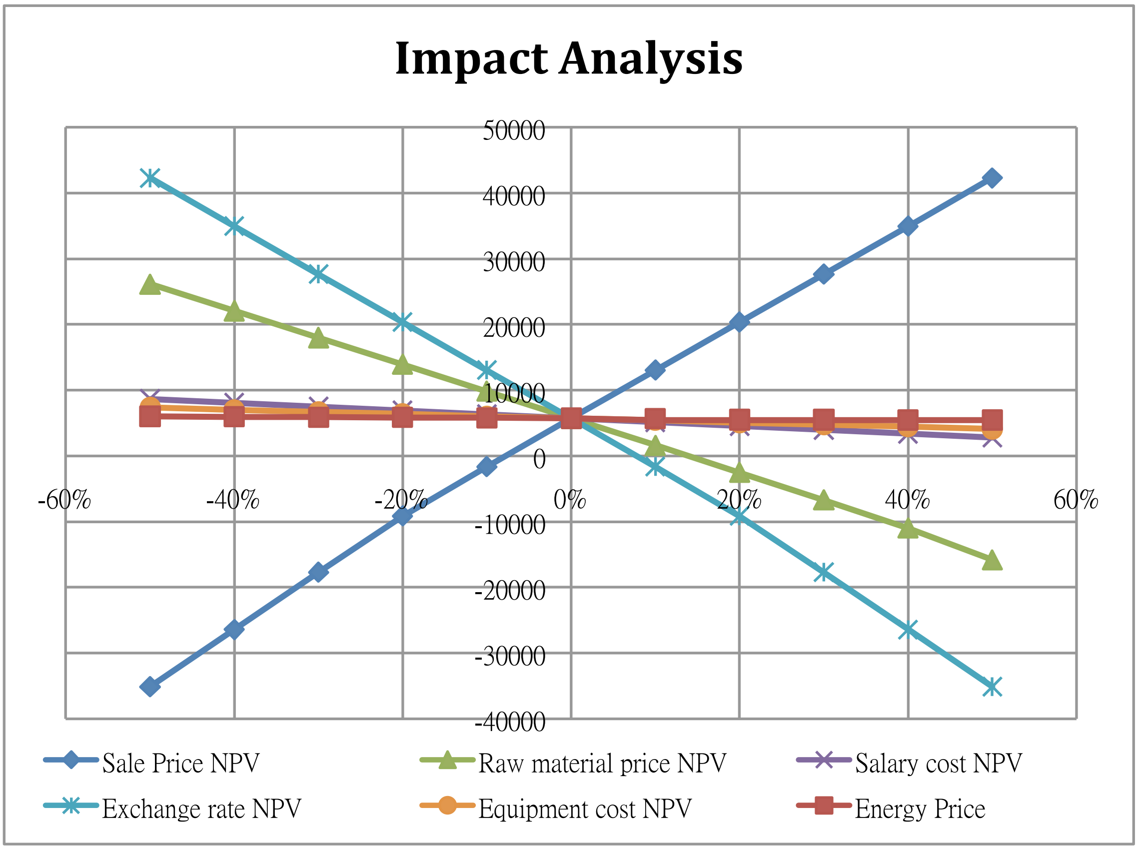


Figure 5.14 Impact analysis of this project

Sale price

In the model, we have already set the sale price will decrease 3% on each year. Here, we change the sale price from -50% to +50% of original price. In Figure 5.14, the line of sale price is positive and relatively steep compare to other factors, thereby it means that net present value is very sensitive to the sale price. When the sale price increases 50%, the net present value will increase to 9 times. On the contrary, the company will lose huge amount of profit, if the sale price go down. In real world, it's difficult to predict the sale price of lithium iron battery. Basically, the sale price is determined by demand and supply of battery market. So far, the limited lithium iron phosphate battery suppliers and the limited production capacity ensure its higher margin. But, we have already seen many big lithium companies increase their production capacity for this new type of battery from 2008 due to the high growth rate of electric market. If the demand of lithium doesn't increase as fast as them predict, the extra production might result the price drop sharply. In that case, the sale price might drop 20~30%.

Exchange rate

As we can see in Figure 5.14, the net present value is also very sensitive to exchange rate. Although we have to purchase the raw material from aboard, the depreciation of Icelandic still has benefit for this exporting business. As it depreciates 50%, the net present value will exceed 40000 millions ISK dramatically. In reality, it seems very rare to happen in every country, but did happen in Iceland during the economical crisis. Fortunately, the exchange rate stay stable after central bank put monetary restriction policy on foreign currency. However, the government said they will open the currency market again in the end of 2010, and many experts predict Icelandic has possibility to appreciate. The firm has to put more effort on management of their exposure through forward contract, foreign loan, or option strategies to avoid the loss of profit caused by floating currency.

Raw material price

In the aspect of raw material price, it has an opposed impact to net present value. The higher price of raw material is, the lower net present value of this project will be. In Figure 5.14, it also shows a strong opposite correlation between raw material and net present value. In real world, one of the reasons of rising raw material price is lack of lithium resource. According to Meridian International research, the planned lithium carbonate production will be only sufficient for small fraction of PHEV and EV global market requirement, that demand from portable electronic sectors will absorb much of the increased production in the next decade(Meridian international research, 2008). In this case, the price of raw material might increase by 30%. On the other side, if there is no problem about lithium resource, more suppliers from Asia and Europe will improve the quality of material and reduce the price under big volume production in this competitive market. In USA, due to the patent ownership of cathode material, some conservative companies are still waiting the result of lawsuit between Hydro-Quebec, A123 system, and Valence Technology. However, European Patent Office revokes Dr. Goodenough's $LiMPO_4$ patent, patent number 0904607 on 2008. This decision basically reduces the patent risk of using lithium iron phosphate in automobile application at Europe. The only question mark is left in the United State.

Energy price, salary cost, and equipment cost

When we build a factory in Iceland, net present value is less sensitive to those issues, especially the energy cost. Since the energy cost is really small part of entire budget, we can say the impact of fluctuant energy price is very limited. Even, as the price increases 50% above, net present value will only decrease only 5%. Besides, the energy price seems to be very stable according the historical price in Iceland. However, the fluctuant energy price might bring more impact to the countries, which has higher energy price. For example, if we set up the energy price at 30 ISK/KWh in the same model, the net present value will be increased by 12 times as energy price drop 50%. Regards to salary, the employee's salary is usually stable in developed countries. Hence, we expect that the salary in Iceland will not be changed very dramatically. In the terms of equipment cost, it is also the small part of this project and net present value is less sensitive to it.

5.4.2 Scenario analysis

In scenario analysis, we usually assume that many factors, such as sale price, and fixed cost changed at the same time under different situation. The main point of this analysis is that we can the prediction result under worst and best scenario. In this case, we assume the most optimistic scenario is based on 120% of exchange rate, and sale price for positive effective factors. On the contrary, the negative effective factors, like variable cost, interest rate will be changed to 80% of original value. In table 5.9, we can see the NPV results range from -35,390 to 48,451 MISK in various scenarios, and the internal return of rate could be up to 73% in the most optimist scenario. However, this analysis doesn't tell us the likelihood of various scenarios. In the next part, Monte Carlo method will display the possibility of various simulations.

Table 5.9 Scenario analysis of this project

Scenario Summary					
	Current Values:	*Very optimistic*	*Very pessimist*	*Optimist*	*Pessimist*
Changing Cells:					
Exchange rate	100%	120%	80%	110%	90%
Sale price	100%	120%	80%	110%	90%
Variable cost	100%	80%	120%	90%	110%
Product lines cost	100%	80%	120%	90%	110%
Interest Rate	100%	80%	120%	90%	110%
Result Cells:					
NPV of total cash flow	5744	48451	-35390	26381	-14371
IRR of cash flow	23%	71%	0%	47%	0%
Notes: Current Values column represents values of changing cells at time Scenario Summary Report was created. Changing cells for each scenario are highlighted in gray.					

5.5 Monte Carlo Analysis

Monte Carlo methods are useful for modeling phenomena with significant uncertainty in inputs, such as the calculation of risk in business. Since its high reliance on the repeated computation of random number, it's easier to use the commercial software to compute the result. In this case, we are using @RISK 5.7 and plug it into Microsoft Excel. @RISK can performs risk analysis using Monte Carlo simulation to show you many possible outcomes in the Microsoft Excel spreadsheet—and tells you how likely they are to occur. The first step is to select the uncertainties in this model and define them by different type of distribution. In this case, we selected the main influential parameters into Monte Carlo simulation. They are exchange rate, sale price, variable cost, interest rate, and production lines cost. We define them all have normal distribution. @RISK will plug those random numbers automatically into the simulation model. After computation, all the results are showed in Figure 5.15 and Figure 5.16.

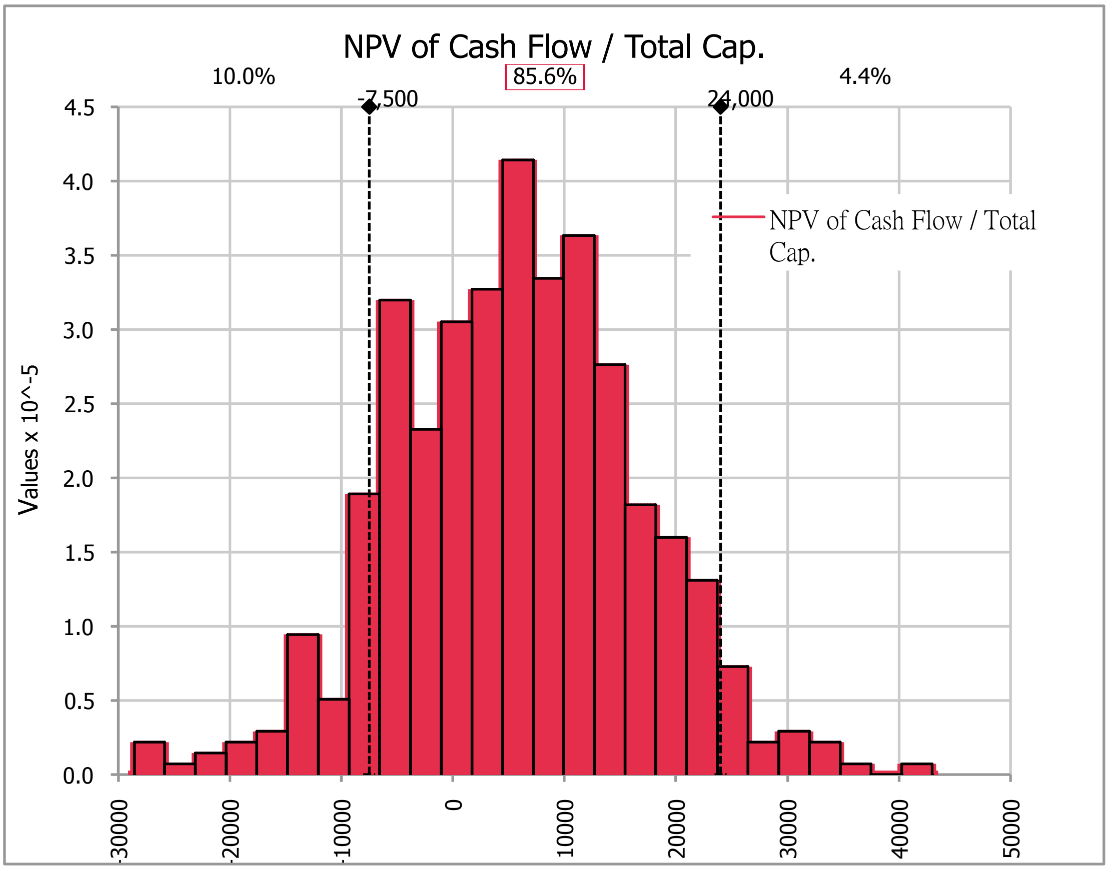


Figure 5.15 Result of Monte Carlo analysis-NPV

In Figure 5.15, it displays the possibility of various value of result. From the distribution, we can see that the possibility of NPV ranges from -7500 to 24,000 is 85.6%. And, the total cumulated possibility of positive NPV of the project is 70%. Additionally, the risk of getting a negative net present value, lower than -7,500 is only 10 %. . In summary, we can say the possibility of getting profit from this project is 70% based on our assumptions. The chance of losing huge or getting amount of profit is relatively small. It seems not a very risky investment according to the result.

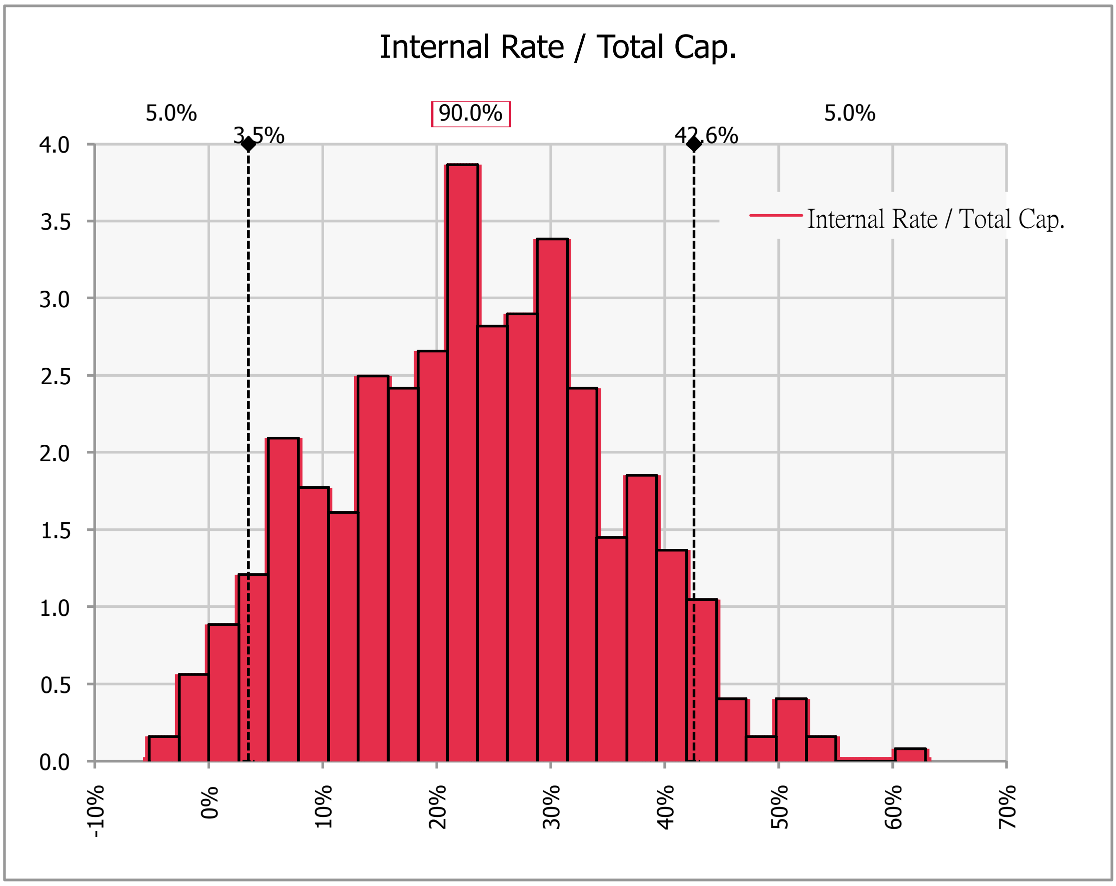


Figure 5.16 Result of Monte Carlo analysis- IRR

In Figure 5.16, the distribution of internal rate of return ranges from -5% to 62%. Most likely, the internal rate of return will be 22%. There is 90% that internal rate of return will fall between 3.5% and 42.6%. There is only 5% it will be lower than 3.5% in our simulation. In the point view of IRR, it is a very profitably and safe investment, especially when central bank's interest rate is low in the most of countries during 2010.

6. Conclusion

With the anticipated reduction in material cost for Lithium-ion batteries, the energy cost for battery production will play a more important role in the overall cost of lithium ion batteries. According to our investigation, the energy consumption could range from 0.54 to 0.68 KWh/Ah depending on the factory's design and production process. Although we did not get access to first-hand energy consumption data of each step from factories directly, we can infer that the main energy consumption steps in the procedure are drying room, vacuum dryers, and testing equipment from our production process analysis. In locations with access to geothermal heat, such as Iceland, we might be able to replace the electricity used as a heat source for the drying processes by geothermal steam. As a result the energy cost could be reduced combining reasonably priced electricity with geothermal heat. Through our theoretical drying model, the energy consumption of removing the moisture content in 1 Ah battery is 0.31 KWh, which is around half of the total energy consumption. Consequently, the variable energy cost in Iceland could be reduced to 0.009 USD/Ah (0.0076 USD for electricity; 0.0015 for geothermal steam) as we ideally use geothermal steam for drying. In the technical aspect of this transition, we suggest using geothermal steam at 9 bar 173°C from an existing geothermal power plant. In this case, the ideal type of dryer and heating method for lithium batteries would be a tray dryer with conduction heating method under vacuum operation. In terms of economic and environmental benefit, we built a profitability model using current cost data based on operating environment in Iceland. According to this model, the accumulated NPV for equity with a 15% discount rate of this project in Iceland is 49.7 million USD and internal rate of return is 27%. On the other hand, if we move the factory to other European countries with higher energy price (0.084~0.055€ /KWh), different salary cost, and the same cost assumption, the NPV for equity will fall down to -2.2~24.1million USD. The internal rate of return will fall from 27% to 9~14%. Moreover, with current feedstock prices the energy cost is estimated to be 1% with the Icelandic cost structure, while it would amount to 9~11% in other European countries based on energy prices in different countries. The lower energy cost in Iceland results in an NPV less sensitive to fluctuation of energy prices. Iceland seems to have a great economic advantage for lithium ion battery production due to lower energy prices, whether it is electric energy or direct use of geothermal heat. Another feature of even more importance is that the lower carbon footprint of geothermal heat and renewable electricity in Iceland, will result in 34429-62953tons lower CO_2 emissions per year from running a battery factory with 10 MW power needs and 160MAh production capacity, compared to the emissions in Europe or China. That means that only 3-5% percent of the carbon dioxide would be emitted as a result from this process as compared to traditional energy usage. This could bring some practical carbon emission credit value or an advantageous position on green marketing. Although most of battery companies still focus on reducing the cost of raw material at this moment, the energy cost will become more and more critical in the entire cost structure with future price reductions of raw material. After a few years of development, if a company considers building a factory in Europe, Iceland's abundant natural resources will make it a feasible location to produce lithium ion batteries.

References

Ármannsson, H. (2003). CO2 emission from Geothermal Plants . Reykjavik: International Geothermal Conference .

A123 System. (2010, 1 1). *A123 System Technology : Life*. Retrieved 7 1, 2010, from A123 System: http://www.a123systems.com/a123/technology/life

Anderson, D. L. (2009). *AN EVALUATION OF CURRENT AND FUTURE COSTS FOR LITHIUM-ION BATTERIES FOR USE IN ELECTRIFIED VEHICLE POWERTRAINS .* Durham: Duke University .

Argonne National Laboratory. (2000). *Argonne National Laboratory.* Argonne: Argonne National Laboratory.

Batteryspace. (2010, 11 1). *LiFePo4 18650 rechargeable cell* . Retrieved 11 10, 2010, from Battery space: http://www.batteryspace.com/lifepo4rechargeablesinglecells1c-30crate.aspx

better place . (2009, 9 1). *Better place* . Retrieved 3 1, 2010, from Better place offical website : http://www.betterplace.com/solution/ev-network-software/

Bossche, P. V., Vergels, F. e., & Mierlo, J. V. (2005). An assessment of sustainable battery technology. *Journal of Power Sources* , 913-919.

Carbon trust. (2010). *Carbon footprinting.* London: Carbon trust.

Central bank of Iceland. (2010, 11 1). *Central bank of Iceland: statistics*. Retrieved 11 5, 2010, from Central bank of Iceland: http://www.sedlabanki.is/?PageID=548

Daniel, C. (2009). Materials and Processing for Lithium-ion batteries. *JOM* , 60.

David Kadko, K. G. (2007). Application of radium isotopes to determine crustal residence times of hydrothermal fluids from two sites on the Reykjanes Peninsula, Iceland . *Geochimica et Cosmochimica Acta* , 6019.

Dragana Jugovic, D. U. (2009). A review of recent developments in the synthesis procedures of lithium iron phosphate powders. *Journal of Power Sources* , 538-544.

Electric motorsport EV part. (2010, 10 1). *Electric motorsport EV part*. Retrieved 11 1, 2010, from Electric motorsport : http://www.electricmotorsport.com/store/ems_ev_parts_batteries_lpf.php

Europe's energy portal. (2009, 11 1). *Europe's energy portal>> natural gas, electricity price*. Retrieved 10 1, 2010, from Europe's energy portal: http://www.energy.eu/#industrial

Garrett, D. (2004). *Handbook of lithium and natural calcium chloride.* London: Elsevier.

Gholam-Abbas Nazri, g. P. (2009). *Lithium batteries.* Rome.

GM motor. (2010, 3 1). Retrieved 11 1, 2010, from GM-volt: Chevy Volt electric car site: http://gm-volt.com/2010/03/09/report-reveals-lithium-ion-battery-prices-already-dropping-steeper-than-expected/

Gunnlaugsson, E., & Ragnarsson, A. (2001). Geothermal Energy in Iceland. Turkey: International Symposium in Izmir.

Invest in Iceland Agency. (2010, 03 01). *Invest in Iceland agency :publication.* Retrieved 10 1, 2010, from Invest in Iceland Agency: http://www.invest.is/publications/

Jan A. Schuessler, R. S. (2009). Iron and lithium isotope systematics of the Hekla volcano, Iceland — Evidence for Fe isotope fractionation during magma differentiation. *Chemical Geology* , 78-91.

Jiajun Chen, M. J. (2008). The hydrothermal synthesis and characterization of olvines and related compounds for electrochemical applications. *Solid State Ionics* , 1676-1693.

K.Zaghib, M. (1999). Electrochemical study of Li4Ti5O12 as negative electrode for Li-ion polymer rechargeable batteries. *Journal of power resource* , 81.

Kalhammer, F. R., & Kopf, B. M. (2007). *Status and Prospects for Zero Emissions Vehicle Technology.* Sacramento: State of California Air Resources Board.

Kromer, M. A., & Heywood, J. B. (2007). *Electric Powertrains: Opportunities and Challenges in the U.S. Light-Duty Vehicle Fleet.* Cambridge: Sloan Automotive Laboratory.

Landi, B. J. (2009). *Nanomaterialapproaches to enhance lithium ion batteries .* Rochester Institute of Technology. Rochester : Rochester Institute of Technology.

Landsbanki. (2010, 1 1). *Landsbanki: intrest rate.* Retrieved 10 1, 2010, from Landsbanki: http://www.landsbanki.is/english/aboutlandsbankinn/profile/interestrate-tariff/

Landssvirkjun. (2009). *Landssvirkjun Annual report.* Reykjavik: Landssvirkjun.

Landsvirkjun. (2008). *Landsvirkjun's carbon footprint.* Reykjavik: Landsvirkjun's carbon footprint.

Magnússon, Ó. Þ. (2010, 11 11). Assessment of construction lithium battery in Iceland. (P. Tao, Interviewer)

Masatoshi Majima, S. U. (2001). Development of 1 kW h class lithium ion battery for power storage. *Journal of Power Sources* , 108-119.

Mats Zackrisson, J. O. (2010). Life cycle assessment of lithium-ion batteries for plug-in hybrid electric vehicles e Critical issues. *Journal of cleaner production* , 1517-1527.

Meridian Internation Research. (2008). *The trouble with Lithium2.* Les Leger: Meridian Internation Research.

Mujumdar, A. S. (2006). *Handbook of industrial drying.* Taylor & Francis Group, LLC.

Nuutinen, M. (2007). *Transfering produciton of Li-ion battery factory from China to Finland.* Helsinki: Helsinki Technology University.

Orkustofnun. (2009). *Energy Statistic in Iceland .* Reykjavik: Orkustofnun.

Orkuveita Reykjavikur. (2010, 10 10). *Hellisheidi Geothermal Power Plant*. Retrieved 10 10, 2010, from Orkuveita Reykjavikur: http://www.or.is/English/Projects/HellisheidiGeothermalPlant/

Pike Research . (2010, 6 1). *Asian Manufacturers Will Lead the $8 Billion Market for Electric Vehicle Batteries*. Retrieved 10 1, 2010, from Pike Research : http://www.pikeresearch.com/newsroom/asian-manufacturers-will-lead-the-8-billion-market-for-electric-vehicle-batteries

S.S.Zhang, P. (2004). Li-ion battery separator. *Chemical review* , 4419-4462.

Sheng Liu, Q. L. (2008). Carbon-coated copper-tin alloy anode material for lithium. *Journal of alloys and compounds* , 478.

Statistic Iceland. (2010, 11 1). *Statistic Iceland*. Retrieved 11 10, 2010, from Statistic Iceland: http://www.statice.is/

Statistic Iceland. (2010, 6 1). *Statistics Iceland : Population > overview*. Retrieved 10 1, 2010, from Statistics Iceland : http://www.statice.is/Statistics/Population/Overview

Sumotarto, U. (2007). *DESIGN OF A GEOTHERMAL ENERGY DRYER FOR BEANS AND GRAINS DRYING IN KAMOJANG GEOTHERMAL FIELD, INDONESIA.* Indonesia: Agency for the Assessment and Applied Technology.

Whittingham, M. S. (2006). Hydrothermal synthesis of lithium iron phosphate. *Electrochemistry communication* , 855-858.

World Energy Council. (2010, 1 1). *World Energy council*. Retrieved 10 1, 2010, from World Energy council: http://www.worldenergy.org/publications/survey_of_energy_resources_2007/geothermal_energy/737.asp

Zackrisson, M., Zackrisson, M., & Orlenius, J. (2010). Life cycle assessment of lithium-ion batteries for plug-in hybrid electric vehicles e Critical issues. *Journal of Cleaner Production* , 1517-1527.

Appendix 1-Profitability model

Investment																		
		2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	Total
						4	5	6	7	8	9	10	11	12	13	14	15	
Investment and Financing																		
Investment:																		
Buildings		2000.00	2900.00	3800.00	4700.00	4512.00	4324.00	4136.00	3948.00	3760.00	3572.00	3384.00	3196.00	3008.00	2820.00	2632.00	2444.00	
Equipment		567.92	2271.69	3407.54	4543.39	4089.05	3634.71	3180.37	2726.03	2271.69	1817.36	1363.02	908.68	454.34	0.00			
Other		128.40	258.58	360.38	462.17	369.74	277.30	184.87	92.43	0.00								
Booked Value		2696.32	5430.28	7567.92	9705.56	8970.79	8236.01	7501.24	6766.47	6031.69	5389.36	4747.02	4104.68	3462.34	2820.00	2632.00	2444.00	
Depreciation:																		
Depreciation Buildings	0.04					188.00	188.00	188.00	188.00	188.00	188.00	188.00	188.00	188.00	188.00	188.00	188.00	2256.00
Depreciation Equipm.	0.10					454.34	454.34	454.34	454.34	454.34	454.34	454.34	454.34	454.34	454.34			4543.39
Depreciation Other	0.20					92.43	92.43	92.43	92.43	92.43								462.17
Total Depreciation						734.77	734.77	734.77	734.77	734.77	642.34	642.34	642.34	642.34	642.34	188.00	188.00	7261.56
Financing:																		
Equity	0.30	988.90	1330.19	1241.29	701.29													4261.67
Loans	0.70	2307.42	3103.77	2896.35	1636.35													9943.89
		3296.32	4433.96	4137.64	2337.64													
Repayment	6.00					1657.32	1657.32	1657.32	1657.32	1657.32	1657.32							
Principal		2307.42	5411.20	8307.54	9943.89	8286.58	6629.26	4971.95	3314.63	1657.32	0.00							
Interest	0.12		649.34	996.91	1193.27	994.39	795.51	596.63	397.76	198.88	0.00							
Loan Managem. Fees	0.02	46.15	62.08	57.93	32.73													

Operations

		2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	Total
Operations Statement																		
Sales			5	80	120	160	160	160	160	160	160	160	160	160	160	160	160	
Price	3.3	USD/Ah	156.4	151.7	147.2	142.8	138.5	134.3	130.3	126.4	122.6	118.9	115.4	111.9	108.5	105.3	102.1	
Revenue			782.2	12139.9	17663.5	22844.8	22159.5	21494.7	20849.8	20224.3	19617.6	19029.1	18458.2	17904.5	17367.3	16846.3	16340.9	
Variable Cost	0	0.0	458.9	10167.0	13464.0	13791.2	13508.1	13232.2	12963.1	12700.8	12445.0	12195.6	11952.5	11715.4	11484.3	11258.9	11039.2	
Fixed Cost		492.7	1081.4	1357.5	1639.0	1505.7	1729.9	1708.5	1700.1	1700.1	1700.1	1700.1	1700.1	1700.1	1700.1	1700.1	1700.1	
Diverse Taxes																		
Operating Surplus		-492.7	-758.1	615.4	2560.5	7547.9	6921.4	6554.0	6186.6	5823.5	5472.5	5133.4	4805.6	4489.0	4183.0	3887.3	3601.7	67023.7
EBITDA																		
Inventory Movement			806.4															
Depreciation						734.8	734.8	734.8	734.8	734.8	642.3	642.3	642.3	642.3	642.3	188.0	188.0	7261.6
Operating Gain/Loss		-492.7	48.3	615.4	2560.5	6813.2	6186.7	5819.2	5451.9	5088.7	4830.2	4491.0	4163.3	3846.6	3540.6	3699.3	3413.7	60568.6
EBIT																		0.0
Financial Costs		46.1	711.4	1054.8	1226.0	994.4	795.5	596.6	397.8	198.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	5975.4
Profit before Tax		-538.8	-663.1	-439.4	1334.5	5818.8	5391.1	5222.6	5054.1	4889.8	4830.2	4491.0	4163.3	3846.6	3540.6	3699.3	3413.7	54593.2
Loss Transfer	0	-538.8	-1201.9	-1641.3	-306.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0					
Taxable Profit		0.0	0.0	0.0	0.0	5512.0	5391.1	5222.6	5054.1	4889.8	4830.2	4491.0	4163.3	3846.6	3540.6	3699.3	3413.7	54054.3

Income Tax	18%	0.0	0.0	0.0	0.0	992.2	970.4	940.1	909.7	880.2	869.4	808.4	749.4	692.4	637.3	665.9	614.5	9729.8
Profit after Tax		-538.8	-663.1	-439.4	1334.5	4826.6	4420.7	4282.5	4144.4	4009.7	3960.7	3682.6	3413.9	3154.2	2903.3	3033.4	2799.2	44863.4
Dividend	30%	0.0	0.0	0.0	400.4	1448.0	1326.2	1284.8	1243.3	1202.9	1188.2	1104.8	1024.2	946.3	871.0	910.0	839.8	13789.8
Net Profit/Loss		-538.8	-663.1	-439.4	934.2	3378.6	3094.5	2997.8	2901.1	2806.8	2772.5	2577.8	2389.7	2208.0	2032.3	2123.4	1959.4	31073.6

Cash Flow

	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027
Cash Flow																
Operating Surplus	-492.7	-758.1	615.4	2560.5	7547.9	6921.4	6554.0	6186.6	5823.5	5472.5	5133.4	4805.6	4489.0	4183.0	3887.3	3601.7
Debtor Changes	0.0	-195.6	-2839.4	-1380.9	-1295.3	171.3	166.2	161.2	156.4	151.7	147.1	142.7	138.4	134.3	130.3	126.3
Creditor Changes	0.0	68.8	1456.2	494.6	49.1	-42.5	-41.4	-40.4	-39.4	-38.4	-37.4	-36.5	-35.6	-34.7	-33.8	-33.0
Cash Flow before Tax	-492.7	-884.8	-767.8	1674.2	6301.7	7050.3	6678.8	6307.5	5940.5	5585.8	5243.1	4911.9	4591.8	4282.6	3983.8	3695.0
Paid Taxes		0.0	0.0	0.0	0.0	992.2	970.4	940.1	909.7	880.2	869.4	808.4	749.4	692.4	637.3	665.9
Cash Flow after Tax	-492.7	-884.8	-767.8	1674.2	6301.7	6058.2	5708.4	5367.4	5030.8	4705.7	4373.7	4103.5	3842.4	3590.2	3346.4	3029.2
Interest & Loan Man Fee	46.1	711.4	1054.8	1226.0	994.4	795.5	596.6	397.8	198.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Repayment	0.0	0.0	0.0	0.0	1657.3	1657.3	1657.3	1657.3	1657.3	1657.3	0.0	0.0	0.0	0.0	0.0	0.0
Net Cash Flow	-538.8	-1596.2	-1822.6	448.2	3650.0	3605.3	3454.4	3312.3	3174.6	3048.3	4373.7	4103.5	3842.4	3590.2	3346.4	3029.2
Paid Dividend		0.0	0.0	0.0	400.4	1448.0	1326.2	1284.8	1243.3	1202.9	1188.2	1104.8	1024.2	946.3	871.0	910.0
Financing - Expenditure	600.0	1700.0	2000.0	200.0												
Cash Movement	61.2	103.8	177.4	648.2	3249.6	2157.3	2128.2	2027.6	1931.3	1845.5	3185.4	2998.7	2818.3	2643.9	2475.5	2119.1
Debt Service Coverage		-1.2	-0.7	1.4	2.4	2.5	2.5	2.6	2.7							
LLCR																
NPV of Cash Flow	12%	16280.7	19119.2	22181.3	23168.9	19647.4	15947.0	12152.2	8243.1							
Principal		5411.2	8307.5	9943.9	8286.6	6629.3	4971.9	3314.6	1657.3							
Loan Life Cover Ratio		3.0	2.3	2.2	2.8	3.0	3.2	3.7	5.0							
Critical value		1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5							

Balance

		2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027
Balance Sheet																	
Assets																	
Cash Account	0	61.2	164.9	342.3	990.5	4240.1	6397.5	8525.7	10553.3	12484.5	14330.0	17515.4	20514.1	23332.4	25976.3	28451.8	30570.9
Debtors	25%	0.0	195.6	3035.0	4415.9	5711.2	5539.9	5373.7	5212.5	5056.1	4904.4	4757.3	4614.6	4476.1	4341.8	4211.6	4085.2
Stock	0	0.0	806.4	806.4	806.4	806.4	806.4	806.4	806.4	806.4	806.4	806.4	806.4	806.4	806.4	806.4	806.4
Current Assets		61.2	1166.9	4183.7	6212.8	10757.7	12743.7	14705.8	16572.1	18347.0	20040.8	23079.1	25935.1	28614.9	31124.6	33469.7	35462.5
Fixed Assets		2696.3	5430.3	7567.9	9705.6	8970.8	8236.0	7501.2	6766.5	6031.7	5389.4	4747.0	4104.7	3462.3	2820.0	2632.0	2444.0
Total Assets		2757.5	6597.2	11751.6	15918.3	19728.5	20979.8	22207.0	23338.6	24378.7	25430.1	27826.1	30039.8	32077.3	33944.6	36101.7	37906.5
Debts																	
Dividend Payable		0.0	0.0	0.0	400.4	1448.0	1326.2	1284.8	1243.3	1202.9	1188.2	1104.8	1024.2	946.3	871.0	910.0	839.8
Taxes Payable		0.0	0.0	0.0	0.0	992.2	970.4	940.1	909.7	880.2	869.4	808.4	749.4	692.4	637.3	665.9	614.5
Creditors	15%	0.0	68.8	1525.0	2019.6	2068.7	2026.2	1984.8	1944.5	1905.1	1866.7	1829.3	1792.9	1757.3	1722.6	1688.8	1655.9
Next Year Repayment		0.0	0.0	0.0	1657.3	1657.3	1657.3	1657.3	1657.3	1657.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Current Liabilities		0.0	68.8	1525.0	4077.3	6166.1	5980.2	5867.0	5754.8	5645.5	3924.4	3742.5	3566.4	3396.0	3230.9	3264.7	3110.1
Long Term Loans		2307.4	5411.2	8307.5	8286.6	6629.3	4971.9	3314.6	1657.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Total Debt		2307.4	5480.0	9832.6	12363.9	12795.4	10952.1	9181.6	7412.1	5645.5	3924.4	3742.5	3566.4	3396.0	3230.9	3264.7	3110.1
Equity	0	988.9	2319.1	3560.4	4261.7	4261.7	4261.7	4261.7	4261.7	4261.7	4261.7	4261.7	4261.7	4261.7	4261.7	4261.7	4261.7
Profit & Loss Balance	0	-538.8	-1201.9	-1641.3	-707.2	2671.5	5766.0	8763.7	11664.8	14471.5	17244.1	19821.9	22211.7	24419.6	26451.9	28575.3	30534.8
Total Capital		450.1	1117.1	1919.0	3554.5	6933.1	10027.6	13025.4	15926.5	18733.2	21505.7	24083.6	26473.3	28681.3	30713.6	32837.0	34796.4
Debts and Capital		2757.5	6597.2	11751.6	15918.3	19728.5	20979.8	22207.0	23338.6	24378.7	25430.1	27826.1	30039.8	32077.3	33944.6	36101.7	37906.5

Profitability

		2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027
Profitability Measurements																	
NPV and IRR of Total Cash Flow																	
Cash Flow after Taxes		-492.7	-884.8	-767.8	1674.2	6301.7	6058.2	5708.4	5367.4	5030.8	4705.7	4373.7	4103.5	3842.4	3590.2	3346.4	3029.2
Loans		-2307.4	-3103.8	-2896.3	-1636.3												
Equity		-988.9	-1330.2	-1241.3	-701.3												
Total Cash Flow & Capital		-3789.0	-5318.8	-4905.4	-663.5	6301.7	6058.2	5708.4	5367.4	5030.8	4705.7	4373.7	4103.5	3842.4	3590.2	3346.4	3029.2
NPV Total Cash Flow (Europe)	15%	-3789.0	-8414.0	-12123.2	-12559.5	-8956.4	-5944.5	-3476.6	-1458.8	185.8	1523.4	2604.5	3486.6	4204.7	4788.2	5261.2	5633.5
IRR Total Cash Flow (Europe)									12%	15%	18%	19%	20%	21%	22%	22%	22%
NPV and IRR of Net Cash Flow																	
Net Cash Flow		-538.8	-1596.2	-1822.6	448.2	3650.0	3605.3	3454.4	3312.3	3174.6	3048.3	4373.7	4103.5	3842.4	3590.2	3346.4	3029.2
Equity		-988.9	-1330.2	-1241.3	-701.3												
Net Cash Flow & Equity		-1527.7	-2926.4	-3063.9	-253.1	3650.0	3605.3	3454.4	3312.3	3174.6	3048.3	4373.7	4103.5	3842.4	3590.2	3346.4	3029.2
NPV Net Cash Flow (Europe)	15%	-1527.7	-4072.4	-6389.2	-6555.6	-4468.7	-2676.2	-1182.8	62.4	1100.2	1966.7	3047.8	3929.9	4648.0	5231.6	5704.5	6076.8
IRR Net Cash Flow (Europe)										19%	22%	24%	25%	26%	27%	27%	28%
Financial Ratios																	
Profit+Interest/Debt+Capital (ROI)			1.75%	9.33%	21.79%	42.80%	31.36%	27.74%	24.55%	21.80%	19.81%	17.66%	14.96%	12.81%	11.04%	10.90%	9.46%
Profit/Shareh. Capital (ROE)			-147.34%	-39.33%	69.54%	135.79%	63.76%	42.71%	31.82%	25.18%	21.14%	17.12%	14.18%	11.91%	10.12%	9.88%	8.52%
Asset Turnover Ratio			0.28	1.84	1.50	1.44	1.12	1.02	0.94	0.87	0.80	0.75	0.66	0.60	0.54	0.50	0.45
Equity Ratio			16.93%	16.33%	22.33%	35.14%	47.80%	58.65%	68.24%	76.84%	84.57%	86.55%	88.13%	89.41%	90.48%	90.96%	91.80%
Net Current Ratio			16.95	2.74	1.52	1.74	2.13	2.51	2.88	3.25	5.11	6.17	7.27	8.43	9.63	10.25	11.40
Liquid Current Ratio			5.24	2.21	1.33	1.61	2.00	2.37	2.74	3.11	4.90	5.95	7.05	8.19	9.38	10.00	11.14
Internal Value of Shares			0.48	0.54	0.83	1.63	2.35	3.06	3.74	4.40	5.05	5.65	6.21	6.73	7.21	7.71	8.16

Appendix 2-Cost of production line from LinYi Gelon New Battery Materials Co.Ltd,

Workshop	Equipment name	Use	Equipment Specifications / Model	Quantity demanded	Unit price	Total
Cathode production	Oven	powder baking		2	50000	100000
	Vacuum mixer	Slurry mixing	200L	4	300000	1200000
	Slurry Filter M/C	Slurry particle filter		2	30000	60000
	Storage tank	Slurry storage	200L	4	120000	480000
	Viscometer	Cathode slurry Viscosity test		1	12000	12000
	Coating M/C			2	800000	1600000
	Vacuum Oven	Volume Electrode Baking		4	50000	200000
	Continuous Pressing M/C			2	600000	1200000
	Cuting M/C			2	50000	100000
	Automatic Formation M/C	Automatic formation for electrode		4	300000	1200000
	Vacuum Oven	Pieces Electrode Baking		6	50000	300000
Anode production	Vacuum mixer	Slurry mixing	200L	4	300000	1200000
	Slurry Filter M/C	Slurry particle filter		2	30000	60000
	Storage tank	Slurry storage	200L	4	120000	480000
	Viscometer	Anode slurry Viscosity test		1	12000	12000
	Coating M/C			2	800000	1600000
	Vacuum Oven	Volume Electrode Baking		4	50000	200000
	Continuous Pressing M/C			2	600000	1200000
	Cuting M/C			2	50000	100000
	Automatic Formation M/C	Automatic formation for electrode		4	200000	800000
	Vacuum Oven	Pieces Electrode Baking		6	50000	300000
Assembling	Assembly Line	Assembling	40m	2	50000	100000
	Vacuum Oven	Pieces Positive Storage		1	50000	50000
		Pieces Negative Storage		1	50000	50000
	Automatic Lamination Stacking M/C	Lamination		40	200000	8000000
	Punching M/C			2	30000	60000
	Short-circuit Tester			2	8000	16000
	Laser Welding M/C	Long side sealing		10	100000	1000000
		Short side sealing		5	100000	500000
	Tightness Test Equipment	Sealing performance test		2	8000	16000
Formation/ Grading	Vacuum Oven	Cell baking	three floor	60	50000	3000000
	Short-circuit Tester			2	8000	16000
	Filing System（Glove Box）		6 Station	2	100000	200000
	Hibar pump	Electrolyte filling		4	50000	200000
	Formation M/C	Pre-charging		20	50000	1000000
	Vacuum Oven	Sealing /turnover		2	50000	100000

	Voltage Tester			1	8000	8000
	Ball Sealing M/C			2	8000	16000
	Thickness Tester			2	8000	16000
	Grading M/C	Capacity grading		40	50000	2000000
	Voltage/resistance ranging system			1	15000	15000
Pack	Barcode system			1	100000	100000
Power system	Dehumidification system	To provide dry conditions		1	200000	200000
	Nitrogen Generator	Nitrogen production	10M3	1	150000	150000
	Air Compressor	Compressed gas production	400M3	1	360000	360000
	Dryer	To provide Dry gas		1	150000	150000
	Vacuum Pump	To provide Vacuum		1	150000	150000
Total					2,103,000	29,877,000

Testing equipment planning								
Item No.	**Model**		**Specifications**	**Useage**	**Unit**	**Quantity**	**Unit Price/RMB**	**Amount**
Physical and chemical testing								
1	equipment	Tap test		tap density testing	pcs	1	100000	100000
2	equipment	Laser Particle Sizer		Particle Size Analysis	pcs	1	150000	150000
3	equipment	BET Test		BET Test	pcs	1	100000	100000
4	equipment	Electrochemical Analyzer		Electrochemical Analysis	pcs	1	30000	30000
5	equipment	Water test		Solids moisture test	pcs	1	200000	200000
6	equipment	Electric mixer		Material mixing	pcs	1	8000	8000
7	equipment	Microscope		positive/negative Analysis	pcs	1	50000	50000
8	equipment	I-R Test		Resistance test	pcs	1	20000	20000
9	equipment	Oven		Material or glassware baking	pcs	1	20000	20000
10	equipment	Refrigerator		Storage of liquid substances	pcs	1	5000	5000
11	Table			Laboratory tables	Set	1	100000	100000
Total								783000
Conventional testing								
1	equipment	Capacity test	5V/15A	Capacity test	pcs	1	50000	50000
2	equipment	Cycle test	5V/15A	Cycle test	pcs	1	50000	50000
3	equipment	voltage resistance tester		Battery voltage resistance test	pcs	1	15000	15000
Total								115000
high and low temperature test								

1	equipment	lithium battery performance testing system		Capacity test	pcs	1(8点/台）)	10000	10000
3	equipment	blast oven		battery temperature cycle test	pcs	2	20000	40000
4	equipment	thermal shock oven		150℃ thermal shock	pcs	1	20000	20000
5	equipment	High and low temperature testing oven	-40℃--300℃	Performance test at low temperature and high temperature	pcs	1	200000	200000
6	equipment	Regulators machine		battery test equipment regulators	pcs	1	30000	30000
Total								300000
training and technical support costs								2000000

Appendix 3-Interest rate chart of Landsbankinn-Laoans

Landsbankinn

2010-11-11

Interest rate chart of NBI hf. Landsbankinn - Loans

1. Debentures and bills

Prime rate categories	Premium	Bills of exchange interests	Bills of exchange prev. intr.	Indexed loans interests	Indexed loans prev. intr.	Non-indexed loans interests	Non-indexed loans prev. intr.
0. Prime rate without add. intr.	0,00%	7,25%	7,75%	4,70%	4,80%	6,65%	7,15%
Prime rate categ. 1	1,00%	8,25%	8,75%	5,70%	5,80%	7,65%	8,15%
Prime rate categ. 2	2,00%	9,25%	9,75%	6,70%	6,80%	8,65%	9,15%
Prime rate categ. 3	2,90%	10,15%	10,65%	7,60%	7,70%	9,55%	10,05%
Prime rate categ. 4	3,65%	10,90%	11,40%	8,35%	8,45%	10,30%	10,80%
Prime rate categ. 5	4,30%	11,55%	12,05%	9,00%	9,10%	10,95%	11,45%
Prime rate categ. 6	4,80%	12,05%	12,55%	9,50%	9,60%	11,45%	11,95%
Prime rate categ. 7	5,20%	12,45%	12,95%	9,90%	10,00%	11,85%	12,35%
Prime rate categ. 8	5,45%	12,70%	13,20%	10,15%	10,25%	12,10%	12,60%
Prime rate categ. 9	5,60%	12,85%	13,35%	10,30%	10,40%	12,25%	12,75%
Older loans, not prime rate				7,85%	7,95%	10,25%	10,75%
Real estate mortages				10,30%	10,40%	12,25%	12,75%
Non-indexed housing mortgages, lowest rates						5,80%	
Non-indexed housing mortgages, highest rates						6,30%	
Indexed housing mortgages, lowest rates				4,70%	8,80%		
Indexed housing mortgages, highest rates				5,30%	7,95%		

2. Overdrafts and credit lines

	interests	prev. intr.
Corporate overdrafts and credit lines*	12,50%	12,80%
Personal overdrafts (Einkareikningur accounts)*	12,50%	12,80%
Overdrafts of Varðan Premier account members	12,00%	12,30%
Reduce your overdraft	8,65%	9,15%
Methane-loans	8,65%	9,15%
Naman student account linked to the Icelandic Students' Loan Fund (LÍN)	6,70%	7,00%
Naman computer loan	8,25%	8,55%
Naman general student accounts	8,50%	8,80%

3. Cedit cards, Visa and MasterCard

Longer-term payments and extended payment accounts	12,50%	12,80%
Longer-term payments and extended payment accounts for Varðan members	12,00%	12,30%

4. Penalty interest as determined by the Central Bank of Iceland	13,25%

Appendix 4-Cost estimation of construction lithium factory from Magnússon in Iceland

Lithium battery factory in Iceland

Cost budget of construction the factory

Date 17.11.10

No	Works Item			Total
1	SITE COST AND EARTHWORK		*10.500 kr/m²*	210.000.000 kr.
2	STRUCTURAL		*51.500 kr/m²*	1.030.000.000 kr.
3	UTILITIES AND HEATING		*18.300 kr/m²*	366.000.000 kr.
4	VENTILATING		*15.200 kr/m²*	304.000.000 kr.
5	INTERIOR FINISH		*29.500 kr/m²*	590.000.000 kr.
6	ELECTRICAL		*19.500 kr/m²*	390.000.000 kr.
7	EXTERIOR FINISH		*39.300 kr/m²*	786.000.000 kr.
8	SITE IIMPROVMENTS			105.000.000 kr.
	UNFORESEEN COST AND CHANGE ORDERS	10%		367.600.000 kr.
	CONTRACTORS EXPENSE with VAT			**4.148.600.000 kr.**
	GENERAL COST with VAT			**542.923.150 kr.**
	Design, project supervision, project management	13%	total	518.575.000 kr.
		4%	*Architect*	*145.201.000 kr.*
		1%	*Landscape*	*41.486.000 kr.*
		3%	*Engineering Design*	*103.715.000 kr.*
		3%	*Electrical engineers*	*103.715.000 kr.*
		3%	*Project monitoring*	*124.458.000 kr.*
	License fees, connection fees and assessments			20.000.000 kr.
	Other costs such as printing, advertising, etc.			4.348.150 kr.
	TOTAL COST with VAT			**4.691.523.150 kr.**

All prices include 25.5% VAT
Borrowing costs not included

Key figures

Factorysize	20.000 m²
Site Size	10.000 m²
Contractor's cost per m² factory	207.430 kr/m²
Contractor's cost per m² site	10.500 kr/m²
Total cost á m² of factory and site	234.576 kr/m²

Appendix 5-Quotation of raw material price-electrolyte

北京创亚恒业新材料科技有限公司
BEIJING CHUANGYA HENGYE NEW MATERIALS TECHNOLOGY Co., LTD

Quotation

To: Reykjavik University **Our ref.: 2010112504**
Attn: Mr. Paichun Tao **Date:2010-11-25**

We are pleased to quote you our best price as follows,

Product Name	Product Picture	Model and Specification	Quantity	Price	Price Terms	Payment
Electrolyte		Functional electrolyte	2kg	80USD/KG	EXW Express fee paid by buyer	TT in advance
Electrolyte		Functional electrolyte	50-100Kg	35USD/Kg	FCA Tianjin	TT in advance
Stainless Steel Barrel		1L		USD27/ea		TT in advance

Delivery Time
10 working days after the receipt of your payment
Validity
The above quotation is valid within 5days hereof.

Best Regards
Mary Xu

Beijing Chuangya Hengye New Materials Technology CO., Ltd
Office Add: No. 10, Huoju Street, Changping Science Park, Beijing China
Factory Add: Yanxu industrial Park, Machikou Town, Chuangping District, Beijing
International Department
Tel: 86-10-80116145
Fax: 86-10-80103190
E-mail maryxu.beijing@gmail.com

Appendix 6-Enquiry of raw material price-separator

Re: [tao09@ru.is]Price Inquiry from Paichun
Ekain Zhang [ekainzhang@gmail.com]

Dear Tao

I am sorry for my delay as for the business trip
Regarding the price, as earlier price is for samples price, so we offer you the same price
If for Bulk purchase, the price for 16&18micron is little expensive than 20&25micron
And for the 25micron weight per Sq.m, it is about 13.1g
And we are expectting for your samples testing
Best regards
Ekain

----- Original Message -----
From: "Pai-Chun Tao" <tao09@ru.is>
To: "Ekain Zhang" <ekainzhang@gmail.com>
Sent: Thursday, November 25, 2010 9:50 PM
Subject: RE: [tao09@ru.is]Price Inquiry from Paichun

Dear Ekain:

Thanks for your kind response.
We are wondering does different thickness of separator has the same price.
And, how much does 25 micron separator weight per square m?

Thanks for your help

Best Regards,
Paichun Tao

From: Ekain Zhang [ekainzhang@gmail.com]
Sent: Tuesday, November 23, 2010 8:51 AM
To: Pai-Chun Tao
Subject: Re: [tao09@ru.is]Price Inquiry from Paichun

Dear Tao

Thanks for your new inquiry
For the lithium ion battery separator, we have four type thickness, 16,18,20,25micron thickness
Pls may you inform us for your detail request?
Our MOQ is 50Sq.m, price is USD3.0/Sq.m for FOB Shenzhen
Pls check and inform us for your further news

Appendix 7-Enquiry of raw material price-anode material

ithium iron phosphate battery
Rachel [renjie@kimwan.cn]
The sender of this message has requested a read receipt. Click here to send a receipt.
Sent: Wednesday, November 24, 2010 9:09 AM
To: Pai-Chun Tao
Cc: 'Zang' [dz@kimwan.cn]; tony@kimwan.cn; 'Qian' [qian@kimwan.cn]; '祁平' [qiping@kimwan.cn]; '吴仲福' [wzf@kimwan.cn]; '王丹' [wangdan@kimwan.cn]

Dear Mr. Paichun Tao,

Thanks for your prompt reply.
Our FOB Price is US$9.00/KG.
If necessary, We can send your some sample for testing.

Any further requirements, please feel free to contact me.

Best regards,

Rachel Ren

-----邮件原件-----
发件人: Pai-Chun Tao [mailto:tao09@ru.is]
发送时间: 2010年11月24日 星期三 4:37
收件人: Rachel
主题: RE: [tao09@ru.is]Inquiry from Anode Materials for Lithium Ion Battery

Dear Rachel:

Thanks for your response.
I have reviewed your catalog.
We plan to make lithium iron phosphate battery.
It will be great if you can send us quotation sheet of your products.

Sincerely,
Paichun Tao

Appendix-8 Quotation of Vacuum oven from Votsch

Vötsch Industrietechnik GmbH
Umweltsimulation · Wärmetechnik

Vötsch Industrietechnik GmbH, Postfach 11 63, D-35445 Reiskirchen

Reykjavik University
School of Science and Engineering
Gudrun Savarsdottir
Menntavegur 1
101 REYKJAVIK
ISLAND

Budget Price Quotation

Number/Date
52211623 / 10.01.2011
Delivery period
approx. 20-22 weeks after receipt of order
Cust. no.
70543876
Date of expiration
31.03.2011
Mechanical engineering
Kurt Herber, k.herber@v-it.com
Tel.: +49 6408 84 6553, Fax: +49 6408 84-8053
Area sales manager
Sascha Junker, s.junker@v-it.com
Tel.: +49 6408 84 6145

Your inquiry about a vacuum dryer

Dear Mrs. Sävarsdottir,

enclosed you will receive our Budget price quotation to your inquiry of a vacuum dryer from Mr. Paichun Tao.

To give a complete and fixed price quotation we need a filled out checklist which is enclosed.

If you have any further queries, don´t. hesitate to contact Mr. Herber or me.

Best regards

VÖTSCH Industrietechnik GmbH
Heating Technologie

i.V. Kurt Herber

i.A. Sascha Junker

Director
Dr. Arno Roth
Dr. Jürgen Jakoby
Franz J. Niedermeier
Reg.: HRB 410872 Stuttgart
Tax-No.: 02022710510
USt-IdNr.: DE811112534

Company:
Greizer Straße 41-49
D-35447 Reiskirchen-Lindenstruth
Phone (06408) 84-73
Fax (06408) 84-8747
Internet: http://www.v-it.com
Email: info-wt@v-it.com

Bank:
Commerzbank Balingen (BLZ 653 412 04) 122 90 38
SWIFT: COBA DE FF 655
IBAN DE 37 6534 1204 0122 9038 00

Vötsch
Industrietechnik

Doc. no./Date	Page
52211623 / 10.01.2011	2

Item	Material Description	Qty	Unit price	Currency	Total
000010	59007000 VÖTSCH-Vakuum Drying Oven Type VVT 85/170-E-200°C Alternative to Pos. 10	1 PC	92.090,00	EUR	92.090,00
000020	59007000 VÖTSCH-Vakuum Drying Oven Type VVT 85/170-WW Optional for Pos. 10 and 20	1 PC	81.890,00	EUR	81.890,00
000030	59007005 Vacuum Pump System Type 65/0,1	1 PC	13.600,00	EUR	13.600,00
000040	59007005 VÖTSCH-Software Package S!MPATi*	1 PC	979,00	EUR	979,00

Plus value-added tax to comply with legal requirements

Offer is based on our Standard Conditions of Sale, Assembly and Delivery. Details are available on request or can be found on our web site **http://www.v-it.com**.

Terms of payment
payment due within 10 days net

Terms of delivery:
EXW, ex works

Warranty: 12 months after delivery

Director
Dr. Arno Roth
Dr. Jürgen Jakoby
Franz J. Niedermeier
Reg.: HRB 410872 Stuttgart
Tax-No.: 02022710510
USt-IdNr.: DE811112534

Company:
Greizer Straße 41-49
D-35447 Reiskirchen-Lindenstruth
Phone (06408) 84-73
Fax (06408) 84-8747
Internet: http://www.v-it.com
Email: info-wt@v-it.com

Bank:
Commerzbank Balingen (BLZ 653 412 04) 122 90 38
SWIFT: COBA DE FF 655
IBAN DE 37 6534 1204 0122 9038 00

Appendix-9 Paper version for World Renewable Energy Congress in Sweden 2011

World Renewable Energy Congress 2011 – Sweden
8-11 May 2011, Linköping, Sweden

Geothermal application (GA)

Potential use of geothermal energy sources for the production of lithium-ion batteries

Pai-chun Tao, Hlynur Stefansson, William Harvey, Gudrun Saevarsdottir*

[1] *Reykjavik University, Reykjavik, Iceland*

* *Corresponding author. Tel: +354 599-6345, Fax: +354 599-6201, E-mail: gudrunsa@ru.is*

Abstract: The lithium-ion battery is one of the most critical technologies for energy storage in many recent and emerging applications. However, the cost of lithium-ion batteries limits their penetration in the public market. Energy input is a significant cost driver for lithium batteries due to both the electrical and thermal energy required in the production process. The drying process requires 45~57% of the energy consumption of the production process according to our model. In Iceland, it is possible to use geothermal steam as a thermal resource in the drying process. The most feasible type of dryer and heating method for lithium batteries would be a tray dryer (batch) using a conduction heating method under vacuum operation. Replacing conventional heat sources with heat from geothermal steam in Iceland, we can lower the energy cost to 0.008USD/Ah from 0.13USD/Ah based on average European energy prices. The energy expenditure after 15 years operation could be close to 2% of total expenditure using this renewable resource, down from 12~15% in other European countries. According to our profitability model, the internal rate of return of this project will increase from 11% to 23% by replacing the energy source. The impact on carbon emissions amounts to 393.4-215.1g/Ah lower releases of CO_2 per year, which is only 2-5 % of original carbon emission compared to traditional energy sources in other countries.

Keywords: lithium ion battery, geothermal energy, energy cost, carbon emission

1. Introduction

The exponential growth in the use of portable electronic devices and electric vehicles has created enormous interest in inexpensive, compact, light-weight batteries offering high energy density. Clearly, the lithium-ion battery is one of the most appealing technologies to satisfy this need. It is estimated that the global market for lithium-ion batteries could grow from $877 million in 2010 to $8 billion by 2015[1]. However, the cost of lithium-ion batteries limits their penetration in the global market. Energy is a significant cost driver for lithium batteries as both electrical and thermal energy is required in the raw materials processing and battery manufacturing and assembly. Iceland offers a number of potential avenues for cost and carbon emissions reductions in the manufacturing process, due to readily available medium grade thermal energy from geothermal or industrial sources, access to inexpensive renewable electricity, and a skilled workforce. The purpose of this paper is to quantify the economic advantages and carbon emission reductions to be gained by siting a lithium iron phosphate ($LiFePO_4$) factory in Iceland close to geothermal heat sources, versus sites in other locations where fossil sources of energy must be used. Furthermore, we will also present the sensitivity of profitability to energy cost.

2. Methodology

The project consists of three main tasks: 1) Collection of relevant data and information. 2) Estimation of energy consumption and temperature levels at various steps in the production process and 3) Assessment of profitability and impact on carbon emissions. Firstly, the literature review, including interview data, provides with us information to draw a complete production process map of the lithium iron phosphate battery manufacturing process. Unfortunately, the detailed energy consumption data from each step in lithium battery production is not readily available from factories due to confidentiality reasons in this competitive market. Consequently, we build a theoretical energy consumption model for the drying process based on the thermal properties and moisture content of materials in the batteries, basic physical formulas, and industrial experience. There are some uncertainties existing in this model, such as energy efficiency, heat loss, and other assumptions. The result of this energy consumption model is therefore not an accurate value from an actual factory, but should be realistic none the less. In reality, it could be lower or higher depending on design of industrial equipment components. In terms of the profitability assessment, there are some common standards of estimating the profit of an investment, for example, net present value (NPV) and the internal rate of return (IRR). Consequently, we build a comprehensive profitability assessment model of building a new lithium iron battery factory in Iceland. Most cost data are obtained directly from suppliers or the publicly available information. The main assumptions will be listed in Table 2.1. In the model, we make several financial assumptions, such as rate of debt based on conditions in Iceland. The profitability calculation and Monte Carlo analysis are performed by Microsoft Excel plug in with @Risk5.7.

Table 2-1 Main assumptions of profitability model

Items	Value
Interest rate of loan	12%
Sale price	1.44 (USD/Ah) with 3% annual decreasing trend
Raw material price	0.69 (USD/Ah) with 2.75% annual decreasing trend
Initial investment	9612 million ISK
Discount Rate	15%
Capital structure	70% loan, 30% equity
Exchange rate	156 (ISK/Euro) 112 (ISK/USD)
Salary for workers	Iceland: 238,000 (ISK/Month) Germany: 1944 (€/Month)

3. Energy consumption of lithium ion battery production process

3.1. Energy consumption of entire process

Energy consumption in lithium iron battery production is not openly available information from this emerging industry. Lifecycle analysis of lithium iron battery by Mats Zackrisson and Lars Avellán in 2010 claims that the total energy consumption corresponds to 11.7 kWh electricity and 8.8 kWh of thermal energy from natural gas per kg lithium-ion battery [2]. This corresponds to an energy consumption for 1Ah battery of approximately 0.68KWh, assuming that one kg lithium-ion provides 30Ah capacity of battery. In addition, energy consumption data were obtained from Matti Nuutinen, who reported data from a Chinese lithium iron battery factory and for European Batteries Oy[3]. In this report, Nuutinen shows that 5000kw electric power is required to produce 80MAh battery per year. This equates to energy consumption for producing 1Ah battery is approximately 0.54KWh. Based on these sources the energy consumption could range from 0.54 to 0.68 KWh/Ah according to our investigation.

3.2. Production process map

In general, our analysis of the lithium iron battery production process starts with the various raw materials and components from suppliers. The overall process can be divided into two parts: preparation of electrodes and cells assembly. Fig 3-1 shows the main steps

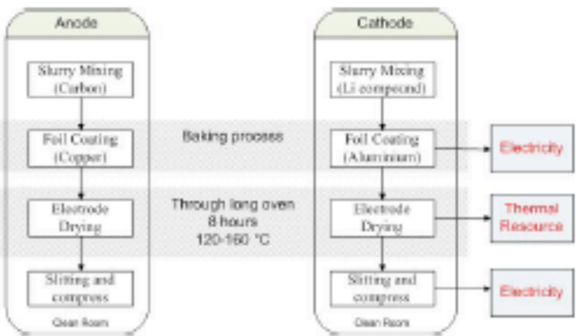


Figure 3-1 Production process map of Part 1

in first part of the production process. In first part, the first step is to mix anode and cathode powders with solvent and binder, coat them on the respective foils, and dry them in the vacuum oven at around 120°C for 8 hours. Traditionally the heat applied at each of the drying steps is obtained by electric heating. However, since the temperature needed in the vacuum oven is relatively low, we might be able to replace electric heating with heat exchangers using geothermal steam as a thermal source. After this drying step the electrode disks would be cut into suitable sizes and compressed thinner by automatic machines. At this stage, the individual electrode is ready for assembly.

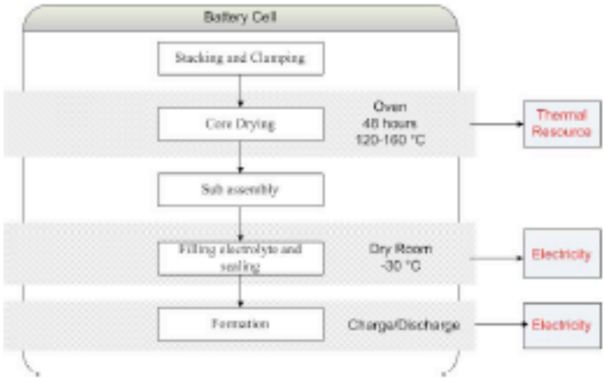


Figure 3-1 Production process map of Part 2

Fig 3-2 shows the second part, which is to assemble the various components, such as the separators, internal circuits, anodes and cathode altogether. In this step, the electrodes can be stacked and clamped first and put into a metal packing case. Afterwards, the battery cells are placed in the core drying machines. The purpose of this step is to remove the remaining moisture from electrodes completely. This is the most energy intensive step of the whole process. In principle it would seem feasible to accelerate this drying step by increasing the temperature in the oven. However, the melting point of the binder (PVDF) is around 170°C, so the temperature in the vacuum oven must be kept below 170°C. As an alternative the process is accelerated by lowering the pressure in the oven in order to efficiently remove the vapor formed. Thereby the boiling point of water and solvent is decreased in order to shorten the drying process. In the end, the moisture content rate in the electrodes is reduced to 500ppm [4]. After the core drying process, the electrolyte is injected into cell and it is sealed completely. Since the electrodes are very sensitive to moisture, those processes are usually operated in a room, where the humidity is kept at an acceptable level. In principle, the battery pack is ready for use at this stage. However, most producers test their products several times in order to ensure its performance and collect data before shipping the product to consumers.

3.3. Energy consumption of the drying process

Through production analysis, the approximate energy consumption figure has been already addressed in the previous text. But, we need to know the energy consumption of the drying process, if we want to consider alternative energy resources for the drying process. Consequently, we build a theoretical calculation model. It is not perfect, but a reasonable approach to figure out the approximate energy consumption of the drying process. The first step of building an energy consumption model of drying is to collect the weight percentage and thermal properties of component materials. Table 3-1, shows the physical thermal properties of each material in the lithium iron battery.

Table 3-1 Physical properties of component material

Information of 1 kg lithium iron battery component material			
Cathode Composition	Weight (g)	Heat capacity	Others
$LiFePO_4$	422 g [2]	C_v: 0.9 J/g-K [2]	Melting point: 223°C
Al foil	19 g [2]	C_P(25°C) 0.89 J/g-K	Melting point: 660.3°C
Carbon black	27 g [2]	C_P(25°C): 0.71 J/g-K	Melting point: 3500°C
Binder (PVDF)	28 g [2]	C_v: 1.9J/g-K [5]	Melting point: 170 °C
NMP solvent	Initial: 244.2 g Outlet: 10g[6]	C_v: 1.76 J/g-K [7]	Boiling point: 202°C Heat of vaporization, 20°C: 550.5 KJ/g [6]
Anode Composition			
Graphite	169 g [2]	C_P(25°C): 0.71 J/g-K	Melting point: 3500°C
Cu foil	46 g [2]	C_p(25°C): 0.385 J/g-K	Melting point: 1084.6°C
NMP solvent	Initial: 116.2 g Outlet: 4.8g [6]	C_v: 1.76 J/g-K [7]	Boiling point: 202°C Heat of vaporization, 20°C: 550.5 KJ/g [6]
Total moisture	Initial: 4.5g Outlet: 0.5g [4]	C_v (25°C): 4.18 J/g-K C_v(100°C, steam): 2.08	Evaporation energy: 2270 KJ/g)

The model predicts how much thermal energy we need in order to remove the moisture and NMP from the electrodes. It is accompanied with the increasing temperature of other materials and some heat lost to environmental. The thermal energy consumption of the drying process calculation could be divided into two parts. (1) The energy for increasing the temperature of all component materials. (2) The energy for evaporating the moisture and NMP away from the feedstock. Through the thermal properties and some basic physical formulas, we obtain theoretical results for both parts respectively. And then, we take the empirical energy efficiency of the vacuum dryer into account to get more realistic data. The energy required for heating the materials to the dryer temperature would is 128.62kJ/kg. The second part is the energy consumption of evaporation. It dominates the energy consumption of drying process. The overall energy consumption of evaporation is 198197.8kJ/kg. The key factors in this calculation are the initial weight and outlet weight of moisture because the heat of evaporation of water and solvent dominates as compared to the sensible heat. However, the energy efficiency is not 100%. Based on the literature we assume that the energy efficiency of the vacuum dryer is 0.6 according to the Handbook of Industrial Drying [8]. In this case, the practical energy consumption would be 0.186/0.6 = 0.26 KWh/Ah. As a consequence the energy required is approximately 0.31 KWh thermal to dry 1Ah of lithium iron phosphate battery. This number does not include the electricity for vacuum machines and drying rooms, which are also part of the drying system. It only focuses on the thermal energy that can be replaced by geothermal steam. According to the energy consumption data in previous research, the whole energy consumption of producing 1Ah lithium battery would raised from 0.54~0.68 KWh. Based on this information 45~57% of the energy consumed by the process can be replaced by an alternative thermal source.

3.4. Alternative drying technology

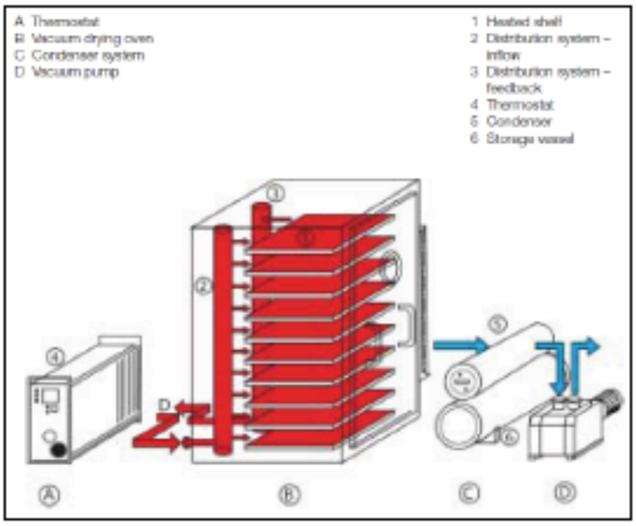


Figure 3-3 Schematic model of vacuum oven could use working fluid as thermal resource [9]

The main targeted materials are moisture and organic solvent (NMP) that are trapped in the cathode or anode paste. The oven would provide thermal energy to the feedstock continuously by convection, conduction, or radiation in order to remove the targeted materials from the batteries. In Iceland, geothermal power plants are typically operated with steam at 10-12 bar, but in some cases, such as in Reykjanes a higher pressure up to 18 bar is applied. In this case, we would propose applying geothermal steam at 18 bar, 207°C as a thermal resource in order to reduce the energy cost and carbon emissions. If the factory is located close to the geothermal power plant, the steam from two-phase separators could be applied directly. Hitaveita Sudurnesja, the power company operating the Reykjanes power plant, has offered 20 bar steam to other customers at 4USD/ton and 6 bar at 3 USD/ton in 1995[10]. A diatomite processing plant at Lake Myvatn that was in operation until 2004 paid 1 USD/ton for geothermal steam. In this model, a steam price of 4 USD/ton is assumed. In reality, this price highly depends on the negotiation with power companies. Regarding the dryer, the ideal type of dryer and heating method for lithium batteries would be a tray dryer (batch) using conduction heating method under vacuum operation. Although the geothermal steam from well contains some deleterious materials, most of them would be contained within the liquid phase in the separators. Thus, we would be able to fill the geothermal steam into the entire cavity of shelves directly. As you can see in Fig 3-3, while the feedstock is placed on the shelves, the thermal energy is transferred to products by conduction. In addition to the conduction, it also could be combined with radiation heating method in order to accelerate the drying rate in the final period. In this case, we assume the new type of dryers will cost 20% more than normal electrical dryers. Because the cost of dryers is only 14% of production lines, it does not affect the overall cost of production significantly.

4. Reduction in carbon emissions

From the data shown in Table 3-2, we can see that the energy structure of each country has different features. Based on that data, the average emission from electricity generation for each energy profile is calculated. If we build a lithium iron phosphate battery production facility with 10MW power requirement in other countries, it will emit 36247~64771 tons of CO_2 per year depending on the country's electric energy production profile. In Iceland, approximate 50% of energy consumption is still electricity, which emits 23.5 g/KWh CO_2 on average [11]. The rest of the energy consumption will be replaced by geothermal steam, which emits 18g/KWh CO_2 in this case. Thus, the total CO_2 emission in Iceland would be around 1818 tons of CO_2 per year. In summary, this project in Iceland has 393.4-215.1 g/Ah lower CO_2 emission advantage compare to other countries. However, we have to put it in mind that most of carbon dioxide emits naturally from geothermal area in Iceland. The this comparison. The energy price will play more substantial part of the total variable cost after predicted reductions of raw material prices in the next 10 years.

5.1.2. *Internal rate of return*

In terms of internal rate of return, it is used in capital budgeting to measure and compare the profitability of the investment. Fig 5-2 shows the internal return rate of total cash flow and net cash flow in Iceland is 22% and 27%, respectively. On the other side, the internal return rate of total cash flow and net cash flow in Europe is 11% and 12%, respectively. Although there is some risk and uncertainty in this project, IRR is higher than the cost of capital in the normal situation in Iceland. To compare to a common investment, it has a relatively high internal rate of return based on the assumption. However, 11~12% of IRR is a normal and acceptable result for an investment project in other European countries.

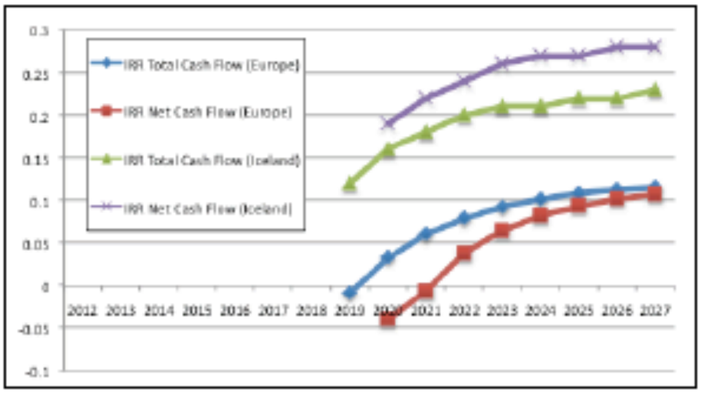
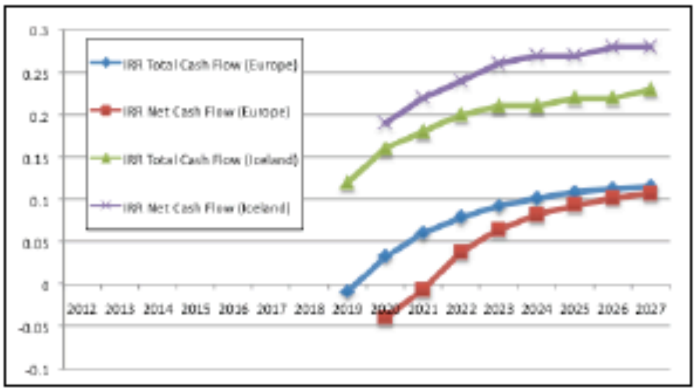


Figure 5-2 IRR comparison between Iceland and other European countries

6. Conclusion

With the anticipated reduction in material cost for Lithium-ion batteries, the energy cost for battery production will play a more important role in the overall cost of lithium ion batteries. According to our investigation, the energy consumption could range from 0.54 to 0.68 KWh/Ah depending on the factory's design and production process. Although we did not get access to first-hand energy consumption data of each step from factories directly, we can infer that the main energy consumption steps in the procedure are drying room, vacuum dryers, and testing equipment from our production process analysis. In locations with access to geothermal heat, such as Iceland, we might be able to replace the electricity used as a heat source for the drying processes by geothermal steam. As a result the energy cost could be reduced combining reasonably priced electricity with geothermal heat. Through our theoretical drying model, the energy consumption of removing the moisture content in 1 Ah battery is 0.31 KWh, which is around half of the total energy consumption. Consequently, the variable energy cost in Iceland could be reduced to 0.012 USD/Ah (0.007 USD for electricity; 0.005 for geothermal steam) as we ideally use geothermal steam for drying. In the technical aspect of this transition, we suggest using geothermal steam at 18 bar 207°C from an existing geothermal power plant. In this case, the ideal type of dryer and heating method for lithium batteries would be a tray dryer. In terms of economic and environmental benefit, we built a profitability model using current cost data based on operating environment in Iceland. According to this model, the accumulated NPV for equity with a 15% discount rate of this project in Iceland is 52.5 million USD and internal rate of return is 27%. On the other hand, if we move the factory to other European countries with higher energy price (0.18€ /KWh[13]) and the same cost assumption, the NPV for equity will fall down to -20.6 million USD. The internal rate of return will fall from 27% to 11%. Moreover, with current feedstock prices the energy cost is estimated to be 1% with the Icelandic cost structure, while it would amount to 12~15% in other European countries based on average energy prices. The lower energy cost in Iceland results in an NPV less sensitive to fluctuation of energy prices. Iceland seems to this comparison. The energy price will play more substantial part of the total variable cost after predicted reductions of raw material prices in the next 10 years.

5.1.2. Internal rate of return



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6. Conclusion

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References

[1] Pike Research, Asian Manufacturers Will Lead the $8 Billion Market for Electric Vehicle Batteries, Retrieved 10 1, 2010, from Pike Research: http://www.pikeresearch.com/newsroom/asian-manufacturers-will-lead-the-8-billion-market-for-electric-vehicle-batteries

[2] Zackrisson M & Orlenius J, Life cycle assessment of lithium-ion batteries for plug-in hybrid electric vehicles e Critical issues. Journal of Cleaner Production, 2010, pp.1517-1527.

[3] Nuutinen, M, Lithium-ion battery factory relocation from China to Finland. Material science and engineering. Helsinki: Helsinki university of technology, 2007, pp.68-69.

[4] She Haung Wu and Yang-Ting Lai, The effects of the moisture content of LiFePO4/C cathode and the addition of VC on the capacity fading of the LiFePO4/MCMB cell at elevated temperatures. The electrochemical Society, 2007.

[5] Dr. Michael Eastman, Smart Sensors Based on Piezoelectric PVDF, 2010, pp-6

[6] LICO Technology Corporation, LHB-108P Hydrophilic Binder, 2008, pp-6

[7] Taminco Co, N-Methylpyrrolidone Electronic grade Technical Data Sheet, 2004, pp-1

[8] Mujumdar A. S, Handbook of Industrial Drying. Taylor & Francis Group LLC, 2006, pp.1108-1109.

[9] Weiss Gallenkamp, Vacuum oven and drying oven VVT, 2010, pp-4.

[10] Invest in Iceland Agency, Diversified Usage of Renewable Energy in Iceland, Reykjavik: Iceland investment agency, 2010.

[11] Landssvirkjun, Landssvirkjun's carbon footprint, Reykjavik: Landssvirkjun, 2009, pp-11.

[12] World Energy Council, World Energy council. Retrieved 10 1, 2010, from World Energy council: http://www.worldenergy.org/publications/survey_of_energy_resources_2007/geothermal_energy/737.asp

[13] Europe's Energy Portal, Industrial Electricity Rate, November 2009, http://www.energy.eu/#Industrial

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