Feasibility of a Small Scale Electrical Storage System - Potential for Technology Learning

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PREFACE

This 30 ECTS Master's thesis in Renewable Energy was written under the Department of Ecology and Natural Resource Management (INA) at the Norwegian University of Life Sciences (UMB).

The main goal of this project was to determine the feasibility of a proposed idea of energy storage technology, developed by my former University of Agder (UiA) classmates Casper Kielland, Håkon Gabrielsen and myself. This project was chosen because of my interest in energy storage and my personal engagement in the development of Kielland's idea. It was former UMB lecturer and supervisor Professor Terje Gjengedal at INA who suggested that a technical feasibility study of the idea would make an interesting master's thesis. However, after Gjengedal left UMB in December 2012, Associate professor Thomas Martinsen was chosen as my new supervisor. Martinsen suggested the feasibility study also to include technology learning, i.e. to predict potential future cost reductions of the proposed energy system using the learning curve method.

I would like to thank my supervisor, Associate Professor Thomas Martinsen, for his advice on the learning curve method and thesis in general. I would also like to give thanks to my former UiA classmate, Håkon Gabrielsen, for advice and aid in thermodynamics. Last, I thank Frank Häberli at Lincoln Composites, Erik Ulevik at Parker Olaer, Per Nyborg at Hydac, Petri Virrankoski at Hydroll, Morten Hansen at Rainpower, and Professor Arthur Williams at the University of Nottingham for their correspondence.

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ABSTRACT

Intermittent renewables, e.g. windturbines and PVs, are in need of stand-by power and energy storage systems in order to provide reliable electricity to the grid. Energy storages could result in a more powerful penetration of renewables, hence phasing out fossil fuels earlier than expected. Also, the electrical grid in itself would become more reliable if utilizing electrical storage systems. Stand-by emergency generators in the grid could prevent brownouts and blackouts worth millions of NOK in both social and industrial benefits. Also, stand-alone energy storage systems could be utilized in remote off-grid areas, hence providing reliable power to, e.g. tele-com base stations, military- and refugee camps, or battery recharge stations for electrical cars.

This thesis investigated the feasibility of a new electrical storage system related to mechanical systems, e.g. pumped hydro storage (PHS), compressed air (CAES) and flywheels (FES). The feasibility analysis indicated the system to be novel and that it could be utilized in all of the above-mentioned scenarios, e.g. intermittent renewables, grid reliability and as stand-by emergency generator. The analysis reviewed a case-scenario where the system was utilized in a household for storing surplus electricity from local renewable generation. The analysis indicated that storing electricity, subsequently to regenerate the electricity to the grid, was not profitable for households at the initial investment cost. However, technology learning indicated the case-scenario to have potential profitability in the future.

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ACRONYMS AND ABBREVIATIONS

BES	Battery Energy Storage
Blackout	Complete loss of power
Brownout	Voltage drop in the power supply
CAES	Compressed Air Energy Storage
EC	Electrochemical capacitors
EPO	European Patent Office
FC	Fuel cell
FES	Flywheel Energy Storage
GHG	Greenhouse gases
INA	Department of Ecology and Natural Resource Management
LR	Learning rate
lpm	Litres per minute
NIPO	Norwegian Industrial Property Office
NOK	Norwegian krone
NPV	Net Present Value
NVE	Norwegian Resources and Energy Directorate

PED	Pressure Equipment Directive
PR	Progress ratio
PSH	Pumped-storage hydropower
PV	Solar photovoltaic
Renewables	Renewable energy technologies
SFFE	Centre for renewable energy
SMES	Superconducting Magnetic Energy Storage
UMB	Norwegian University of Life Sciences
USD	United States dollar
W_p	Peak/nominal power

1 INTRODUCTION

The world energy consumption has increased rapidly since the 1950s and fossil fuel still prevails as the most commonly used energy resource. According to the annual *BP Statistical Review of World Energy* (2012) consumption of oil, coal and gas holds a share of approximate 80% of the global energy consumption. Although renewable energy technologies (renewables), e.g. hydro-, wind- and solar photovoltaic power (PV), have increased from scarce 0,7% in 2001 to 2,1% in 2011 (BP, 2012). In other words, a revolutionary low-carbon energy technology is still astray as the use of fossil fuel is still increasing more rapidly than renewables. This thesis introduces a new energy storage technology that might contribute to the long overdue penetration of renewables.

1.1 BACKGROUND

Wind, water and sun are all intermittent energy sources, i.e. the power output is variable and restricted to the conditions of wind, rain and sun. The current energy system today relies on coal, nuclear and large hydro reservoirs where hydro is the only supply that can easily be adjusted according to the various demands. The energy demand varies throughout the day with high demand in the morning and afternoon (peak hours), moderate demand at mid-day and low demand during night (off-peak hours). Wind and solar seldom correspond with the peak/off-peak hours and often need back up from reliable sources, e.g. nuclear or gas-fired generators. Paradoxically, due to the irregular intervals of supply and demand, environmental friendly renewables are somewhat dependent on fossil fuels. However, an energy system, fully supplied by renewables, is feasible according to Delucchi and Jacobson (2010). In the article *“Providing all global energy with wind, water, and solar power,”* Delucchi and Jacobson list seven ways of how to create a reliable renewable energy system (Delucchi and Jacobson, 2010):

1) Interconnection of dispersed renewables
2) Use a reliable energy source, e.g., hydro reservoirs as stand-by for wind and PV
3) Use ”smart” demand-response management for more efficient use of electricity

4) Use electrical storage at generation site
5) Over-size peak generation capacity of renewables
6) Store electric power in vehicle batteries
7) Plan the energy supply according to the weather forecast

This thesis investigates a proposed idea of storing electricity at generation site. Energy storage systems can store surplus electricity generated at off-peak hours and subsequently regenerate it at peak hours. Several storage systems for electricity is utilized today, e.g. pumped hydro (PSH), compressed air (CAES), flywheel (FES), batteries (BES), fuel cells (FC) and capacitors (EC). In addition to on-going innovation of the utilized systems, media and research papers indicate flourishing studies of new and interesting technologies, e.g. liquid air, nanomaterials, adiabatic compression of air, superconducting magnets (SMES) etc. The concept of the proposed new system is to utilize surplus electricity from intermittent renewables to pressurize water in high-pressure accumulators. The electricity is regenerated when subsequently releasing the pressurized water via a hydroelectric generator at profitable peak hours.

The cost of initiating a new technology to the energy market is often skyhigh compared to the status quo. In order to interest investors, and to access the market, a new technology needs to be proven feasible, i.e. the technical, economic and commercial potential must be analysed, hence to identify risks and opportunities. However, many products must go through a learning period before becoming market competitive. Technology learning says that the more frequently a new technology is used, or the more units produced of a product, the more cost efficient the technology or product will become. This is referred to as learning-by-doing, or the learning curve-method, which will be used to predict future cost reductions of the proposed energy storage system.

The main goal of this thesis is to determine the technical feasibility of a small-scale electrical storage system. The system will be analysed and broken into component-level, i.e. a top-down approach. The components will be identified as market available or unavailable (black-boxes), hence to estimate the system cost. A profitability analysis will be conducted of a case scenario, where the system operates as a buffer between intermittent renewables and the electricity grid. The research question is therefore: *"Can high-pressure accumulators store surplus electricity at off-peak hours for profitable regeneration at peak hours?"* and the thesis goal will be achieved after completion of the following objectives:

1) Study the electrical storage systems utilized today.

   A literature study must be conducted on the storage systems utilized today in order to detect competitive technologies of the proposed technology.

2) Identify the proposed system.

   The proposed energy storage system will be visualized and described according to a prior investigation done by the inventor and the thesis author. Also, the system components will be fully identified.

3) Determine the potential energy and power output of the system.

   The energy and power output need to be determined in various volumes in order to design a suitable system for the various consumers.

4) Determine the availability of all the components in the technology.

   A design specification, i.e. an analysis of the components will determine the product feasibility of the system. In order to achieve this objective, developers and purchasers must be contacted. Some components may need adjustments or even turn out to be patentable, thus a service feasibility of possible developers must be made.

5) Identify the consumer demands.

   Data on the electricity consumption for households is analysed via SSB.

6) Determine the investment cost.

   Determine investment costs and specific capital cost of energy for the developing of a first unit and the cost of a consumer's unit.

7) Determine the profitability.

   Look at the variations of elspot prices and determine whether the system is profitable.

8) Determine potential future cost reduction

   Estimate future cost reduction of the system using the learning curve method on the different components.

1.2 PROBLEM SOLUTION

Several methods were used in this study, which involved studying energy storage technologies, energy and power calculations, patentability study, material and component study, cost estimation, studying the yearly and hourly elprice variations, profitability analysis and future cost reduction analysis. Energy and power capacity were calculated from the laws of thermodynamics with iterations in excel. Cost estimations were based on personal communication with developers and distributors of the components. The components that were not available on the market were calculated from assumingly cost of materials and developing. Profitability was based upon a net present value analysis.

1.3 LIMITATIONS AND ASSUMPTIONS

The limitations and assumptions of the thesis is as follows:

1) A cost-benefit analysis of the proposed technology would indicate a more socioeconomically profitability than a feasibility analysis. However, this study will only focus on the cost of a system and the profitability of a system utilized at a household with local production of renewables.
2) The profitability study is limited to storing low-cost electricity for profitable regeneration to the grid at peak hours.

3) The profitability study excludes all taxes and extra charges unless the investment is proved positive.
4) Estimating learning curves for the system proved to be too time-consuming and was almost in vain. After several correspondences, none of the possible developers and manufacturers could present data of cumulative production – nor historical prices. The learning curves in this thesis are therefore based upon suggested values from literature. However, in order to cover risks and vague values, basic analysis with 7 and 20% LR of the entire system are included as recommended by Associate Professor Thomas Martinsen.

1.4 SIGNIFICANCE OF THE STUDY

If the proposed idea proves to be feasible it could be a competitor to other electrical storage systems, e.g. batteries, fuel cells, small scale CAES etc. A stand-by, rechargeable electrical power utility could yield positive social benefits for the distribution of electricity, i.e. brownouts and blackouts may be prevented. The study will give insight in the possibility of storing electrical energy in pressurized liquid for profitable regeneration. Hopefully, the thesis will determine the novelty of the idea, thus give an indication of the system patentability.

Distributors and developers, of the system components, will be identified in order to make a presentable cost estimate to future investors. Furthermore, the study will study the consumer's demand and analyse the profitability of storing surplus electricity for regeneration. Hopefully, this master`s thesis will become a technical document to aid future decisionmakers in whether to finance a prototype or not.

2 THEORETICAL BACKGROUND

In order to determine what type of storage the proposed system is, a background study on different electrical energy storage was conducted. The literature study provides information of competitors, where to utilize the proposed storage system and why it should be utilized. The study focuses on technologies for electrical storage from renewables in the Norwegian grid. However, available information on similar electrical storage concepts was rather poor since this is a “new” method of storing electricity. Also, technology learning, and how to predict future cost reduction of the proposed system, was studied in order to use the learning curve method in the thesis. The literature study was based on journals, reports, books, lecture slides, web pages and personal communication.

2.1 ELECTRICAL STORAGE SYSTEMS

The topic of this thesis is electrical storage hence will this chapter provide some theoretical background of different electrical storage systems utilized today. Electrical storage systems are widely covered in books, scientific journals and updated web pages. *Enova, Innovation Norway, Norwegian Resources and Energy Directorate (NVE)* and *The Research Council of Norway* have made an online resource for information on renewable energy called *Fornybar*. Similar is the homepage of *Centre for renewable energy (SFFE).* Both web pages cover topics regarding electrical storage systems, but are very elementary and poorly updated. More updated is the online version of the Norwegian weekly technological magazine, *www.tu.no*. However, the most updated news was found at the homepage of energy storage developers, universities and research facilities. Other helpful reviews were found in journals via *Renewable Energy* and *Renewable and Sustainable Energy Reviews* published by *Elsevier*.

2.1.1 BACKGROUND

Most of renewable energy supplies are weather based, i.e. wind turbines do not generate power without wind, PV works poorly during a cloudy day and a hydro electrical plant are dependent on rainfall. Electricity generation from intermittent energy sources is as much reliable as the weather is reliable. However, areas with natural geographical advantages for hydropower can accumulate GWs of power in large reservoirs during off-peak hours. Other areas, e.g. mainland Europe, does not have the geographical advantages for accumulating energy and are more dependent on wind and solar as renewable energy supply.

The world cumulative installed PV in 2011 was 70 GW raising up from 9 GW in 2007 and are estimated to reach 343 GW by policy-driven development in 2016 (EPIA, 2012). Germany, the largest PV installer in the world, had reached astonishing 32.7 GWp by January 2013 (Bundesnetzagentur, 2013). As for wind power, the global installed capacity has increased to 282 GW in 2012 compared to 31 GW in 2002 (GWEC, 2013). These somewhat unreliable renewable sources are in need of stand-by power or energy storage systems in order to increase the flexibility and to enhance the power quality of the grid. Electricity generated at off-peak hours often becomes excessive with a low profitability. Vice versa, a low generation at peak hours can cause an increased equilibrium of supply and demand, i.e. the cost of electricity increase whilst income is lost because of a low generation.

2.1.2 OVERVIEW OF DIFFERENT ELECTRICAL ENERGY STORAGE SYSTEMS

There are several technologies utilized for electrical storage. Figure 2.1 shows that they are categorized as four types: Electrical, magnetic, mechanical and chemical (Zach et al., 2012). The investigated technology in this study relates to indirect storage systems and the following sub-sections gives an overview of indirect storage systems utilized today.

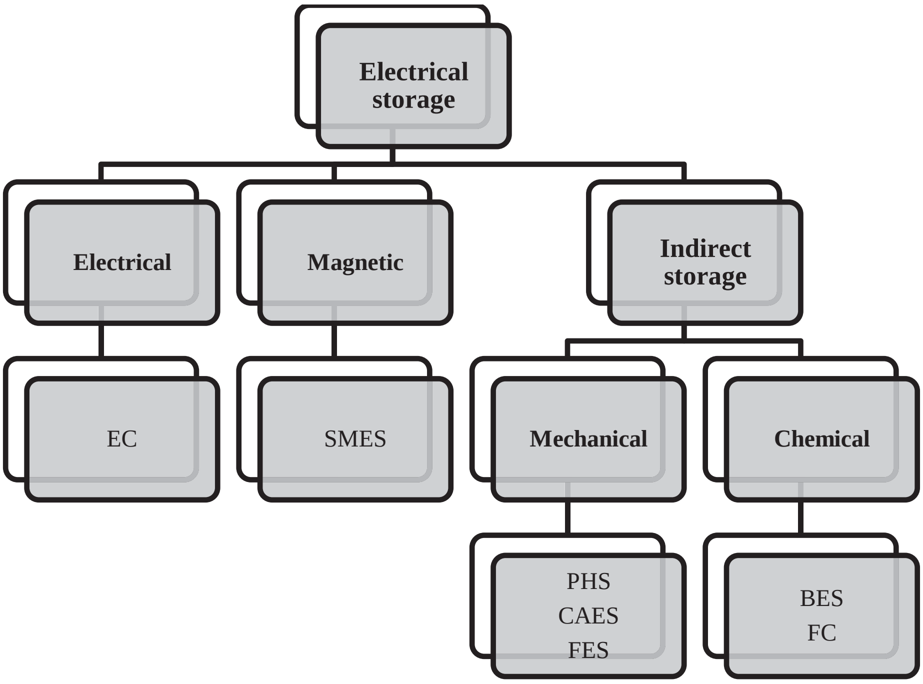

Figure 2.1: Different electrical storage systems

PUMPED HYDROPOWER STORAGE (PHS)

Storing large amounts of energy in elevated hydropower reservoirs is the most efficient energy storage system today, both technological and economic (Valmot, 2009, Enova et al., 2013c). PHS "recharges" the reservoirs more frequently hence the power plant will be more independent upon the amount of precipitation. The concept of PHS is basically to install a reversible turbine or pump at the lower reservoir, as seen in Figure 2.2. The turbine generates electricity at peak hours, whilst refilling the elevated reservoir at excess power.

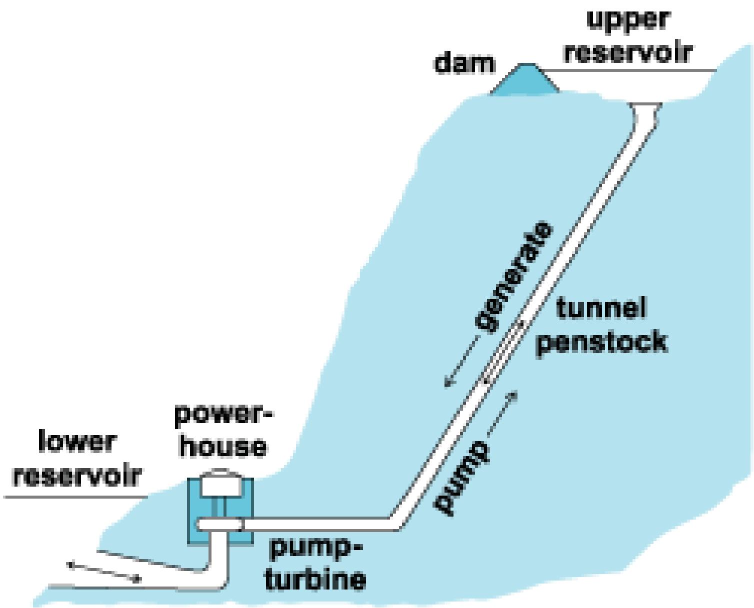

Figure 2.2: Pumped hydro storage (McGraw-Hill Science & Technology Encyclopedia, 2013)

COMPRESSED AIR ENERGY STORAGE (CAES)

CAES relates to PSH, but in this case power is generated by gas turbines. The concept is simple where air is compressed and accumulated in, e.g. underground mines (Figure 2.3), tanks or subsea inflatable bags (The University of Nottingham, 2010, Crotogino et al., 2001). As the air is compressed it generates heat and expands thus giving either a diabatic or isothermal process that utilizes energy. Utility scale CAES, e.g. *Huntorf* in Germany and *McIntosh* in USA, is based upon diabatic process, which requires additional gas firing due to heat loss into the atmosphere and is therefore not entirely independent of fossil fuels (E.ON ERC, 2013). A more eco-friendly approach is the adiabatic, which is a process where no heat dissipates from the system thus generating power by the expansion from the compression. Adiabatic storage systems is still under investigation, but an utility scale project called *ADELE* is expected to commence in Germany 2013 (RWE, 2013).

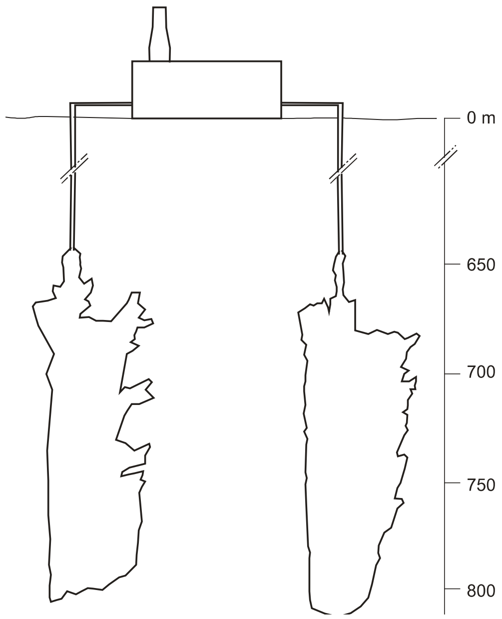

Figure 2.3: CAES plant with underground caverns (Crotogino et al., 2001)

BATTERY ENERGY STORAGE (BES)

Commonly used in portable electronics and plug-in vehicles, lithium-ion batteries (Figure 2.4) are the most efficient batteries today regarding size vs. storage capability, with 110 to 160 Wh/kg and 10 min charge time (Enova et al., 2013a, Buchmann, 2013). However, fast rechargeable flow batteries, e.g. vanadium redox batteries, are more suitable for grid reliability and are currently used at wind power plants in Austria, USA and Japan (Enova et al., 2013a).

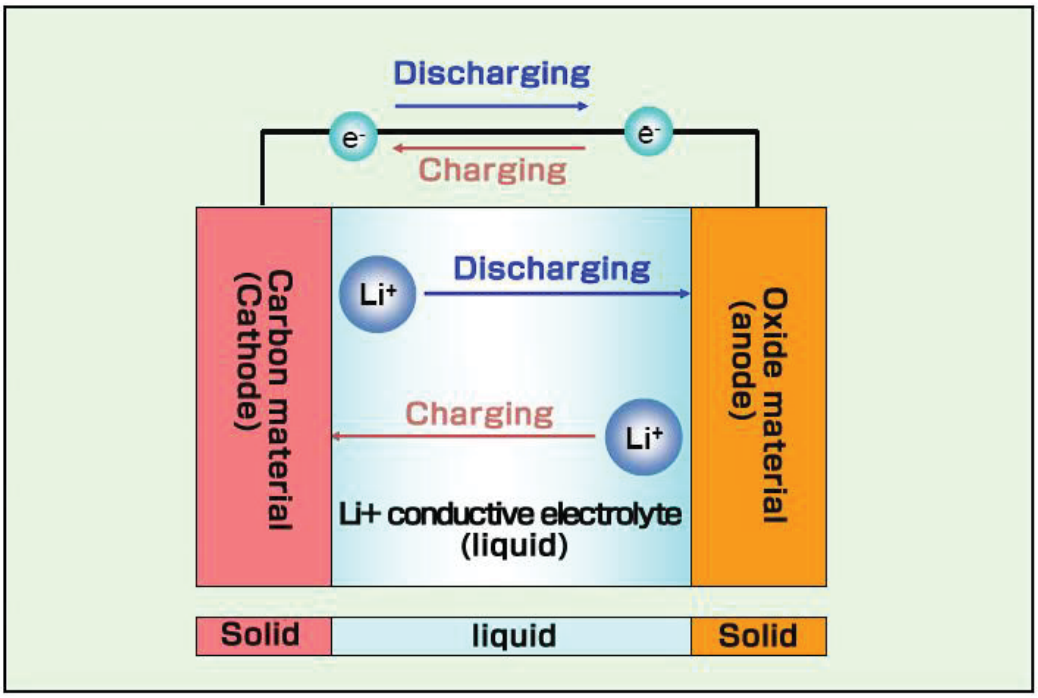

Figure 2.4: Lithium-ion battery (NEDO, 2013)

FUEL CELLS (FC) AND HYDROGEN

FC, also used in portable electronics, vehicles and grid reliability have a lower efficiency than batteries with an output range from 1 kW to 2 MW (Barbir, 2005, Spiegel, 2007). As seen in Figure 2.5, FCs convert chemical energy from fuels directly into electricity. FCs are distinguished from batteries as they produce electricity for as long as the fuel and oxidant are supplied (Spiegel, 2007). The primarily reactants for fuel cells are hydrogen and oxygen, but also natural gas, methanol and ammonia can be used (Barbir, 2005, Enova et al., 2013b).

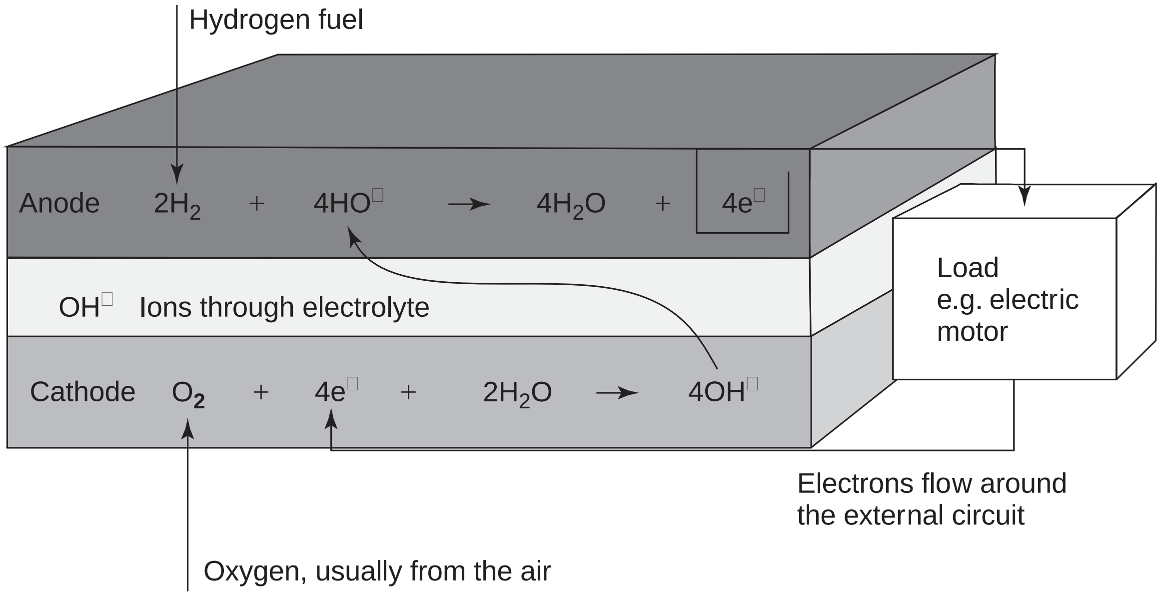

Figure 2.5: Fuel Cell (Larminie and Dicks, 2003)

FLYWHEEL ENERGY STORAGE (FES)

FES is basically a rotating wheel connected to a motor as seen in Figure 2.6. The wheel is accelerated by, e.g. surplus power from the grid, where electricity is stored as rotating energy before transferred back to the system (Beacon Power, 2013, SFFE, 2011). FES from *Beacon Power* has the capacity of storing and delivering 25 kWh and can be used to balance the grid frequency due to the fast response time (Bolund et al., 2007, Beacon Power, 2013).

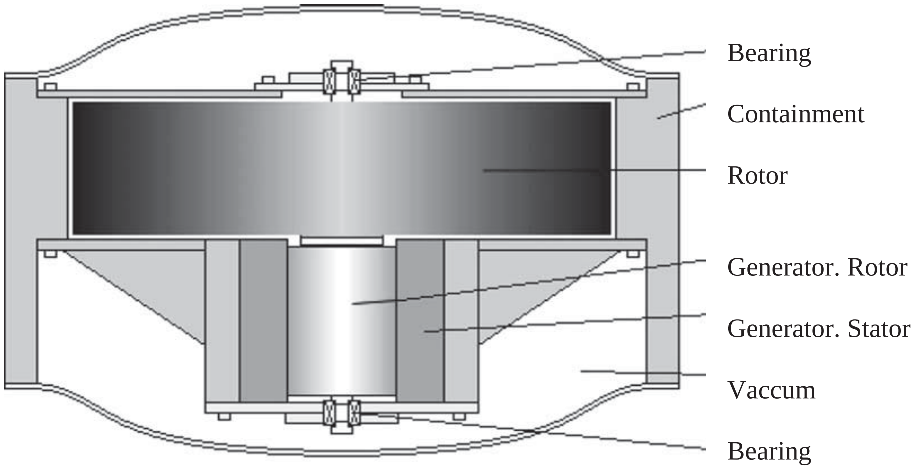

Figure 2.6: Flywheel (Bolund et al., 2007)

2.1.3 STORAGE POWER AND ENERGY

There are two values to consider in an electrical storage system, namely power and energy. The power (W) determines at what rate the storage system can deliver energy, i.e. if a load works at the rate of 3 kW, the storage system ought to be able to deliver 3 kW. Energy (Wh) determines the duration of the energy delivered at a certain power rate, i.e. if a storage system discharges a power rate of 3 kW and has an energy capacity of 100 kWh, it can deliver that power rate for 33,3 hours before recharging. The energy and power capacity differs among the utilized storage systems as shown in Figure 2.7 where PHS scores highest on both duration and power.

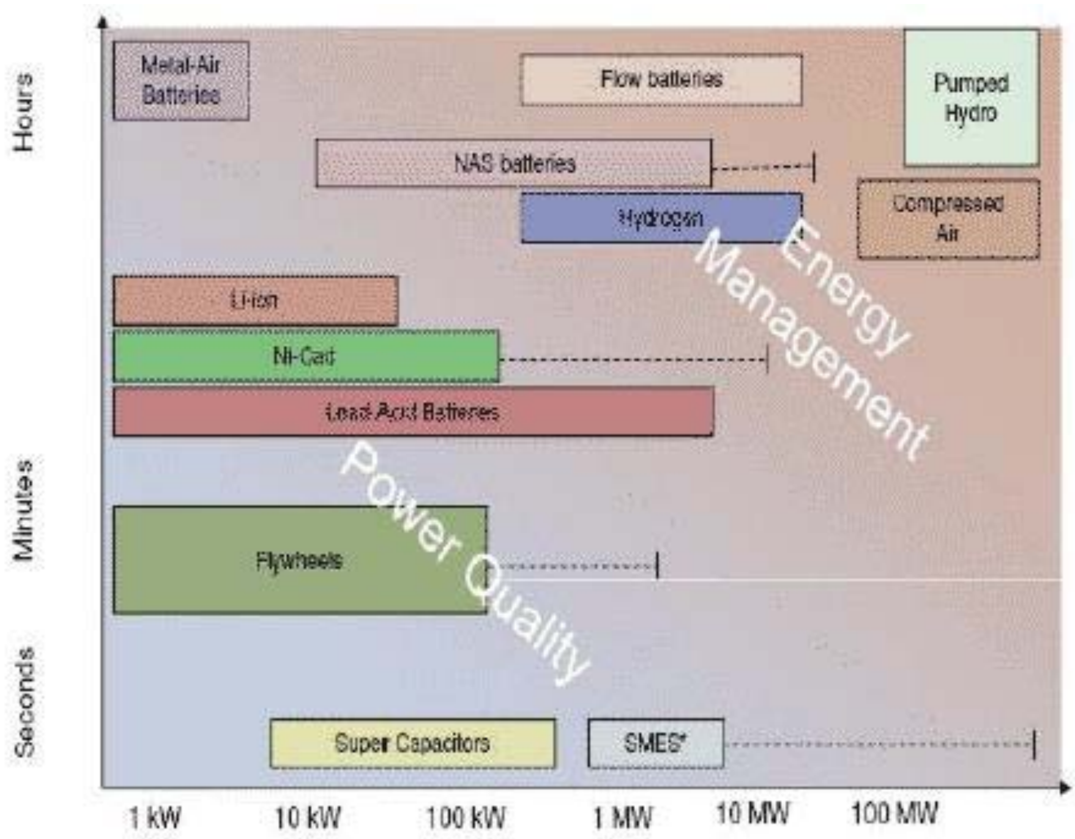

Figure 2.7: Storage capacity/ discharge time for energy storage systems (The Scottish Government, 2010)

2.1.4 SYSTEM EFFICIENCY

Losses occure when energy is transferred from one state to another. The energy that is put into an energy storage system cannot be regenerated at 100% as shown in Figure 2.8. The ratio between input and output energy determines the efficiency (η) of the system and is expressed as:

$$\eta = \frac{E_{out}}{E_{in}}$$

The efficiency of the different storage systems ranges from 40 to 85% for BES and FCs, 70 to 80% for CAES, 75 to 80% for PHS and 90% for FES (Eyer and Corey, 2010, The Scottish Government, 2010).

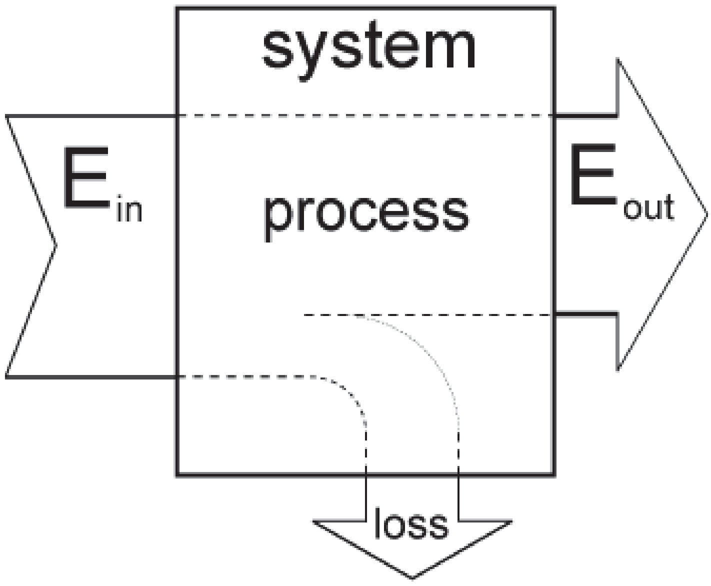

Figure 2.8: Sankey diagram of energy process (Zurex, 2013)

2.1.5 ADVANTAGES AND DISADVANTAGES OF ELECTRICAL STORAGE SYSTEMS

The utilized energy storage systems differ from one another in many terms, e.g. size, efficiency and special geographical site requirements. PHS has high energy and power capacity and can be used for bulk storage, i.e. storing large amount of energy, and discharge it with high power capacity. Also, CAES has a high energy capacity, but lower power capacity compared to PHS. Both PHS and CAES demand large and special geographical locations for utilization. BES, FES and FC are smaller in size than PHS and CAES, hence lower capacity. However, with exception of FC, BES and FES have high efficiency. Table 2.1 is based on values from the University of Oregon (2013), The Scottish Government (2010) and Larminie and Dicks (2003) and summarizes some of the advantages and disadvantages of the electrical storage systems.

Table 2.1: Advantages and disadvantages of utilized electrical storage systems

System	Capacity (MWh)	Power (MW)	Capital cost (NOK/kW)	Efficiency	Advantages	Disadvantages
PHS	< 1000	<5000	5000-20000	70-80%	Mature technology High energy and power capacity Low Cost	Demands special geographical site requirements
CAES	<1000	<300	5000-6000	70-80%	Mature technology High energy and power capacity Low cost	Gas firing Somewhat in need of special geographical site requirements
BES	<34	<34	1000-30000	80-99%	High power and energy density High efficiency Quiet operation Portable	High production cost
FC	<10	<3	10000-20000	40-60%	High power density Quiet operation	Low efficiency High production costs Requires fuel supply
FES	<10	<20	5000-7000	80-90%	High power	Low energy density Immature technology

2.2 TECHNOLOGY LEARNING

The book *"Technological Learning in the Energy Sector"* by Junginger et al. (2010) and the lecture slides and article *"Technology learning in a small open economy"* by Martinsen (2011) explains the fundamentals of applying technology learning in energy systems. However, several articles and books proved to be essential in order to gain a deeper understanding on the topic.

In the article *"Learning rates for energy technology"*, McDonald and Schrattenholzer (2000) propose a basis for using learning rates of energy conversion technologies for energy models. The book *"Cost Estimator's Reference Manual"* by Stewart et al. (1995), only found via web pages, estimates learning curves for different products (Federation of American Scientists, 2013). In fact, most of the learning curves in this thesis are based upon the estimations of Stewart et al. Also, the article *"Use and limitations of learning curves for energy technology policy"*, by Ferioli et al. (2009) who proposed that cumulative learning from single components can give an aggregated learning curve for the overall technology and introduced a component-learning hypothesis.

2.2.1 BACKGROUND

Renewable energy technologies often have high capital cost due to their niche markets. In the competitive market, new and innovative energy technologies often portray high costs and risks more evident than a beneficial harvest. R&D, testing, sertifications, adjustement of production equipment and inefficient start-up production demand a large amount of seed money thus often convincing decision-makers to keep the status quo. However, once a new technology is implemented in the market and the production increases, costs and performance of successive units will be far more efficient due to the experience gained from the first unit. This phenomenon is referred to as technology learning, i.e. the concept of learning either by doing or using (Wene, 2011, Arrow, 1962, Junginger et al., 2010). The effect of production related learning was discovered by T.P. Wright, when in 1936 developed the learning curve model after he detected that unit costs declined at a constant rate for every doubling of cumulative production of airframes (Junginger et al., 2010, Wright, 1936). Compared to Wright's concept, where less labour hours determined the declining costs, modern use often refers to the term experience curves, extending the study also to include improvements in, e.g. production technology, process of materials, manufacturing and even business strategies (Bye et al., 2002, Junginger et al., 2010). The learning curve concept predicts future cost reduction and competiveness of new technologies and is today frequently used in governmental energy strategies for a future low-carbon society (Bye et al., 2002, IEA, 2000). In other words technology learning, combined with governmental incentives and public measures, rises a bright harvest moon as an impetus for the penetration of renewables.

2.2.2 THE LEARNING CURVE METHOD

The more time spent on making a product, the more experience is gained thus making the product more cost efficient. A learning, or experience curve, shows the cost development of, e.g. the cumulative production of a technology. It is often displayed as a declining curve with cost per unit on the y-axis and cumulative production on the x-axis as shown in Figure 2.9 (Wright, 1936).

The learning curve can be expressed as:

$$C(x_t) = C_0 \times X_t^{\ b}$$

where:

$C(x_t)$ = *unit cost or price at* X_t

C_0 = *cost of the first unit produced or the starting point of the analysis*

X_t = *cumulative production or number of units produced*

b = *the experience parameter*

In order to estimate future cost reduction, as in this case, the starting point should be the present cumulative production (Ferioli et al., 2009). The unit cost drops for every redoubling of cumulative production and the progress ratio (PR), at which it declines, shows the relative cost reduction for each redoubling:

$$PR = 2^b$$

The learning rate (LR) is expressed as:

$$LR = 1 - 2^b$$

For example, if LR is 40%, the costs will decrease with 40% for each doubling of cumulative production.

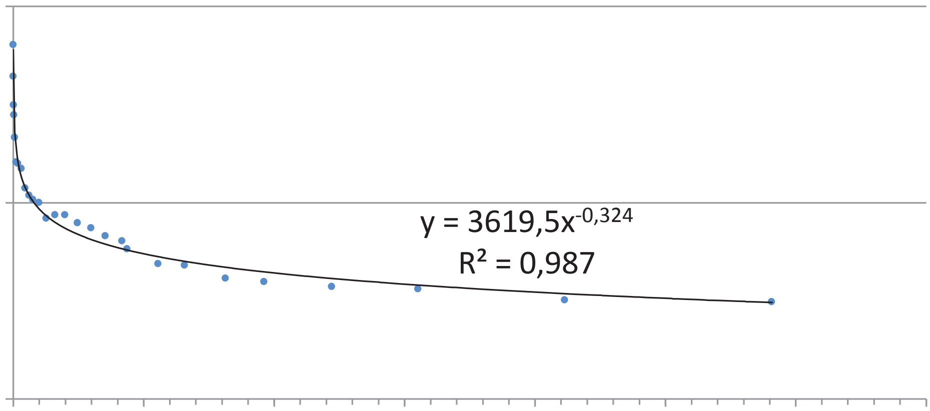

Figure 2.9: A typical learning curve where PR is 79,9% and LR is 20,1% (Martinsen, 2012)

Many analysis have been undertaken to find a theoretical approach to the phenomenon of learning-by-doing, whereof none agree upon the explanation of the cost-production relation (Ferioli et al., 2009). However, in the article *"Use and limitation of learning curves for energy technology policy"*, Ferioli et al. (2009) suggest a new approach determining experience curves as the function of learning of single or a few components only – the component-learning method:

$$C(x_t) = C_1 + C_2 + C_3 \ldots + C_n$$

3 THE PROPOSED ELECTRICAL STORAGE SYSTEM

The data used in this study were collected from literature and personal correspondence with distributors and developers. Costs and materials were partly identified together with the inventor, Casper Kielland. The energy capacity in the accumulator was partly based on precalculations done by my former classmate, Håkon Gabrielsen. *Excel* was used for calculations, iterations tables and figures. Also, autocad was used for designing diagrams of the proposed energy storage.

3.1 THE CONCEPT

The proposed idea can be described as a stationary, or mobile, hydropneumatic energy storage system for storing excess electrical power from local renewables during off-peak hours. Later, at peak hours the storage regenerates power for either local consumption or profitably grid supply.

Traditional hydropower generates electricity from either the kinetic energy of running water or the potential energy of water stored in elevated reservoirs. In this case, the power of compressed air will force the water to the turbine thus the hydraulic head at, e.g. 700 bar, compensates for a height of 7000 metres. The concept is shown in Figure 3.1. A fluid, preferably water is pumped (4) from an atmospheric pressure reservoir (3) from excess electricity from local renewables, or the grid (6, 7 and 8). The water is pumped into a high-pressure accumulator (1) pre-charged with a compressible gas, preferably ambient air. As the water fills the accumulator, the air will be compressed thus creating potential energy on the pressurized water. Subsequently, the water is discharged from the accumulator flowing through a hydroelectric generator (2 and 5) that generates electricity to the grid. Finally, the water is collected back into the atmospheric pressure reservoir and the system is ready to be recharged.

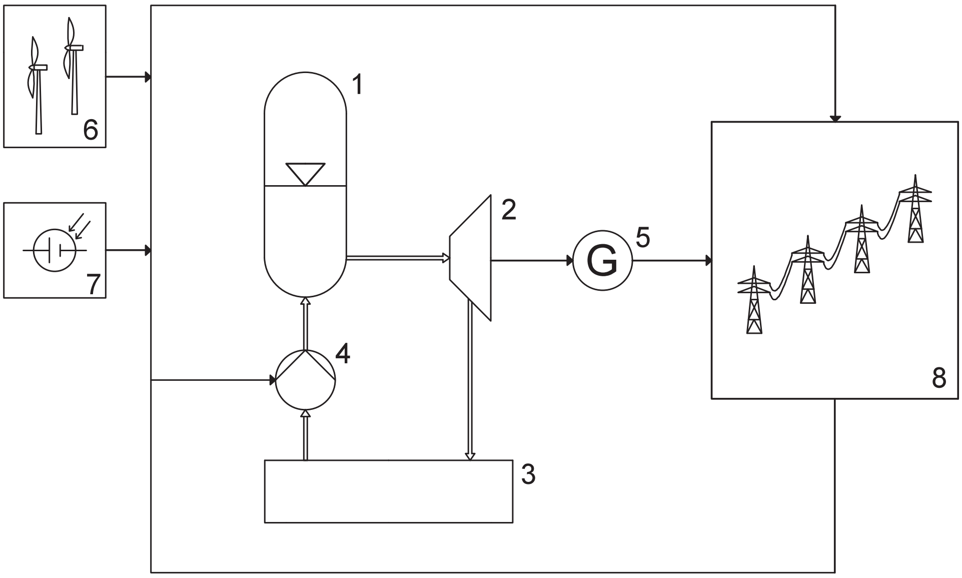

Figure 3.1: Simplified diagram of the proposed energy storage system

3.2 PATENTABILITY

Storing a pressurized hydraulic liquid in accumulators is not a new technology. It is commonly used in hydraulic systems where liquid is pressurized for mechanical operations. Although, these accumulators are small and intended for a rapid charge/discharge to boost the hydraulic power to, e.g. cranes, bridges or automotive brake systems. Also, many systems, utilizing renewables for the accumulation of hydraulic liquid and subsequently driving a generator, can be found via patent searching. Assumingly, in the case of patentability, it is not the technology, but rather the system and the unavailable components (the system's black boxes) that are novel.

3.3 ENERGY AND POWER CAPACITY

3.3.1 ENERGY

The energy stored in the accumulator relates to pneumatics and the laws of thermodynamics. Assuming that the air will behave as an ideal gas and that the compression is slow enough for the heat to extract to the surroundings, i.e. an isothermal process, following calculations will determine the energy of the proposed energy storage.

The work performed by gas can be written as:

$$W_{A \rightarrow B} = \int_{VA}^{VB} \rho dV = \int_{VA}^{VB} \frac{nRT}{V}\, \partial V = nRT \int_{VA}^{VB} \frac{1}{V}\, \partial V = nRT ln \frac{VB}{VA}$$

Where:

W = work = Joules

p = pressure

V = volume

n = number of moles

R = the gas constant = 8,314 J/mol

T = temperature

Using the ideal gas law:

$$pV = nRT$$

In an isothermal process nRT become constant hence:

$$P_B V_B = P_A V_A$$

Thus:

$$W = P_A V_A \, ln \frac{VB}{VA}$$

The final answer, in Joules, is negative because the gas is being worked upon. In order to find kWh the answer is to be divided by 3 600 000 J:

$$kWh = \frac{W}{3{,}6 \times 10^6 \, J}$$

Finding the pre-pressure (P_A) can be determined by iterations, e.g. if P_B is set to 700 bar, iterations in excel indicates P_A to be 250 bar. Pre charging the accumulator with less or more pressure will decrease the energy capacity.

The efficiency of the pump will determine the efficiency of the system. However, assuming the water to be pressurized at no cost, the storage efficiency is set to zero. Net output efficiency is determined by turbine efficiency:

$$\eta = \frac{W_{input}}{W_{output}} \times 100\%$$

3.3.2 POWER

The amount of power in the energy storage depends upon the time it takes to empty the accumulator. Plotting operating pressure and accumulator volume into the ideal gas law equation will estimate the energy of that specific volume and pressure. To determine the power, the kWh is divided by the amount of hours the storage is set to generate before emptied, i.e. an interval of many hours of utilization generates less power than an interval of just a few hours:

$$kW = \frac{kWh}{h_{interval}}$$

3.4 COMPONENTS

Figure 3.2 shows the technology separated from the overall system. The main components of the technology are accumulator (1), turbine (2), generator (5), atmospheric reservoar (3) and pump (4). However, all the main components must be connected by pipes and fittings, which can operate at a pressure up to 1000 bar. Operating at this high pressure, sensors must be installed on the system hence to monitor both pressure and temperature. Also, two safety valves on manifolds are needed to secure relief if the overpressure should exceed 5 and 10%. A check valve is needed between the pump and accumulator. The speed of the water hitting the turbine wheel is proportional to the square root of the pressure in the accumulator and an actuated spear valve controls the amount of water flowing. A microcontroller automates the system and finally, a frequency converter controls the speed of the generator and enables power exchange with the grid.

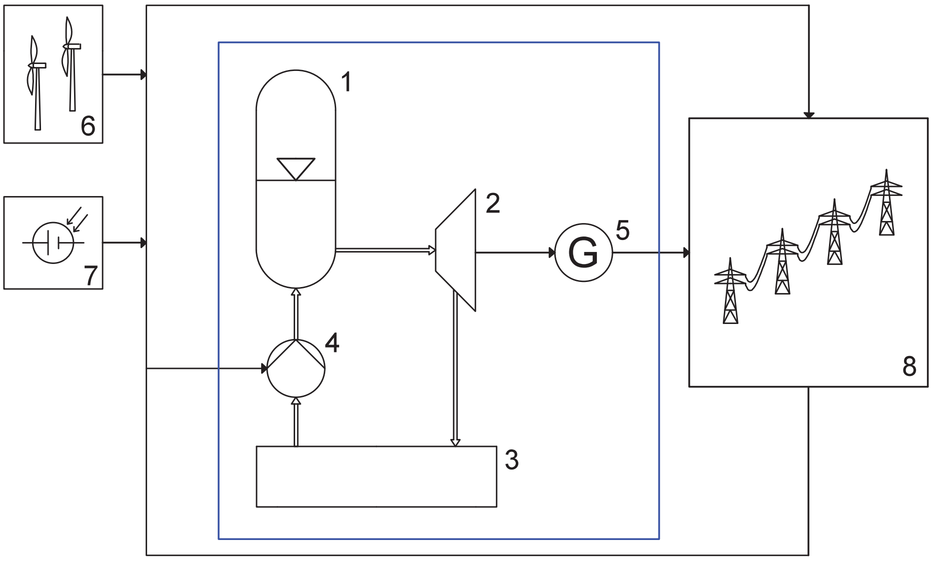

Figure 3.2: The proposed energy storage system with main components

3.4.1 MARKET AVAILABLE COMPONENTS

Searching web pages and contacting manufacturers indicated that most of the components are available on the market.

Pumps used in high-pressure hydraulic systems is preferably radial piston pumps (KLM Technology Group, 2012). In this case the pump flow rate (lpm) needs to be kept at a low level to achieve an isothermal compression of the gas. *Hawe Hydraulik* can deliver piston pumps of flow rates, depending of number of cylinders, from 12,7 lpm down to 0,3 lpm for a 700 bar system pressure. *Bieri, Bosch* and *Dynex* also have piston pumps for up to 700 bar from 4,5 lpm to 0,67 lpm. The cost of the pump will be high due to corrosiveness and low viscosity of water, which is preferred in the proposed energy storage system.

ABB can deliver a generator for the system (Dyrendahl, 2012). The generator size has to match the size of the turbine, i.e., the generator must be able to drive the lowest rpm to the highest rpm of the turbine wheel.

The atmospheric reservoir between turbine outlet and pump inlet can be fabricated in plastic or stainless steel at any mechanical- or fabrication workshop.

Valves, actuators, pipes and couplings can be purchased from either *Proserv* or *Haskel*.

3.4.2 THE SYSTEM'S BLACK BOXES

The market availability study indicated that there were two black boxes, or components unavailable, that need to be developed, namely accumulator and turbine.

ACCUMULATOR

Accumulators are containers in which energy is stored by keeping an incompressible fluid under pressure by, e.g. spring, weight or compressed gas. They are commonly used in hydraulic systems giving power boost to temporary demands in cranes, lifts and braking system, or to improve the performance of wind turbines (Casey, 2009, Hydroll, 2013, OilAir Hydraulics, 2005).

There are three types of accumulators to consider for the proposed energy storage system: Light-weighted open composite accumulator, bladder accumulator and piston accumulator. Cross-sectional views of different accumulator types are shown in Figure 3.3.

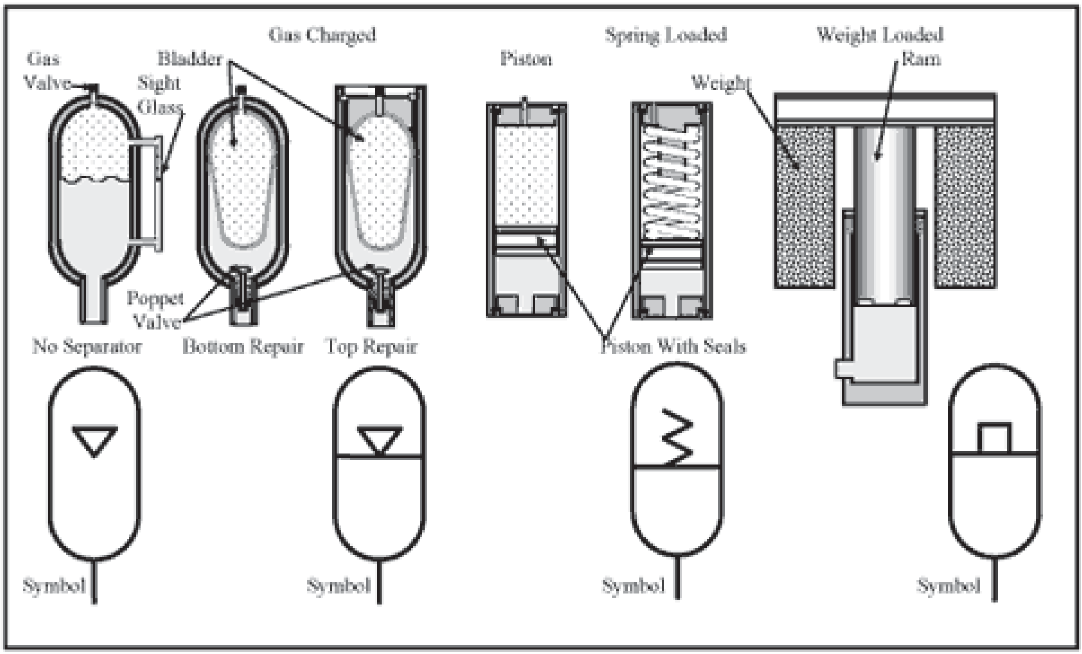

Figure 3.3: Different accumulator types (Hydraulics & Pneumatics, 2007)

In an open accumulator, air and water will intermix and only be separated by a compressed-air cushion similar to a hydroelectric surge tank. Both of the latter are hydro-pneumatic accumulators where gas and liquid, typically nitrogen and hydraulic oil, are separated by either a bladder or a piston (Casey, 2009). The bladder type is used for rapid charge/discharge of fluid with a gas compression ratio of 4:1, whilst the piston tolerates higher operating pressure, has a better size optimization ability, and has a gas compression ratio of 10:1 (Hydac, 2013, Hydroll, 2013).

Available production equipment is supposedly the main challenge producing large-scale accumulators. The cost of developing a large-scale, high-pressure accumulator was based on material and volume of market available accumulators. Today, open accumulators range to approx. 690 bar and volumes up to 1000 liters, Pressure Equipment Directive (PED) approved. Contacting several developers proved that *Hexagon* can develop high-pressure composite accumulators for 900.500 NOK, but the costs for developing the first unit would reach 90 million NOK (Häberli, 2013). Bladder accumulators at 690 bar are manufactured by *Hydac* and *Olaer* with size ranging from 1 to 54 litres PED approved. A stainless accumulator for 690 bar and 1 m^3 would roughly be 10 million NOK (Nyborg, 2013, Virrankoski, 2013).

The input cost of the analysis was estimated from correspondence with the developers and is shown in Table 3.1 to 3.3. The cost per volume is not fully linear and decreases with approx. 30% per doubling of accumulator size. However, costs of bladder and piston used in the result section were based upon accumulators of 1 m^3 in modules. The module solution will appearantly give the best efficiency of both bladder and piston and will be easier and more cost-efficient to transport (Virrankoski, 2013, Nyborg, 2013).

Table 3.1: Cost estimation of undeveloped large-scale bladder accumulator in NOK

Pressure (bar)	**Volume** (litres)	**Unit cost**	**Cost water coating**	**Cost of engineering**	**Total cost first units**
330	1 000	51 074	127 686	4 000 000	4 127 686
330	3 000	108 424	271 060	4 000 000	4 271 060
330	6 000	174 338	435 844	4 000 000	4 435 844
480	1 000	72 963	182 408	4 500 000	4 682 408
480	3 000	154 892	387 229	4 500 000	4 887 229
480	6 000	249 054	622 635	4 500 000	5 122 635
690	1 000	291 853	729 633	5 000 000	5 729 633
690	3 000	619 566	1 548 916	5 000 000	6 548 916
690	6 000	996 216	2 490 540	5 000 000	7 490 540

Table 3.2: Cost estimation of undeveloped large-scale piston accumulator in NOK

Pressure (bar)	**Volume** (litres)	**Unit cost**	**Cost water coating**	**Cost of engineering**	**Total cost first unit**
300	1 000	102 149	153 223	4 000 000	4 255 371
300	3 000	216 848	325 272	4 000 000	4 542 120
300	6 000	348 676	523 013	4 000 000	4 871 689
415	1 000	124 038	186 056	4 000 000	4 310 094
415	3 000	263 316	394 973	4 000 000	4 658 289
415	6 000	423 392	635 088	4 000 000	5 058 479
690	1 000	583 706	875 559	4 000 000	5 459 265
690	3 000	1 239 132	1 858 699	4 000 000	7 097 831
690	6 000	1 992 432	2 988 648	4 000 000	8 981 080

Table 3.3: Cost estimation of undeveloped large-scale open composite accumulator in NOK

Pressure (bar)	**Volume** (litres)	**Unit cost**	**Cost of engineering**	**Total cost first unit**
700	6 000	900000	87000000	87900000

TURBINE

Hydro turbines come in different types and are designed for low-head, medium-head or high-head (Paish, 2002). In this case, the air-pressurized water in the accumulator will enter the turbine at a high pressure, i.e. a high-head impulse turbine is required. Pelton, Cross-flow, Turgo and Multi-jet Pelton are all impulse turbines, i.e. the velocity of the water hits the turbine wheel instead of flowing through it (Paish, 2002, U.S. Departement of Energy, 2011). Most suitable for this technology is assumingly a pelton or turgo with one jet as seen in Figure 3.4 and 3.5.

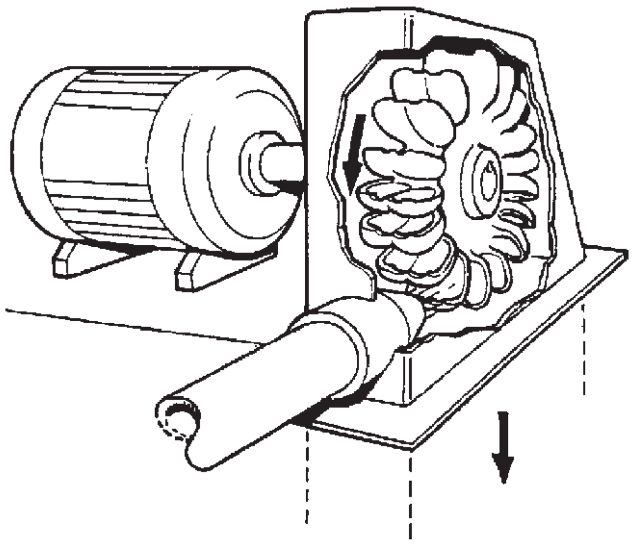

Figure 3.4: Pelton turbine (Paish, 2002)

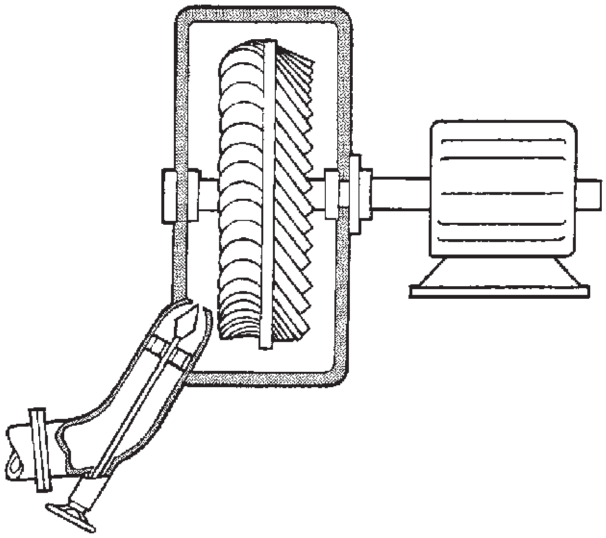

Figure 3.5: Turgo Turbine (Paish, 2002)

The turbine size must be designed to what determines the system to be most cost efficient – constant flow, constant moment or constant power. According to Morten Hansen (2013), at Rainpower, flow is the highest cost driver. Although in the case of the proposed storage system, Hansen expects the cost of production equipment to be the main concern. He estimates that a prototype could be made in 800 to 2000 hours and at material costs of 2000 to 3000 NOK/kg. An assumption weight of approx. 150 kg would be "normal" for this design.

3.5 TARGET GROUP

The target group is local distributors of intermittent renewables and groups who are in need of reliable stand-by emergency power, e.g. households, cabins, small communities, electricity distributors, the army, remote science facilities, refugee camps, telecommunication companies etc. Table 3.4 shows the energy and power demand of various consumers or target groups.

A household, supplied only by intermittent renewables would probably need a system generating electricity for at least one day's consumption before reloading it. Also, the system ought to be designed for the capacity of storing long intervals of excess power. Applied for the use as stand-by power, the system must be designed to provide reliable power during periods of blackout, e.g. telecommunication companies in Norway is currently deciding whether to have a minimum stand-by generator of six hours or three days at every tele-com base station (Blaker, 2013, Zachariassen, 2012). Data from *SSB, Telenor* and *Norwegian Centre for Transport Research* was used to determine the consumption of the intended target groups.

Table 3.4: Energy- and power consumption of various target groups

Target group	**Energy baseload demand *(kWh/day)***	**Max power demand *(kW)***	**Source**
Households	37,5	9	(SSB, 2013, Enøk Norge, s.a.)
Cabin	4,5	3	(Dybedal and Farstad, 2012, SSB, 2013)
Tele-com base station	27,4	0,45/fan	(Telenor, 2012, Dantherm, s.a.)
Household in developing countries	0,5	x	(Sandanger, 2011)

3.6 COST AND PROFITABILITY

The cost of the system was determined by the cost of components and the estimated costs of development. The investment cost of a first unit is high because of development, production equipment, engineering and certifications. In this study, two cost estimations are presented. The first cost analysis aims at the system developer's cost, including cost of engineering of the unavailable components. The second cost analysis presents a cost estimation of what a potential target group would have to pay for the system, i.e. engineering and developing cost has been excluded.

The amortizatition factor (a) for the capital cost is:

$$a = \frac{r(1+r)^n}{(1+r)^n - 1}$$

Where:

r = discount rate

n = lifetime expectancy

The capital costs are based upon following assumptions:

Annual energy production:

43 kWh x 2 interval/day x 365 days/year = 31390 kWh/year

Discount rate:

6% (Jensen et al., 2003)

Efficiency:

90%

Lifetime expectancy:

Composite system = 20 years (Häberli, 2013)

Bladder and piston system = 15 years (Nyborg, 2013)

Amortization factor:

Composite system: 0,0872

Bladder and piston system: 0,103

The proposed electrical storage system can be utilized either as a stand-by emergency generator or as a storage system for surplus electricity from intermittent renewables. On the subject of utilizing the proposed system as a stand-by emergency generator, the profitability could be taken under the consideration of the cost of upgrading the Norwegian emergency grid. According to *Directorate for Emergency Communication (DNK)*, securing every base stations has a price tag of 1,3 billion NOK (NTB, 2013). The profitability could also be compared with the capital cost of the utilized storage systems listed in Table 2.1. A cost-benefit analysis should be done in addition to this master’s thesis in order to determine the social benefits of having the proposed storage system as national emergency generator.

The profitability of the system is based upon the case where a household is storing surplus electricity from local renewables. Instead of selling the energy at a low price during off-peak hours, the energy is stored and subsequently sold to the grid at peak hours when elprice is high. This case is set up in a scenario where the cost of storing the electricity is considered at lowest elprice, i.e. the household has the ability to sell even at off-peak hours, thus would lose that income while storing.

Off-peak and peak elprice is determined via historical prices found at *Nord Pool Spot*. Transmission charge and other charges are taken from *Agder Energi* and *Eidsiva*. However, unless the system proves to be profitable at spot price, extra charges are neglected from the survey.

The profitability is estimated by net present value (NPV). NPV is one of the most commonly used method to determine a project's profitability (Winther et al., 2007). In a NPV analysis, the present value (PV) for each year throughout the project's estimated lifetime is summarized and compared to the sum of investment (Boye and Koekebakker, 2006). The project should only be commenced if NPV is positive:

$$NPV = -CF_0 + \frac{CF_1}{1+r} + \frac{CF_2}{(1+r)^2} + \cdots \frac{CF_n}{(1+r)^n} = -CF_0 + \sum_{t=1}^{n} \frac{CF_t}{(1+r)^t}$$

Where:

CF_0 = *cash flow first year of investment*

Loans/fundings and interests are excluded (Boye and Koekebakker, 2006). Also, in this case taxes are neglected unless the system proves to be profitable.

3.7 FUTURE COST REDUCTIONS

In this thesis, the overall energy storage system is viewed as one unit and the potential future cost will be described as the sum of the assembled components.

It was very hard to get data on cumulative production and historical prices from developers and distributors. After several attempts to contact persons with knowledge on the matter, time became critically limited thus the learning rates were taken from *"Cost Estimator's Reference Manual"* by Stewart et al. (1995). Accumulator was based upon raw material (4% to 7% LR) and complex machining or punch-press operations (5% to 10% LR). Turbine was based upon raw materials and complex machine tools for new models (15% to 25% LR), and misc. components were also based on raw materials. The learning curve for the system assembly was calculated from labour hours estimated by engineers at *BLE Engineering*, who estimated that assemblying the first unit would take approx. 1000 hours (900 NOK/hour). However, after having assemblied, say 20 units, experience would be gained and the amount of hours would decrease to approx. five days (37,5 hours). The LR used for assembly was set to 20%. Finally, in addition to the individual component LRs, the overall system cost was analysed based on the 7 and 20% LR as recommended by Associate Professor Thomas Martinsen.

3.8 CASE SCENARIO

The case was based upon a household with local production of renewables, e.g. a wind turbine or PV.

3.8.1 HOUSEHOLD ENERGY DEMAND

The energy consumption of an average household is approx. 25000 kWh/year, whereas 16000 kWh is electricity (SSB, 2013). If excluding electricity for heating, which is stated by *Enøk Norge* (s.a.) to be 14400 kWh/year (although it appears that *Enøk Norge* is mixing up total energy and electricity demand), the assumingly electricity consumption of a household is set to 12000 kWh/year (Enøk Norge, s.a., SSB, 2013).

3.8.2 HOUSEHOLD POWER CONSUMPTION

In the case scenario, it is assumed that the electrical storage system can provide emergency power to the necessary consumption of a household over a 12 hours discharge interval. In order to determine the size of the system power capacity, the average consumption and power demand of a household was analysed from values given by Enøk Norge (s.a.) and shown in Table 3.5.

Supposing all of the utilities were to be utilized at the same time, the power capacity of the system would need to be approx. 20 kW. However, assuming that the system will not be utilizing any electricity for heating, and that the household will manage the consumption rationally, the power capacity can be minimized. Minimizing the power capacity would also minimize the system size, thus lower the investment cost.

Assuming the highest consumer utility to be the stove and necessary utilities, e.g. refrigerator, freezer, water heater and lighting, in coordination, the total power consumption during emergency discharge is expected to be somewhere between 3 to 4 kW.

Table 3.5: Average power demand of different household utilities

Utility	**Power (W)**
Stove	2200
Kitchen fan	75
Coffee machine	1500
Dishwasher	2000
Refrigerator	160
Deep freeze	175
Toaster	1000
Washing machine	2500
Tumble dryer	3000
Hair dryer	750
TV	100
Hifi	25
Vacuum cleaner	1000
Water heater	1000
Lighting	1080
Heating	3300

3.8.3 COST OF ELECTRICITY

The system, placed in a household is to be charged by local renewables, or grid electricity, hence the cost of charging is based upon the minimum average elprice found at *Nord Pool Spot*. As seen in Figure 3.6 to 3.8, the profitability varies greatly throughout the seasons (Nord Pool Spot, 2013). The hourly variations throughout the day show a profit of approx. 0,1 NOK/kWh. Assuming the energy storage to operate every day, the average minimum cost of energy is 0,26 NOK/kWh and average maximum is 0,33 NOK/kWh. Also, a transmission charge (set to 0,44 NOK/kWh) must be added the elprice if the household has no local production from renewables.

The elprice curves in Figure 3.6 show that the highest gap between minimum and maximum elprice, i.e. most profitable, is during spring. Winter show a minor gap, whilst summer gives minimum profit. Figure 3.7 also indicates that the daily variation in elprice is low throughout the summer.

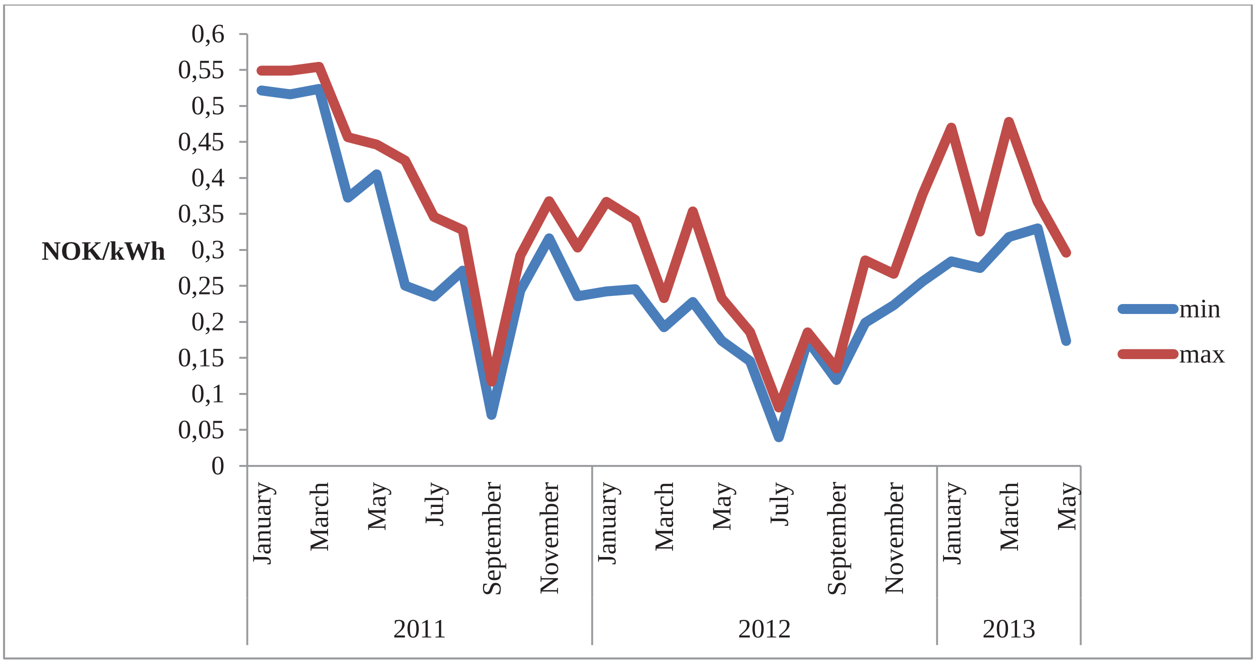

Figure 3.6: Monthly variations of spot price throughout a 3-year period showing gap between min and max elprice

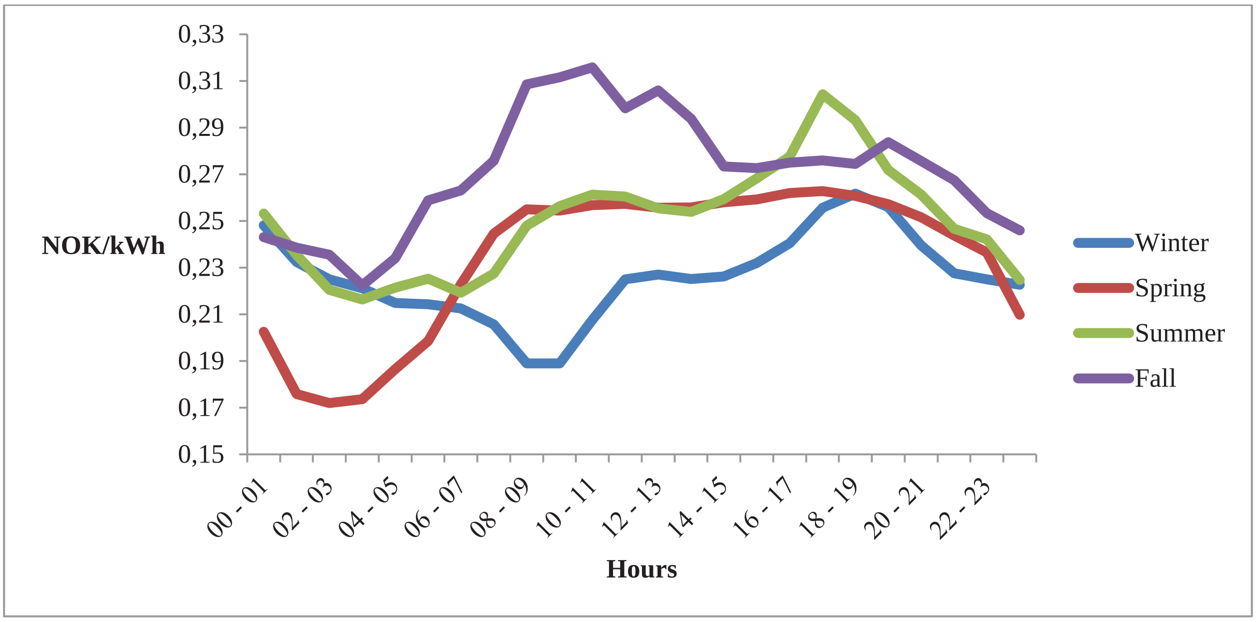

Figure 3.7: Average daily elprice of the different seasons

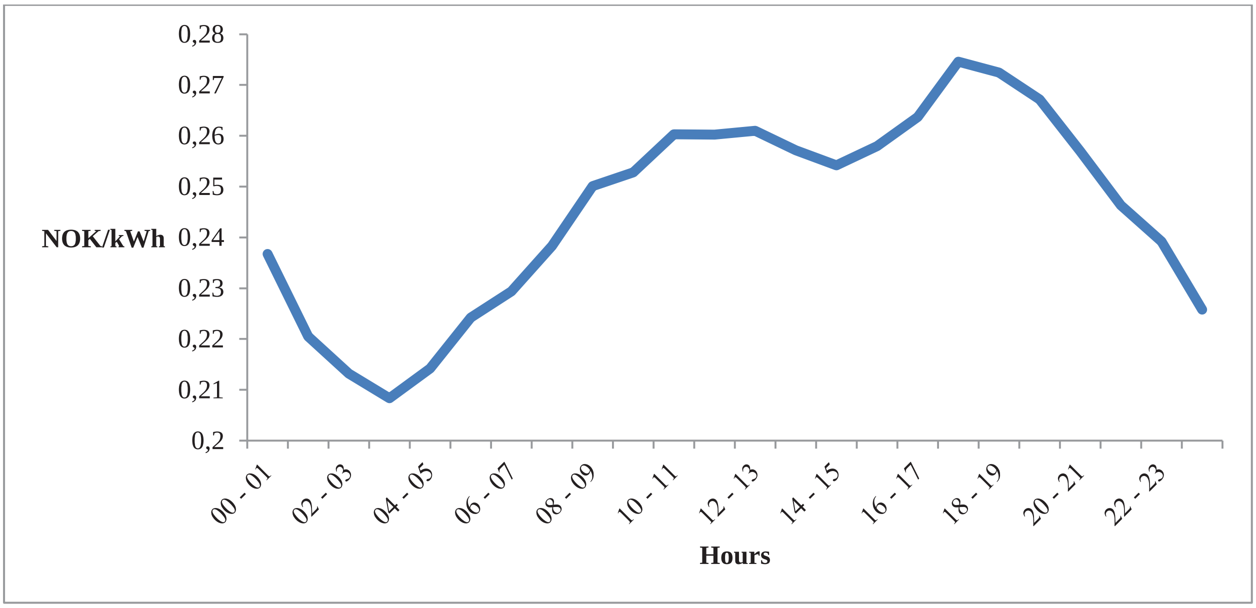

Figure 3.8: Average daily elprice throughout all seasons

4 RESULTS

4.1 ORDER OF PRESENTATION

1) Patentability analysis
2) Energy capacity analysis
3) Power capacity analysis
4) Component availability analysis
5) Cost estimate analysis
6) Profitability analysis with case-scenario
7) Potential future cost reduction analysis

4.2 PATENTABILITY ANALYSIS

Although the patentability analysis indicated that the technology is not novel, following claims could be drawn from the analysis that might ensure patentability and novelty of the proposed system:

1) A hydro-pneumatic energy storage for storing electricity from excess electricity produced locally from intermittent energy resources and/or to store low cost electricity from the grid at off peak hours, e.g. during the night, hence to regenerate the electricity locally and/or to the grid at profitable peak hours.
2) A hydro-pneumatic energy storage as stated in Claim 1 where excess or low cost electrical energy is used for driving a pump, which replace a hydraulic fluid, e.g. water, from an atmospheric reservoir or container into high-pressure accumulators at operating pressure of 200-1000 bar.
3) A hydro-pneumatic energy storage as stated in Claim 2 where the air-pressurized fluid held at 200-1000 bar subsequently is released from the accumulator through an impulse turbine.

4) A hydro-pneumatic energy storage with an impulse turbine as stated in Claim 3 where turbine is designed to operate at high head equal to a water head of 2000 to 10000 meters and to operate at flow rates as low as 1 to 50 l/min and to weigh approx. 100 to 200 kg.
5) A hydro-pneumatic energy storage as stated in Claim 4 where the turbine drives a generator for at least one day of consumption generating electricity to local consumption and/or to the grid at profitable peak hours.
6) A hydro-pneumatic energy storage as stated in Claim 5 where the fluid is reused after driving the turbine wheel, i.e. a closed loop system.

4.3 ENERGY CAPACITY ANALYSIS

The potential energy of, e.g. a 700 bar system, was found to be 7,2 kWh/m^3 accumulator and 5,1 kWh/m^3 for a 500 bar system. Figure 4.1 shows that the amount of energy is almost proportional to the operating pressure. Figure 4.2 gives the stored capacity in different accumulator volume. Looking back at Table 3.4, the analysis indicates that a 6 m^3 large accumulator, operating at 700 bar, is adequate for a household's energy demand of 38 kWh/day. However, for tele-com base station, a 700 bar system must be designed to a size >10 m^3 in order to fulfil the 3 days of required emergency power.

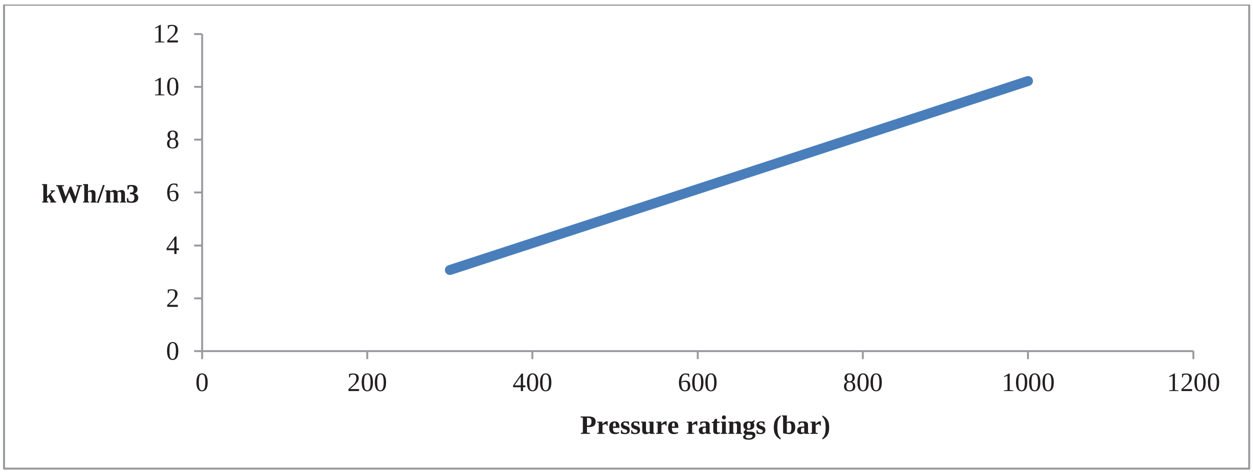

Figure 4.1: Stored energy capacity per m^3 accumulator at different pressure ratings

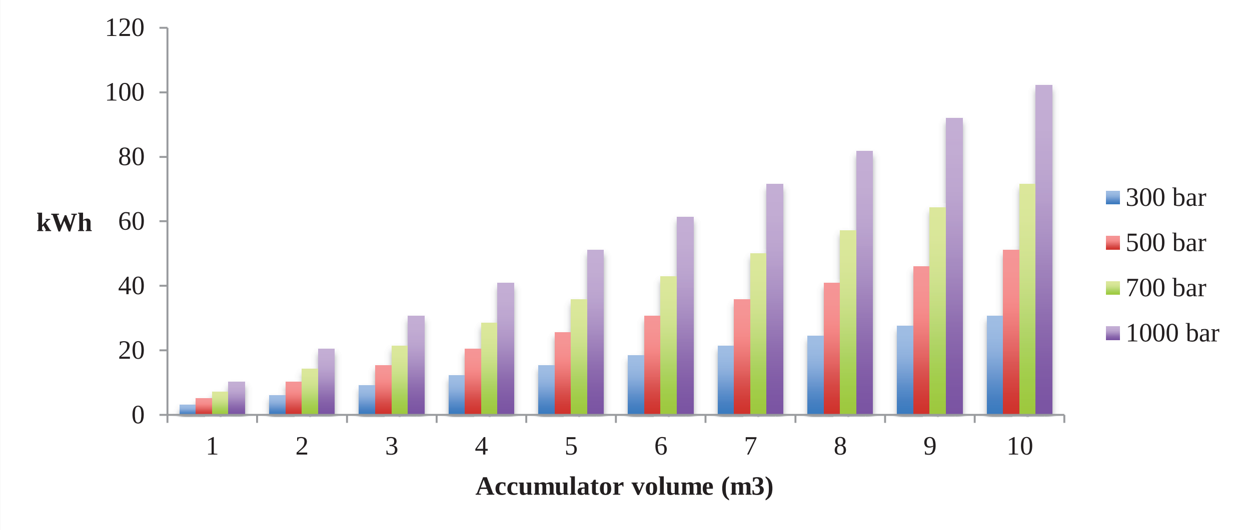

Figure 4.2: Stored energy capacity for various accumulator volumes

4.4 POWER CAPACITY ANALYSIS

Assuming that the energy storage will have a maximum charge/discharge interval of 12 hours, the power capacity will range from 0,6 kW/m^3 to 7,2 kW/m^3 for a 700 bar system, and 0,4 kW/m^3 to 5,1 kW/m^3 for a 500 bar system. Depending on hours of discharge, size and operating pressure will determine the power capacity to be adequate for the various target groups. The analysis shows that a 500 or 700 bar system should be adequate to cover the coordinated consumption of a household. The curves in Figure 4.3 show that the longer the discharge is, the lower the power is. Figure 4.4 gives an indication of what accumulator size, and pressure, the system should be designed for to gain the preferable power rating.

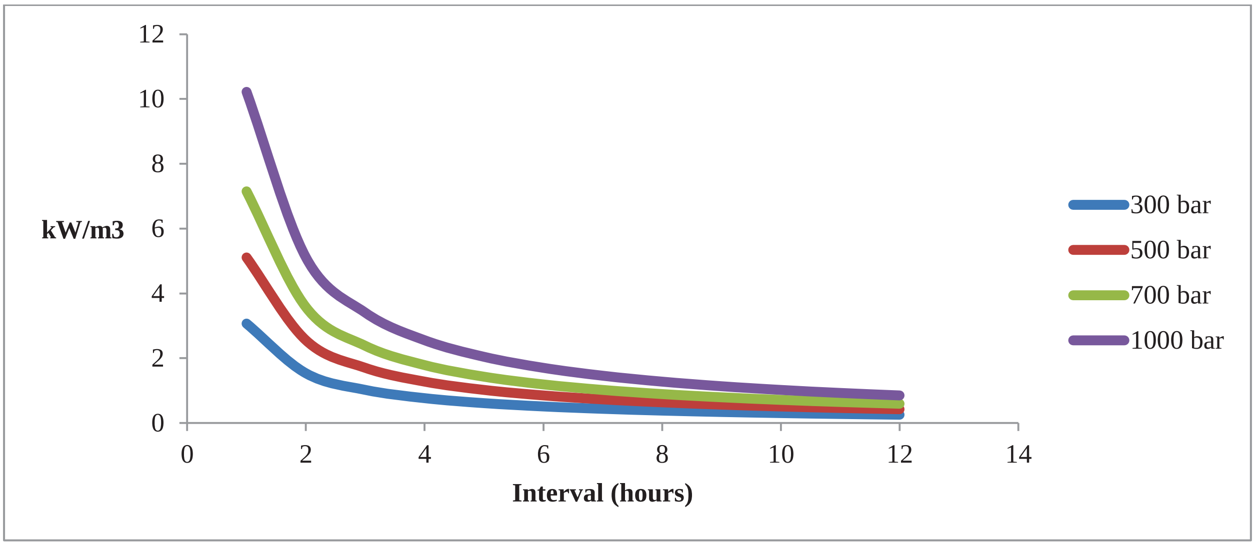

Figure 4.3: Potential power per m^3 during a 12 hour interval

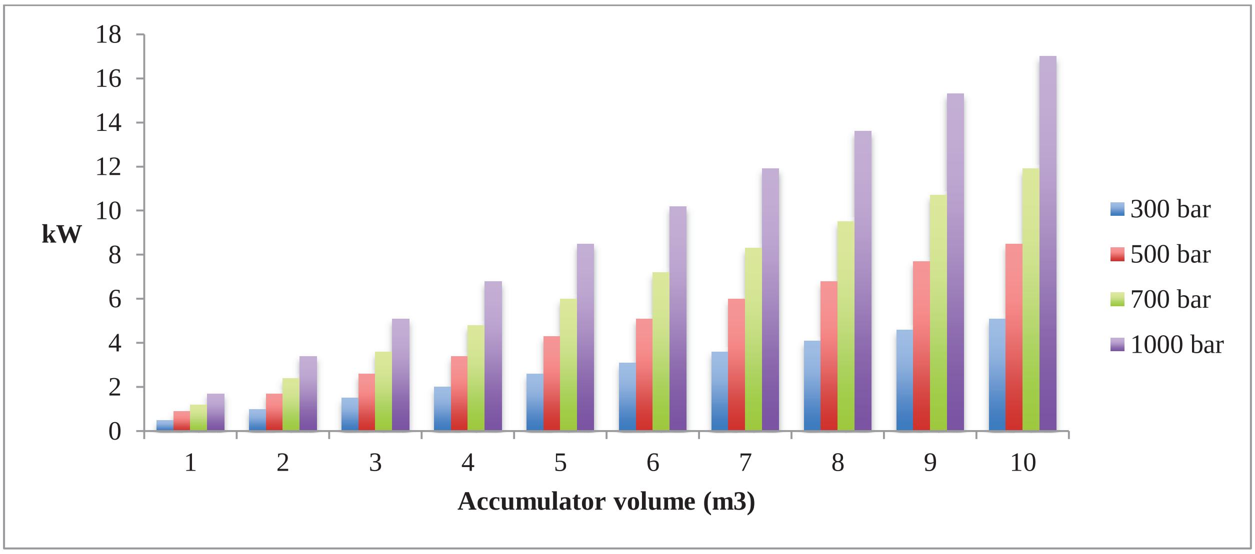

Figure 4.4: Potential power for various accumulator volumes

4.5 COMPONENT AVAILABILITY ANALYSIS

The main components of the system are listed in Table 4.2. All components, except accumulator and turbine, were identified as market available. The preferred accumulator size over 1 m^3 can be fabricated at *Hexagon*, *Hydac* or *Olaer*. Also, a pelton turbine operating at 2000-10000 m head, and a low flow rate of 1 to 50 l/min, can be developed by Rainpower.

Table 4.1: The market availability of the main components in the storage system

Component	**Market availability**	
	Yes	**No**
Accumulator		X
Turbine		X
Generator	X	
Pump	X	
Atm reservoir	X	
Safety valve	X	
Spear valve	X	
Check valve	X	
Actuators	X	
Pressure transmitter	X	
Microcontroller	X	
Pipes	X	
Couplings	X	
Temperature gauge	X	
Pressure gauge	X	
Manifold	X	

4.6 COST ESTIMATE ANALYSIS

4.6.1 COST OF THE FIRST UNIT

The total investment costs are based on a system with accumulator size of 6 m^3 and an operating pressure of 700 bar. The cost of the first unit varies from 7,5 million NOK to 48,5 million NOK, depending on the type of accumulator that is preferred. Table 4.2 lists the different costs of a system with bladder, piston in stainless steel and an open accumulator in composite material.

Table 4.2: Total investment cost of developing a 700 bar system with 6 m^3 accumulator

Accumulator system		**Bladder**	**Stainless piston**	**Open composite**
Accumulator				
Direct materials	NOK	2 500 000	5 500 000	900 000
Engineering/fabrication	NOK	4 700 000	4 000 000	90 000 000
Product cost accumulator	**NOK**	**7 200 000**	**9 500 000**	**90 900 000**
Turbine				
Direct materials	NOK	250 000	250 000	250 000
Engineering/fabrication	NOK	1 260 000	1 260 000	1 260 000
Product cost turbine	**NOK**	**1 510 000**	**1 510 000**	**1 510 000**
Misc. components				
Generator	NOK	30 000	30 000	30 000
Hydraulic piston pump	NOK	100 000	100 000	100 000
Atm reservoir	NOK	5 000	5 000	5 000
Safety valve	NOK	14 000	14 000	14 000
Spear valve	NOK	10 000	10 000	10 000
Check valve	NOK	2 000	2 000	2 000
Actuator	NOK	15 000	15 000	15 000
Pressure transmitter	NOK	7 000	7 000	7 000
Microcontroller	NOK	1 500	1 500	1 500
Pipes	NOK	3 000	3 000	3 000
Couplings	NOK	4 000	4 000	4 000
Temperature gauge	NOK	8 000	8 000	8 000
Pressure gauge	NOK	8 000	8 000	8 000
Manifold	NOK	6 000	6 000	6 000
Product cost misc.	**NOK**	**213 500**	**213 500**	**213 500**
Overall system				
Design	NOK	1 350 000	1 350 000	1 350 000
Assembly	NOK	900 000	900 000	900 000
Test	NOK	900 000	900 000	900 000
Product cost system engineering	**NOK**	**3 150 000**	**3 150 000**	**3 150 000**
Sum direct materials	NOK	2 963 500	5 963 500	1 363 500
Sum engineering/fabrication	NOK	9 110 000	8 410 000	94 410 000
Total cost	**NOK**	**12 073 500**	**14 373 500**	**95 773 500**
Potential funding (Enova)	NOK	-4 555 000	-4 205 000	-47 205 000
Total investment costs	**NOK**	**7 518 500**	**10 168 500**	**48 568 500**

The direct material costs are much lower for the composite accumulator, whilst the fabrication- and engineering costs are skyhigh. However, the fabrication of accumulator will drop for the next developed system unit, as shown later in Section 4.8. Figure 4.5 visualizes the distribution of costs for a first unit of an average system and indicates that the cost-driver is mainly the development of the accumulator, which holds a share of approx. 85%.

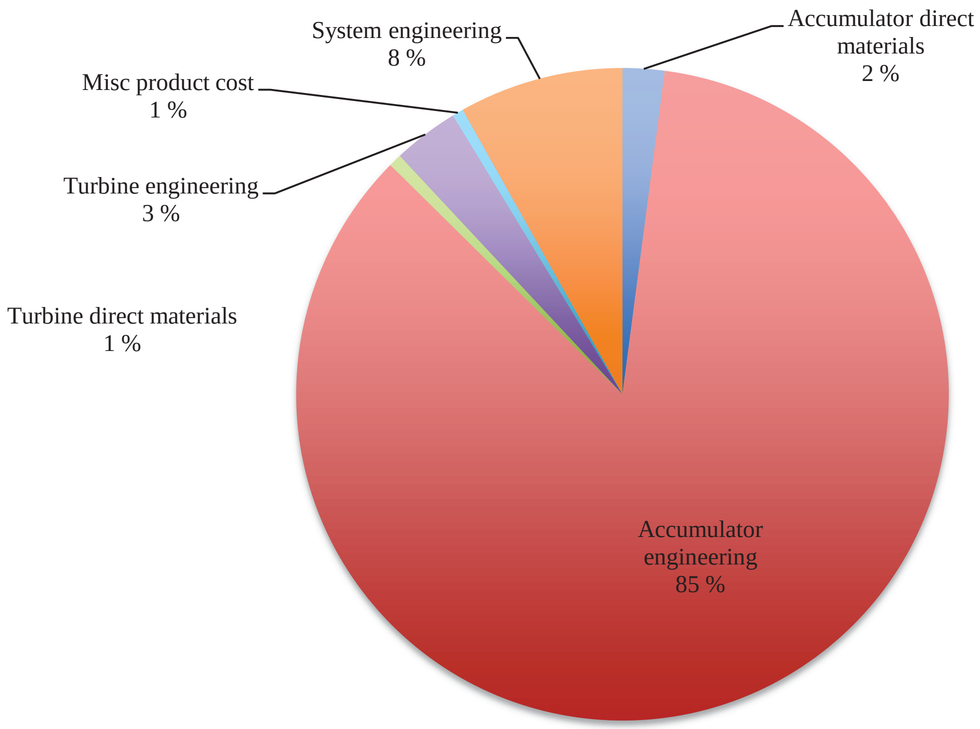

Figure 4.5: Distribution of costs of an average system

4.6.2 CAPITAL COST

The storage capacity of a 700 bar system and 6 m^3 accumulator is 43 kWh. Assuming the system to discharge for 6 hours, the installed power capacity will become 7 kW. A discharge of 6 hours would allow two charge/discharge intervals per day, thus the capacity is 31,4 MWh per year. The capital cost of developing a first unit is therefore 1 million NOK to 7 million NOK as seen in Table 4.3. However, comparing the capital cost of the proposed system to the capital cost of other utilized storage systems, listed in Table 2.1, would be wrong as the presented capital cost include engineering and developing.

Table 4.3: Capital cost of developing a first unit of a 700 bar system with 6 m^3 accumulator

Accumulator system		**Bladder**	**Piston**	**Open**
Energy storage system	NOK	7 518 500	10 168 500	48 568 500
Investment cost	**NOK**	**7 518 500**	**10 168 500**	**48 568 500**
Installed capacity	kW	7	7	7
Capital cost	**NOK/kW**	**1 074 071**	**1 452 642**	**6 938 357**

4.6.3 COST OF ENERGY

The costs of 25 NOK/kWh to 135 NOK/kWh, as seen in Table 4.5, are the specific cost of energy of a first unit of bladder-, piston- or open composite system. The cost of energy is high due to the engineering and developing cost, hence cannot be used for comparison to other utilized storage systems. However, future units will become more cost efficient to fabricate as production equipment and accumulator moldings are already in place.

Table 4.4: Cost of energy of a first unit of a 700 bar system with 6 m^3 accumulator

Accumulator system		**Bladder**	**Piston**	**Open**
Energy storage system	NOK	7 518 500	10 168 500	48 568 500
Sum investment costs	**NOK**	**7 518 500**	**10 168 500**	**48 568 500**
Fixed capital	NOK/year	774 126	1 046 977	4 234 423
Operating costs	NOK/year	0	0	0
Sum fixed costs	**NOK/year**	**774 126**	**1 046 977**	**4 234 423**
Variable energy costs	NOK/year	0	0	0
Sum variable costs	**NOK/year**	**0**	**0**	**0**
Sum annual costs	**NOK/year**	**774 126**	**1 046 977**	**4 234 423**
Annual energy production	kWh	31 390	31 390	31 390
Specific fixed costs	NOK/kWh	24,66	33,35	134,90
Cost of energy	**NOK/kWh**	**24,66**	**33,35**	**134,90**

Assuming that the cost, of fabricating the energy storage system, only will become business profitable if the system is profitable for the end-consumer, the consumer's cost of energy will therefore be more interesting to investigate. The latter sections focuse primarily on the potential sale price of the storage system, i.e. the cost of engineering and developing the system was excluded. The investment cost of a 700 bar system with a 6 m^3 accumulator, was set to 2,9 million NOK for a bladder system, 5,9 million NOK for a piston system and 1,3 million NOK for the open composite system. The energy capacity of the case-scenario system is 31390 kWh per year, as stated in Section 3.6. Also from Section 3.6, the lifetime expectancy of a bladder and piston system is approx. 15 years, thus amortization factor of 0,103. Lifetime expectancy of a composite system is 20 years, thus amortization factor of 0,0872. The discount rate was set to 6%. Operating cost is potentially none, as the system is intended to be automated. Potential funding and tax-refund, for providing electricity to the grid, was excluded due to uncertainties. The cost of energy was set to the lowest average elprice (0,26 NOK/kWh) from Section 3.9.3. The transmission fee of 0,44 NOK/kWh will be paid back to the user when utilizing electricity to the grid, thus this was neglected from the analysis. However, according to Agder Energi Nett, every kWh utilized to the grid is given 0,04 NOK in addition to the momentary elprice (Agder Wood, s.a.). Assuming that the cost of charging the system is depended on the lost profit of not selling local energy to the grid at low cost off-peak hours, a user would "pay" 0,34 NOK/kWh, assuming 85% system efficiency. Table 4.5 shows that the open composite system is the most cost efficient (6,61 NOK/kWh) of the three types.

Table 4.5: Potential cost of energy of a utilized 700 bar system with 6 m^3 accumulator

Accumulator system		**Bladder**	**Piston**	**Open**
Energy storage system	NOK	2 963 500	5 963 500	1 363 500
Assembly	NOK	900 000	900 000	900 000
Sum investment costs	**NOK**	**3 863 500**	**6 863 500**	**2 263 500**
Fixed capital	NOK/year	397 797	706 685	197 342
Operating costs	NOK/year	0	0	0
Sum fixed costs	**NOK/year**	**397 797**	**706 685**	**197 342**
Variable energy costs	NOK/year	9 103	9 103	9 103
Sum variable costs	**NOK/year**	**9 103**	**9 103**	**9 103**
Sum annual costs	**NOK/year**	**406 900**	**715 788**	**206 445**
Annual energy production	kWh	31 390	31 390	31 390
Specific cost of charging	NOK/kWh	0,34	0,34	0,34
Specific fixed costs	NOK/kWh	12,67	22,51	6,29
Cost of energy	**NOK/kWh**	**13,01**	**22,85**	**6,63**

SENSITIVITY ANALYSIS

With reservation of overlooked issues or cost fluctuations, Table 4.6 shows the specific costs with a 10% decreasement in system and assembly cost, whilst Table 4.7 shows with 10% increasement. The elprice is also sensible to changes, but that issue is neglected in this analysis.

Table 4.6: Cost of energy if investment cost decreases by 10%

Accumulator system		**Bladder**	**Piston**	**Open**
Energy storage system	NOK	2 667 150	5 367 150	1 227 150
Assembly	NOK	810 000	810 000	810 000
Sum investment costs	**NOK**	**3 477 150**	**6 177 150**	**2 037 150**
Fixed capital	NOK/year	358 017	636 016	177 608
Operating costs	NOK/year	0	0	0
Sum fixed costs	**NOK/year**	**358 017**	**636 016**	**177 608**
Variable energy costs	NOK/year	9 103	9 103	9 103
Sum variable costs	**NOK/year**	**9 103**	**9 103**	**9 103**
Sum annual costs	**NOK/year**	**367 120**	**645 120**	**186 711**
Annual energy production	kWh	31 390	31 390	31 390
Specific cost of charging	NOK/kWh	0,34	0,34	0,34
Specific fixed costs	NOK/kWh	11,41	20,26	5,66
Cost of energy	**NOK/kWh**	**11,75**	**20,60**	**6,00**

Table 4.7: Cost of energy if investment cost increases by 10%

Accumulator system		**Bladder**	**Piston**	**Open**
Energy storage system	NOK	3 259 850	6 559 850	1 499 850
Assembly	NOK	990 000	990 000	990 000
Sum investment costs	**NOK**	**4 249 850**	**7 549 850**	**2 489 850**
Fixed capital	NOK/year	437 576	777 353	217 076
Operating costs	NOK/year	0	0	0
Sum fixed costs	**NOK/year**	**437 576**	**777 353**	**217 076**
Variable energy costs	NOK/year	9 103	9 103	9 103
Sum variable costs	**NOK/year**	**9 103**	**9 103**	**9 103**
Sum annual costs	**NOK/year**	**446 679**	**786 457**	**226 180**
Annual energy production	kWh	31 390	31 390	31 390
Specific cost of charging	NOK/kWh	0,32	0,32	0,32
Specific fixed costs	NOK/kWh	13,94	24,76	6,92
Cost of energy	**NOK/kWh**	**14,28**	**25,11**	**7,26**

The cost of energy is minor to change of a 10% sensibility analysis. This is due to the generally high cost of energy of a 31 MWh per year system. If cost of energy dropped below 1 NOK, the sensibility analysis would probably show a more distinct change of cost.

4.7 PROFITABILITY ANALYSIS WITH CASE SCENARIO

The case scenario chosen for this analyse, was to investigate the possibility for a household to speculate in storing electricity from local renewables for subsequently selling it at back to the grid at profitable peak hours.

The specific costs given in Section 4.6.3 could easily indicate that a profitability analysis would be negative. The NPV analysis is presented in Table 4.9. A 700 bar system, with a 6 m^3 open composite accumulator, was chosen for the NPV analysis. Yearly production was set to 31 400 kWh with system efficiency of 85%. Minimum cost of charging was set to 0,26 NOK/kWh and maximum profit was set to 0,38 NOK/kWh, interest to 5% and the lifetime expectancy to 20 years. Table 4.8 shows directly that the system will not be profitable for the speculation of the variations in elprice, even if the cost of charging is based upon minimum average elprice. In order to profit from the daily variation in elprice, the NPV show that the investment cost ought to be reduced to 76 360 NOK.

Table 4.8: Net present value of a system intended for selling electricity to the grid

Year	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**	**2022**	**2023**
Energy cost	-9 071	-9 071	-9 071	-9 071	-9 071	-9 071	-9 071	-9 071	-9 071	-9 071	-9 071
Operating cost											
Investment cost	-2 263 500										
Gross profit	10 519	10 519	10 519	10 519	10 519	10 519	10 519	10 519	10 519	10 519	10 519
Net profit	-2 262 052	1 448	1 448	1 448	1 448	1 448	1 448	1 448	1 448	1 448	1 448
PV	-2 262 052	1 379	1 313	1 251	1 191	1 134	1 080	1 029	980	933	889
Year		**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**	**2031**	**2032**	**2033**
Energy cost		-9 071	-9 071	-9 071	-9 071	-9 071	-9 071	-9 071	-9 071	-9 071	-9 071
Operating cost											
Investment cost											
Gross profit		10 519	10 519	10 519	10 519	10 519	10 519	10 519	10 519	10 519	10 519
Net profit		1 448	1 448	1 448	1 448	1 448	1 448	1 448	1 448	1 448	1 448
PV		847	806	768	731	696	663	632	602	573	546
NPV	**-2 244 008**										

4.8 POTENTIAL FUTURE COST REDUCTION ANALYSIS

The high investment cost, presented in Section 4.6 proved the profitability to be negative. However, all new technologies have a potential future cost reduction. Using technology learning on the development cost, listed in Section 4.5, could indicate the system to become more profitable in the future. The phenomenon of technology learning says that the more units that are fabricated, the more cost-efficient the system will become. The NPV analysis, in Section 4.7, showed the break-even cost to be approx. 76 000 NOK, i.e. the investment cost needs to decrease to 76 360 NOK in order to be profitable. By using learning rates (LR) on the components, as well as the entire system, the potential future cost reduction can be estimated and indicate the number of units that need to be produced in order to reach break-even cost.

The learning rates, listed in Table 4.9, are based on *Cost Estimator's Reference Manual* by Stewart et al. (1995) except the labour of system assembly, which was calculated from estimated assembly hours and cost by *BLE Engineering*. The learning rates on the total system cost were set to 7 and 20%, as reckommended by Associate Professor Thomas Martinsen at UMB.

Using the values in Table 4.9, the potential future cost reduction of the components and assembly are shown in Table 4.10-13 and in Figure 4.6-9. The components and assembly is then summarized in Table 4.14 and Figure 4.10. However, the potential future cost reduction is finally presented in Table 4.15-16 and Figure 4.11-12. The method of using technology learning was explained in Section 2.2.

Table 4.9: Suggested and estimated learning rates used in the analysis

Component	***b***	**LR**
Accumulator	-0,112474729	7,5%
Material	-0,081613766	5,5%
Turbine	-0,321928095	20%
System Assembly/labour	-0,321928095	20%
Total system cost scenario 1	-0,1046974	7%
Total system cost scenario 2	-0,321928095	20%

4.8.1 POTENTIAL FUTURE COST REDUCTION OF COMPONENTS AND ASSEMBLY

The learning rate, of the open composite accumulator, was based on LR for repetitive machining, or punch-press operation, and material, thus total LR was set to 7,5%. Figure 4.6 show that the cost of the accumulator will decrease to 50% of its initial value, of 900 000 NOK, after cumulative production has reached 1000 units. After producing 1 million accumulators, the potential cost will be 235 000 for a 700 bar, 6 m^3 open composite accumulator. The total, or cumulative, cost of 1 million accumulators is 253 billion NOK.

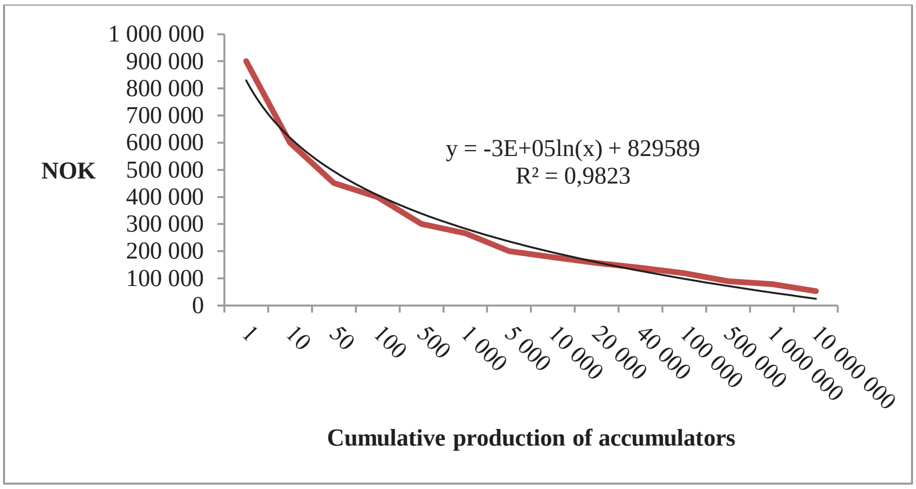

Figure 4.6: Potential future cost reduction of composite accumulator with 7,5% LR

The initial material cost of turbine was estimated to be approx. 250 000 NOK, whilst the cost of developing was estimated to be approx. 1,2 million NOK. Combining material LR and LR for complex machining tools, the total LR was set to 20%. Figure 4.7 indicate that the cost of turbine will decrease to 50%, of initial cost, after producing 10 to 50 turbines. The curve show a steep falling slope before the cumulative production has reached 1000 units. Closing in on 500 000 turbines, the cost per unit will drop to approx. 100 000 NOK, which is competitive to utilized small scale turbines.

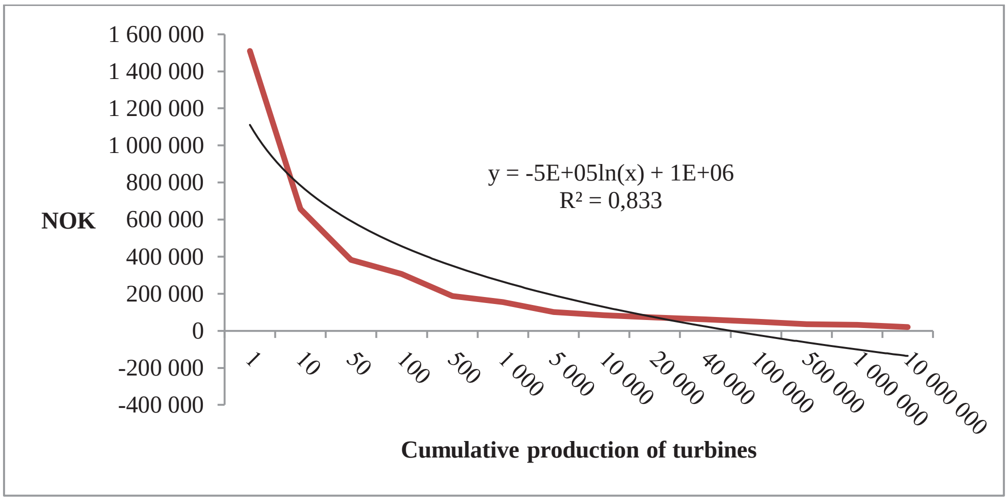

Figure 4.7: Potential future cost reduction of turbine with 20% LR

Misc. components, e.g. generator, pump, valves and electronics, was combined and given a 5,5% LR. The misc. components are all market available and are minor cost-drivers to the total system. However, Figure 4.8 shows that the initial cost of misc. components have a potential cost decreasement after cumulative production increase.

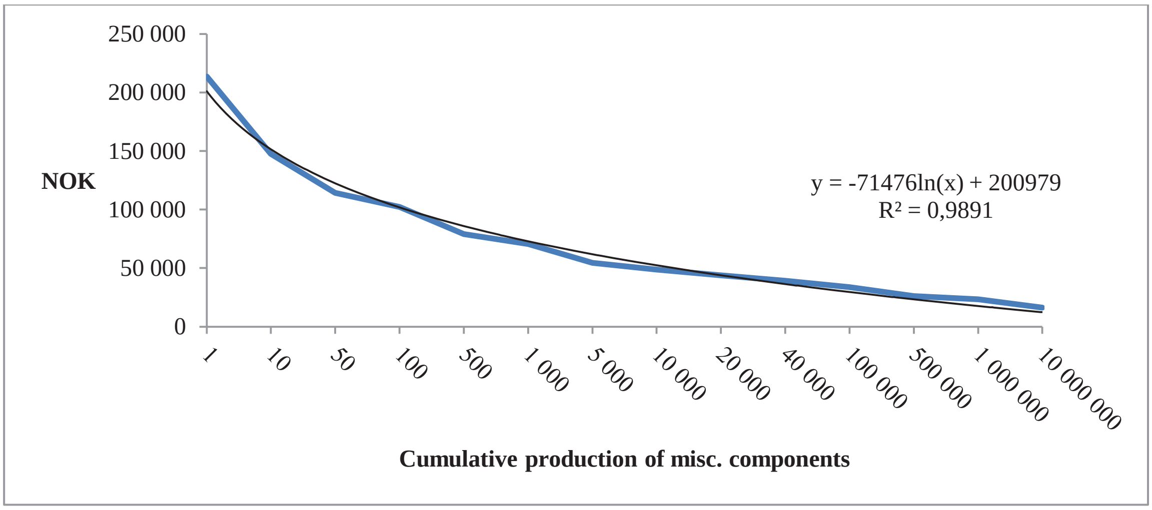

Figure 4.8: Potential future cost reduction of misc. components with 5,5% LR

Assemblying the system was estimated to be approx. 1000 hours at the total cost of 900 000 NOK. In correspondence with *BLE Engineering*, the LR of labour hours was set to 20%. Figure 4.9 indicates that the labour hours will be 50% more efficient after assemblying 10 units of the storage system.

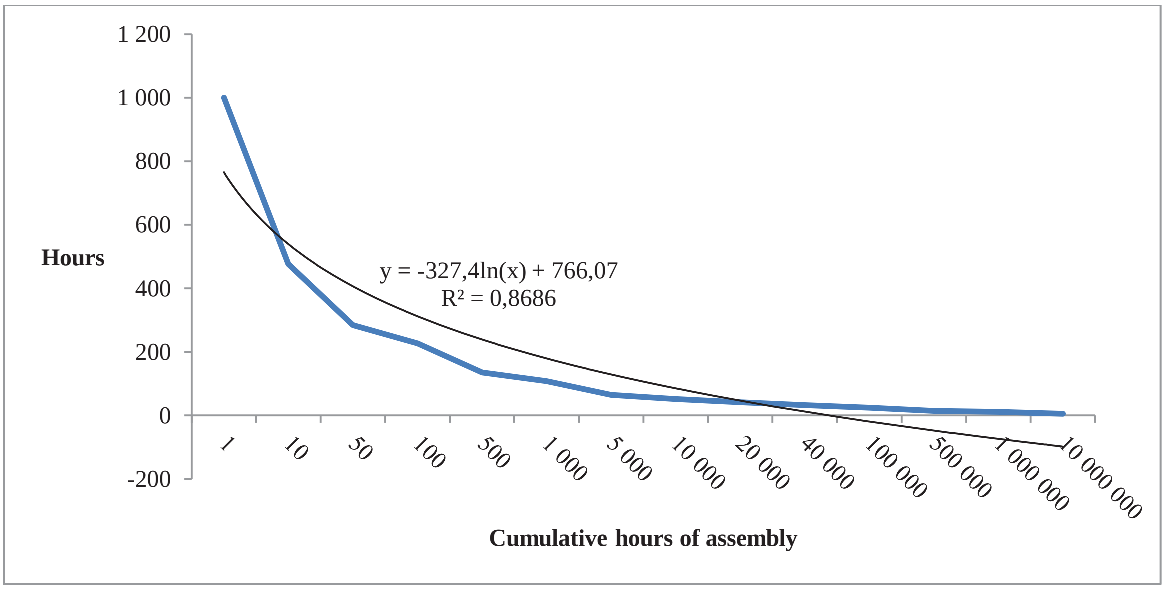

Figure 4.9: Potential future reduction of hours for system assembly with 20% LR

Summarizing the learning curves from Figure 4.6-9, Figure 4.10 shows the total system learning curve. Break-even cost at 76 300 NOK will not be reached even after a cumulative production of 10 millions.

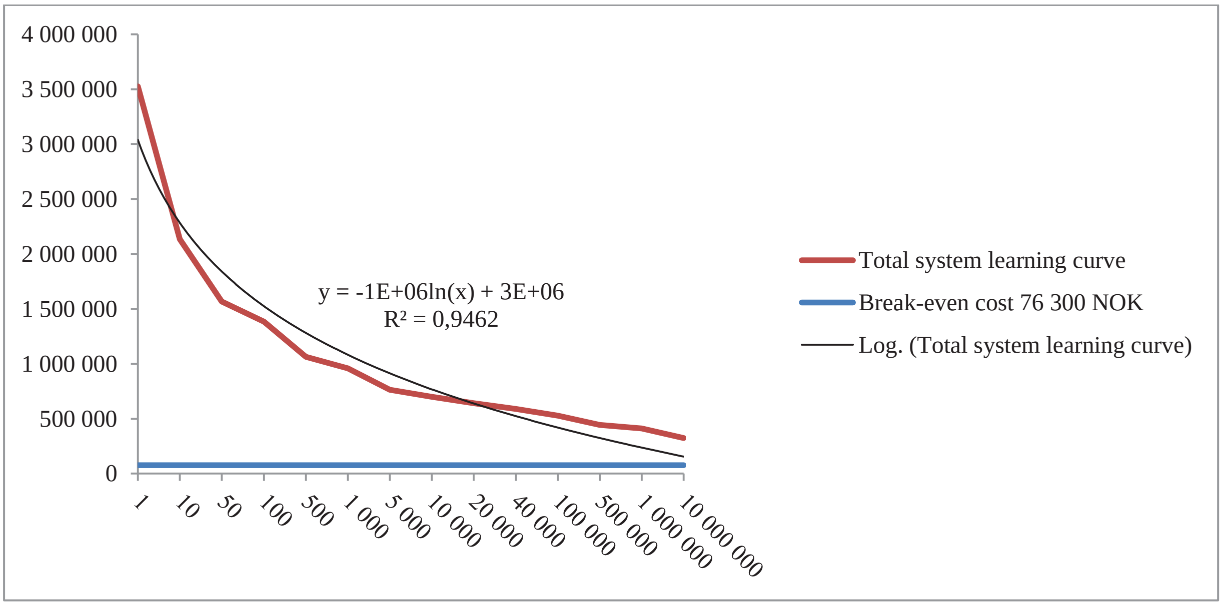

Figure 4.10: Potential future cost reduction of system based on component and assembly LR

4.8.2 POTENTIAL FUTURE COST REDUCTION OF THE ELECTRICAL STORAGE SYSTEM

According to Associate Professor Thomas Martinsen, the total system should be analysed with 7% and 20% LR. Break-even cost for system in household is 76 300 NOK or at energy cost of 0,21 NOK/kWh. Table 4.10-11 list the values of cumulative production, cost per unit, cost of energy and capital cost. The capital cost can give an indication of when the competitive break-even cost of utilized energy storage system can be reached. Looking at Table 2.1, break-even cost of BES is 30 000 NOK/kW, PHS and FC is 20 000 NOK/kW and CAES and FES is 6000 NOK/kW. The learning curves from Table 4.10-11 is shown in Figure 4.11.

Table 4.10: Potential future cost reduction of total system with 7% LR

Cumulative production of electrical storage system	**Cost of system** (NOK)	**Capital cost** (NOK/kW)	**Cost of energy** (NOK/kWh)
10	2 768 706	386 152	12,30
50	2 339 357	326 270	10,39
100	2 175 602	303 431	9,67
500	1 838 227	256 378	8,17
1 000	1 709 551	238 431	7,60
5 000	1 444 448	201 457	6,42
10 000	1 343 336	187 355	5,97
20 000	1 249 303	174 240	5,55
40 000	1 161 852	162 043	5,16
100 000	1 055 571	147 220	4,69
500 000	891 881	124 391	3,96
1 000 000	829 450	115 683	3,69
10 000 000	651 767	90 902	2,90
20 000 000	606 144	84 539	2,69
50 000 000	550 696	76 806	2,45
100 000 000	512 148	71 429	2,28

Table 4.11: Potential future cost reduction of total system with 20% LR

Cumulative production of electrical storage system	**Cost of system** (NOK)	**Capital cost** (NOK/kW)	**Cost of energy** (NOK/kWh)
10	1 678 983	234 168	7,46
50	1 000 065	139 479	4,44
100	800 052	111 583	3,55
500	476 541	66 463	2,12
1 000	381 233	53 171	1,69
5 000	227 076	31 670	1,01
10 000	181 661	25 336	0,81
20 000	145 329	20 269	0,65
40 000	116 263	16 215	0,52
100 000	86 563	12 073	0,38
500 000	51 560	7 191	0,23
1 000 000	41 248	5 753	0,18
10 000 000	19 655	2 741	0,09
20 000 000	15 724	2 193	0,07
50 000 000	11 707	1 633	0,05
100 000 000	9 366	1 306	0,04

If the total system has a LR of 7%, the cost reduction will not reach break-even cost until cumulative production is billions of units. However, with a 20% LR, Table 4.11 indicates the system to be competitive to other utilized storage system after producing only 5 000 units. Also, in Table 4.11 and Figure 4.11, a system for a household, for speculating in profitable grid elprice, can reach break-even cost after a cumulative production of approx. 400 000 units. This analysis indicates that the system can be profitable, depending on the system LR, after a cumulative production of units.

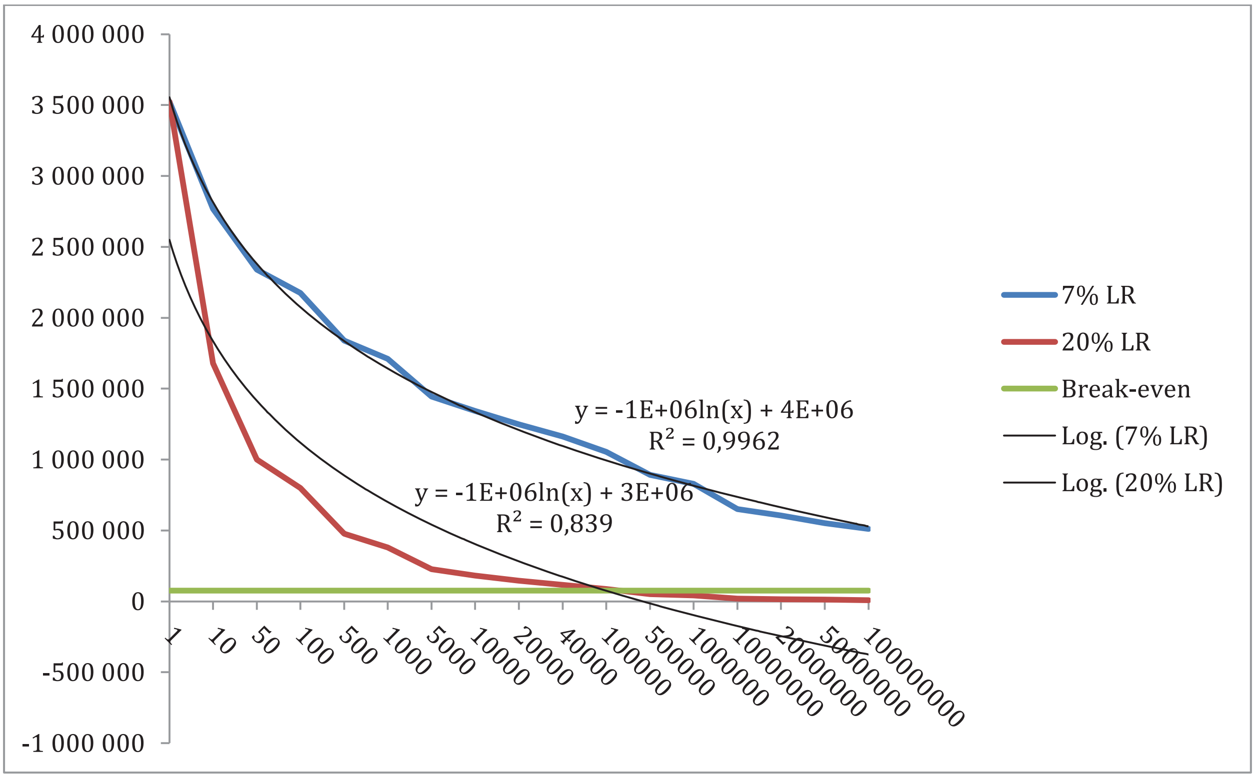

Figure 4.11: Potential future cost reduction of system with 7% and 20% LR

5 DISCUSSION

The patentability analysis could not determine whether the proposed energy storage system to be novel or not. The claims to potential novelty of the system, listed in Section 4.2, need to be further investigated and approved by NIPO.

The energy capacity analysis indicates the proposed system to be feasible of storing surplus electricity in high-pressure accumulators. Figure 4.1-2 show that the energy capacity is almost linear to pressure and accumulator volume. Also, the figures indicate that, in order for the system to reach MWh capacity, the accumulator needs to be much larger than 10 m^3. The potential energy of the system is proportional to the volume and compression in the accumulator. A larger accumulator volume will be able to contain more liquid hence provide power for longer periods. A higher pressure rating will give a more dense compression of the gas, a larger liquid volume and a higher flow rate of the discharged liquid. The capacity of the system is of course dependent on the behaviour of compressed gas and of achieving a fully isothermal process. Designing the system to MWh capacity could categorize the system with other utilized bulk storage system, e.g. PHS and CAES. However, according to the values in Table 3.4, a 700 bar system with a 6 m^3 accumulator, could easily cover the daily energy demand of an average Norwegian household. The same system could also cover the consumption of an average Norwegian cabin for 9 days, a tele-com base station for 1,5 days or cover the daily energy demand of 86 small households in an African village. The utilization of the system in private household could halter, if not only by profitability, by system size too large to be placed on private property. Also, potential laws, against storing large amount of compressible gas near households, could have a negative impact on household systems.

The power analysis indicates that the power capacity of the system to be somewhat low. As shown in Figure 4.3-4, the power capacity will only reach approx. 10 kW for accumulator size below 10 m^3. However, the coordinated power demand, given in Table 3.5, indicate a 700 bar system with 6 m^3 accumulator to supply a household. Net output power and energy will eventually be fully determined by turbine and pump efficiency, hence were only estimated in the analysis to be 85%.

The component analysis indicates most of the components to be market available. The main components of the system are listed in Table 4.2. Accumulator and turbine are the black-boxes of the system and needs to be developed. Accumulators, of several cubic metres in size, seem to be very expencive to develop. As seen in Table 4.4 and Figure 4.5, the accumulator is the cost-driver holding 85% of the total system cost. However, looking at Table 4.6, the composite accumulator will be more cost efficient after production equipment has been developed and engineered.

The cost and profitability analysis indicate that the cost of energy is too high for the initial first unit, considering the elprices shown in Section 3.9.3. Not even a 10% decreasement of investment cost will make the initial system profitable. The NPV analysis in Section 4.7.1 concludes the technology not to be profitable for households with local renewables. Not until unit cost is below 76 000 NOK, or cost of energy is 0,21 NOK/kWh, will the initial system become profitable for speculating in elprice.

In Section 4.8 the potential future cost reductions are estimated in order to predict the amount of units to produce before reaching a competitive price, i.e. the break-even cost. The future cost reduction analysis indicates that, with the assumed LR of 20% seen in Table 4.11 and Figure 4.11, the system will become competitive to other utilized energy storage systems after a cumulative production of 5000 units. A 20% LR also indicate that a system for households will become profitable after cumulative production has reached 400 000 units. However, the analysis also gives the impression that a lower LR could mean that the proposed energy storage system will not become profitable until millions of units have been produced. The learning curves are speculations in system cost based on values from literature. Even if a positive LR of 20% could be gained on the system, the profitability of the proposed energy system will be determined by the cost of charging. If only a small variation in the minimum and maximum gap of elprice should occure, it would have a negative impact on the profitability of a household system.

6 CONCLUSION

The analysis indicates that the proposed energy storage system is feasible. However, the scenario of storing surplus electricity, for subsequently regenerating it back to the grid, seemed not to be profitable at initial development cost. The answer to the research question in Section 1.1: *"Can high-pressure accumulators store surplus electricity at off-peak hours for profitable regeneration at peak hours?"* is therefore unfortunately: no. Only if the system gain a LR of 20% and the cumulative production reach 400 000 units, will the system become profitable for households. However, the technical feasibility of the proposed storage system is positive. LR at 20% indicates the system to be competitive to other utilized storage systems after a cumulative production of 5000 units. This could mean that the social benefits, of utilizing the proposed system as emergency stand-by generators in the grid or at tele-com base stations, are high. The novelty of the idea has some possibility of patentability. The claims listed in Section 4.2 will have to be controlled and approved by NIPO before the novelty of the system can be concluded. The capacity of the proposed system seems to be adequate, to some point, of making intermittent renewables more reliable. The analysis also indicates that the proposed system could be utilized as emergency generators in the grid and as stand-by emergency generators at tele-com base stations. Technology learning indicates the cost of the system to become competitive to other utilized storage systems, e.g. BES, FES and FC.

Improvements of the thesis could have been to investigate the LR of components more thoroughly, instead of only using estimated values from literature. The compression of air and behaviour of pressurized water should also be more thoroughly studied. The profitability analysis was vague due to the uncertainty of profitability. Many aspects, e.g. tax-refund, funding and transmission fee, were intentionally left out until profitability was proven. The case-scenario did not find the system to be profitable for the intended consumer hence a deeper NPV analysis was not commenced.

Further research of the social benefits, of the proposed idea, should be commenced to investigate the possibility of integrating the proposed system in the grid and tele-com base stations.

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