Energy Storage:

What is Energy Storage, and how can this contribute to large-scale integration of Renewable Energy?

"Large-scale electricity storage promises to be a game-changer, unshackling alternative energy." (REN21 2008)

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Preface

This thesis marks the end of my two years master degree in industrial economy, where I have been given the opportunity of combining technical and economical studies. It has been two exciting years of hard work, challenging my self-discipline. I would thank both professors and fellow students, for help and motivation throughout this period, where the wide knowledge and good memories are the result.

First I would express my sincere gratitude to my guidance counselor Kristin Roll, who has been a great source of guidance and support. She have steered me in the right direction when working on this thesis. Also, I am very grateful for all the help Peter Breuhaus at Iris has given me. He is a great source of knowledge, always prepared to help. Thanks!

I would also like to thank my family and friends, who have kept my mood and motivation on top through the total five years of this master study.

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Abstract

Energy represents a very formative need in the world today, produced mainly from fossil resources with consequences as climate change, community interference, and worries about limited energy reserves. Hence, renewable energy has become ever more interesting over the last decades, offering a solution to these problems. A significant increase in installed capacity throughout the world has given these resources ever more confidence among people. Yet, new challenges have raised with the increasing exploitation of renewables. Two are intermittent power supply and distant location far from central areas. Thus, the concept of energy storage has become more interesting the last decades, being considered one of the main solutions to these problematic issues of renewable energy.

In this thesis several energy storage technologies are introduced, with existing or future large-scale storage potential as their common characteristic. Important issues as cost, storage capacity and flexibility are evaluated, reckoned as the basic characteristics of an ES facility. Costs are assessed more detailed, considered the most crucial factor in a

A scenario analysis is used to assess high and low cost scenarios for a 50 MW wind/ES power plant. This is a common procedure to account for the uncertainty in the future of these immature technologies. The analysis confirms the fact that the mature technologies are the low-cost options for both scenarios. Though, optimistic prognosis for the developing potential of the immature technologies makes them good future candidates for the application of renewable energy integration.

The findings underline the importance of energy storage to solve the challenges of intermittent nature and restricted locations following renewables. Though this can’t solely solve these challenges, it is a great helping hand for handling them.

Contents

Figures

Tables

Abbreviations

BES – battery energy storage

CAES – compressed air energy storage

ES – energy storage

FBES - flow battery energy storage

GHG – greenhouse gases

GW – giga watt

GWh – giga watt-hours

HES – hydrogen energy storage

kW – kilo watt

kWh – kilo watt-hours

Lead-Acid - LA

MW- mega watt

MWh – mega watt-hours

NPC – net present cost

NPV – net present value

O&M – operation and maintenance

PHES – pumped hydro energy storage

PV – present value

R&D – research and development

RE – renewable energy

Sodium-sulphur - NaS

Vanadium-Redox Battery – VRB

Chapter 1 - Introduction

1.1. The current energy market

Today, energy it the most crucial factor to keep the world running in its current manner. Apart from water and nutrition, it covers the most formative needs of human beings. The term primary energy[1] comprise a high number of resources found in nature, many of which we don't see the magnitude of in our daily life. The sun for example, though a well-known energy supplier, is the most extensive energy resource we have. The heat it supplies equals approximately 15,000 times the world's annual energy consumption (Renewable Energy 2007). Globally versatile environment and geology offers a great energy potential stored in the nature.

The energy supplied today is provided mainly from carbon-based fuels, and fossil energy is main reason why energy demand has readily been covered in the developed countries for the last century. Great resources in term of coal, oil and gas have supplied the world with enormous amount of energy, and generated 78% of the global energy consumption in 2008 (REN 21). Later years concerns about their limited nature have been increasing, and also the environmental damages/costs have become common knowledge. Different prognoses have been made on the duration of these resources maintaining present consumption, but they are all within decades.

1.2. Recent development/changes

Increasing awareness on the consequences of fossil fuel consumption has created an ever-growing interest in renewable[2] energy (RE) (renewables) and focus on their future significance in the energy sector. Examples are hydro, wind-, solar-, and biopower.

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[1] Energy found in nature that has not been subjected to any conversion or transformation process.

[2] Defined by the criteria of continuous replenishing by nature.

Comprehensive research is ongoing and several new technologies have been and are being developed to utilize these resources. The renewables give rise to the idea of a sustainable future without damaging emissions of greenhouse gases (GHG) and other atmospheric pollutants.

Exploitation of the renewables as a supplement to the fossil energy is the situation today, while the ideal future is defined as total “green” supply. Despite public support and governmental subsidies related to these resources, the present situation limits their possibilities as technology and economy does not allow use and commercializing in a sufficient manner. Comprehensive research and rapid development still indicates a good possibility that several technologies will become competitive within the next decades, which thereby will increase the exploitation of renewables. Thus, it requires public knowledge and awareness that this is a necessity to drift the world in its present manner, maintaining the same energy consumption witnessed today.

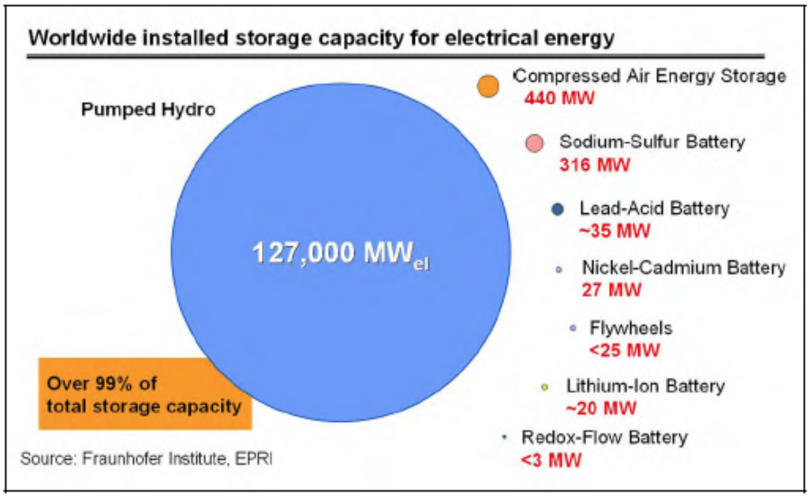
1.3. Challenges

The intermittent nature of the renewables, causing an unpredictable energy production, generates new needs for the electricity production and distribution. One is new and improved grid infrastructure, as these resources are often located in remote areas with limited grid connection. Also, variable voltage supply requires an electricity network that can regulate these irregularities. Another solution is energy storage (ES), which allows the energy to be harnessed when present and generated when necessary. This may be less complex to implement, and may help to optimize the existing grid infrastructures and prevent or defer expensive upgrades (Connolly 2010). These solutions are prerequisites to offer a steady and reliable energy supply from renewable resources.

Energy storage is considered one of the main strategies to integrate renewable energy onto the grid (Crotogino & Huebner 2008 via NREL 2009). There are several possible storage methods, both mature and infants, where the main difference is defined by two properties: storage capacity and reaction time of supply. These factors split the existing

ES technologies into two groups, so-called power applications and energy applications (Chen et al. 2009). In this thesis the focus will be on the energy management application technologies. These are defined by the possibility of large scale ES, with duration ranging from hours to seasonal basis, and are introduced in chapter 3.

Figure 1 shows the share in the worldwide installed storage capacity for electrical energy for different storage technologies. Pumped hydro energy storage (PHES) representing over 99% of the total storage capacity is considered the most mature ES technology as of today, and has been practiced for centuries. Due to limitations considering sites for installation, new competitive technologies are needed.



Source: Fraunhofer Institute, EPRI

Figur 1. Worldwide installed storage capacity for electrical energy (EPRI 2010).

To be able to argue for the development and deployment of ES in combination with renewables, it is important to clarify the characteristics and benefits these technologies. Key issues like operation; advantages; disadvantages; applications; cost; and future potential are common characteristics in comparative analysis of ES (Connolly 2010). The most important is often to prove that these can offer profitable operation, today or in the near future. The difficulty in such analysis is the fact that the technologies are at quite different stages in their development. Yet, wide research, test projects and estimates generates a good foundation for a comparative analysis. Their technical characteristics are crucial in assessment of ES, and very important when deciding which technology is best suited for certain projects. It somewhat simplifies the comparison as these characteristics are common for all the technologies.

1.4. Scope of this study

This ES analysis is based on assessment of the issues considered most crucial for a future storage facility. These are highly application-dependent, as the objectives of storage projects varies for different applications. RE integration is therefore taken into account when deciding which issues to analyze. Generally, the main criterion is cost, as most often the decisive factor considering an investment. The second is the potential storage capacity, with a significant variation within the group of technologies assessed in this analysis. The third is flexibility: how reliable can RE electricity generation operate considering the reaction time on voltage fluctuations and power changes of the ES technologies? Efficiency is the fourth criteria. Whether this is included in the cost-analysis or as an individual criterion is a choice to make, but here it will be included in cost analysis. Thus, the main criterions used for comparison of the technologies are:

- Cost
- Storage capacity
- Flexibility

These criterions are used to compare four possible storage technologies for the application of *energy management in the RE integration and generation of electricity.* These are:

1. PHES
2. CAES: underground
3. Batteries: Electrochemical and flow
4. Hydrogen: tank and underground

A 50 MW wind park connected to a 300 MWh storage unit will be analyzed, with the intention of deciding the best-suited ES in this case. Each of the four technologies mentioned will be included in this analysis, focusing on the main criterions as defined above.

ES is a popular theme today, where much research and several economical analyses have been conducted to map the different technologies with respect to potential and costs. Through using existing research and test results, this thesis aims to answer the main research question:

What is Energy Storage, and how can this contribute to large-scale integration of Renewable Energy?

This question will be answered through the following sub-questions:

i. How is the current energy market, and what are its future prospects?
ii. What is energy storage, and how can these technologies benefit RE integration?
iii. How are the ES technologies positioned according to the criterions highlighted above?
iv. How are the ES technologies suited for supporting a 50 MW wind power plant?

1.5. Structure

In chapter 1, I have introduced the theme and established the research questions for this thesis, with a cursory explanation of the importance of ES in the RE integration. Chapter 2 gives a broader and more detailed introduction to renewables and their potential in the energy market. The challenges of their integration and possible solutions are also explained. In chapter 3, the concept of energy storage is clarified, and the technologies assessed in this thesis are introduced. The main benefits following ES and RE integration are also highlighted. Chapter 4 gives a brief introduction to the methodologies that are used to conduct a comparative analysis of the ES technologies in chapter 6, the windpark. Chapter 5 highlights the comparative characteristics of the technologies. The results of the case study are revealed in chapter 6. The conclusion in chapter 7 completes my thesis, evaluating the concept of energy storage in RE integration.

Chapter 2 - Renewable energy

2.1 Current situation of the Energy market

Current market situation in the energy supply is a dominant share of fossils, representing about three quarters of the global power-generating capacity in 2009, producing 78% of the energy consumed in 2008 (REN21). These energy resources are characterized by delivery guarantee and flexibility in terms of when and where to be used, but also restricted by the fact that the resources are limited. Lately, the questioning considering fossil energy has increased significantly, where environment, health and concerns about future energy supply are important issues.

Nuclear power is an alternative to fossil fuels in energy production, which lately has experienced a growing acceptance in more than 60 countries. Thus, the incident in Japan's Fukushima Daiichi Nuclear Power Station[3] in March 2011 "(…)*prompted a reassessment of nuclear power not just in Japan but across the world."* (Alvarez 2011)[4] where the two crucial issues of health and safety were highlighted.

Reduction of environmental and human risk to avoid disasters like witnessed recently, has raised the need of alternative solutions. Increased utilization of renewable resources is considered the primary solution of these energy problems.

Renewable energy is defined by the criteria of continuous replenishing by nature, and comprises sun, wind, water, Earth's heat, and plants. The exploitation of these resources is becoming ever more increasing, and produced 18% of the total electricity consumption in 2008 (REN21). Only 3% was from non-hydro renewables, but this is aimed to increase from 2.5% in 2007 to 8.6% in 2030 (WEO 2009). The major challenge

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[3] Japan is the world third-biggest nuclear producer, where nuclear power constitutes for more than 30% of their total electricity consumption (REN21).

[4] http://www.manilatimes.net/opinion/after-fukushima-renewable-energy-is-our-only-option/

of these intermittent and transient energy resources it knowing when and how to harness, and when to “let it go”.

The interest in renewable energy and its applications has increased significantly the recent decades. This was proven in 2009, which was “*unprecedented in the history of renewable energy*” (REN21 2010, p 10). Despite the global financial crisis and other economic sectors declining around the world, existing renewable capacity continued to grow at rates close to those in previous years (REN21 2010; SRREN 2011). Public investment for RD&D in low-carbon technology did also reach an all-time high this year (OECD/IEA 2011).

Figure 2 shows the share of global electricity supply from renewables compared to fossil fuels and nuclear power in 2008. Hydropower represents a share of 15 %, which is five times the share of the remaining renewables. This, along with the fact that the sites suitable for hydropower stations are limited, underlines the importance of developing new technologies to increase the exploitation of other “green” resources. One is ES, introduced in chapter 3.

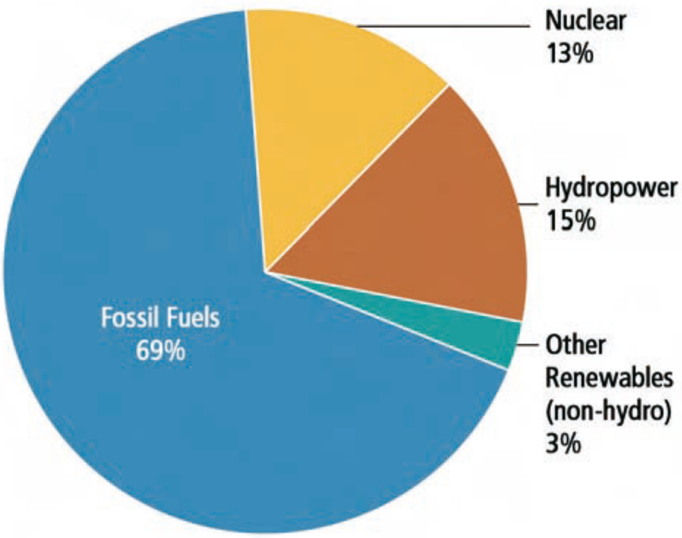

Figure 2. Share of global electricity from renewable energy, 2008 (REN21 2010).

Market shares of energy resources can be expressed both in terms of share of primary energy production[5] and electricity production. In this thesis, the main focus is on the share of electricity, as the issue of ES assessed here is a steady and reliable supply to the electric grid.

2.2 Renewable resources

2.2.1 Introduction

As mentioned in the previous section, the main characteristic of renewable energy is their "unlimited" existence in the world, due to their ability to regenerate. The main issue when promoting renewables today is their positive impact on reduction of the climate change problem. There are also several other benefits following RE utilization. Social and economic development, energy security/ delivery guarantee, reduced the negative consequences considering environment and health are some of these (SRREN 2011).

Renewable resources can be divided into two groups: the "constant" and the intermittent. The so-called baseload renewables – including biomass and geothermal – are those whose output is fairly constant for most of the year (Sandia 2010). These represent the main share of RE in energy production as of today (2008), as shown in figure 3, but will not be included in the group of renewables considered here, as the main characteristic of intermittency (which is to be solved by the ES technology assessed in this thesis) does not apply for these to the same extent.

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[5] http://www.eia.gov/emeu/aer/txt/ptb0102.html

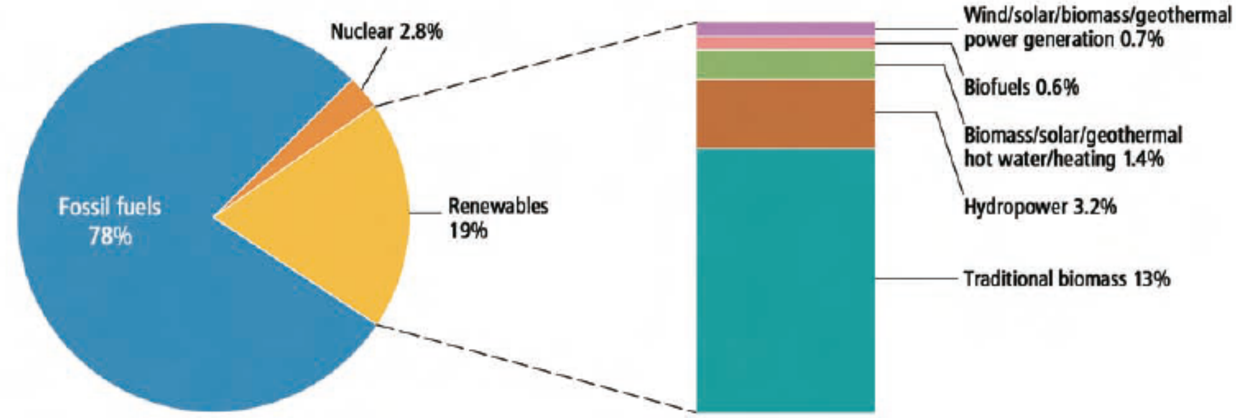


Figure 3. Renewable energy share of global final energy consumption, 2008 (REN 21 2010).

Hydropower is the most conventional renewable resource, and has been harnessed for centuries. It is a somewhat easy technology, using the force of gravity on water masses to generate the power. The technology is applied all around world, with location determined by water access and site. Norway, with a high number of mountains, produces 96 % of its electricity from 1250 hydropower stations located around the country (Renewable energy 2007). Though, this is a distinctive situation that does not reflect the general global circumstances, where only 15% (in 2008) of the electricity is generated from hydropower (REN21 2010).

Since 1990, the development of new hydropower station and production capacity has slowed down. Most of the areas where production is allowed are already in operation, and the rest are either protected or non-profitable. This applies to most of Europe and America, while the developing countries, especially in Asia, have a good potential for hydropower use (Renewable energy 2007).

Solar power represents the global renewable resource with the highest power potential. The radiation reaching the surface of the Earth equals approximately 10,000 times the world's annual energy consumption. Figure 4 shows this annual comparison of the total energy potential supplied by the sun and the global energy consumption, along with the proven reserves of fossil fuels.

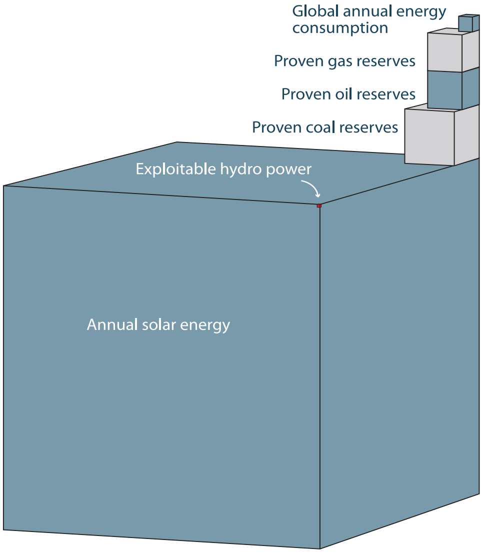
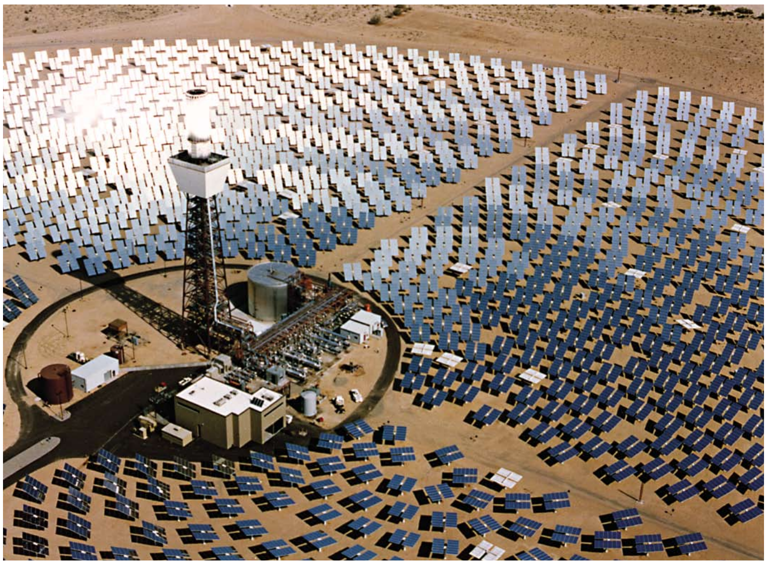


Figure 4. Comparison of the annual total energy potential supplied by the sun and the annual global energy consumption (Renewable Energy 2007).

There are already several solar power plants operating around the world, and more in their planning stage. Large solar plants are often located in desert-like areas, like shown in figure 4. This has several reasons. First, user conflicts due to the visual or spacious impacts are avoided. Second, the solar energy potential is, as explained previously in this chapter, often much higher here. The main drawback is relatively high cost compared to other renewables as hydro- and wave power (SRREN 2011).



The solar power tower "Solar Two" in the Mojave desert in California. Photo: Sandia National Laboratories, US Department of Energy/National Renewable Energy Laboratories.

Figure 5. The “Solar Two” facility, Mojave desert, California (Sandia/ NREL).

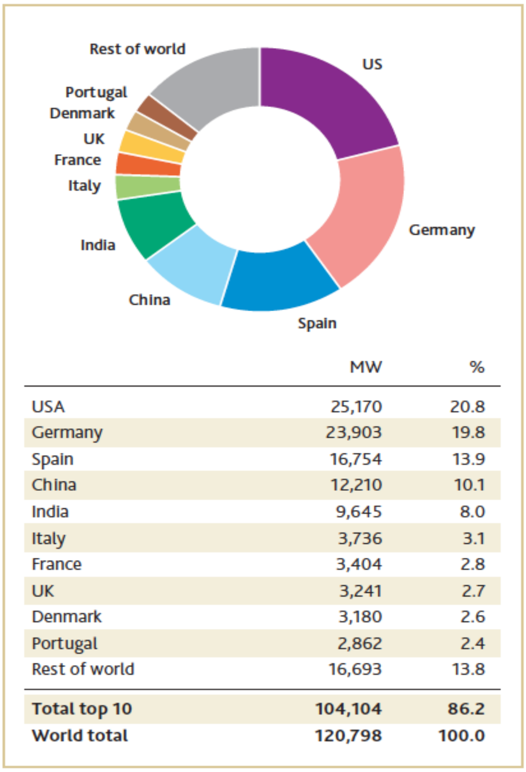
Other types of ocean power (wave and tidal) are emerging technologies, which yet are at a very early stage of their development, and will not be mentioned in details here.

2.2.2 Wind power

Wind power is the new global ”hot” theme in the energy sector. The R&D investment has increased tremendously the last decades, and lately especially the interest in offshore utilization has boosted. Germany and Spain are the leading wind power producers in Europe, with a total installed capacity of 23.9 and 16.8 MW respectively. USA passed both of these in 2008, installing 8.36 MW of capacity (GCEW 2008). Figure 7 shows the 10 leading countries in wind power.

Wind turbines are most often installed as on- and offshore clusters, so-called wind parks. Expensive property, limited areas with good wind conditions, cost of infrastructure and minimizing visual impact are all reasons for this (Renewable energy 2007).

Figure 6. Off- and onshore wind parks.



	MW	%
USA	25,170	20.8
Germany	23,903	19.8
Spain	16,754	13.9
China	12,210	10.1
India	9,645	8.0
Italy	3,736	3.1
France	3,404	2.8
UK	3,241	2.7
Denmark	3,180	2.6
Portugal	2,862	2.4
Rest of world	16,693	13.8
Total top 10	**104,104**	**86.2**
World total	**120,798**	**100.0**

Figure 7. Installed Wind power capacity around the world (GWEC 2008).

The installed capacity experienced an annual growth of 30% from 1992 to 2005 (IEA 2006). As the installed capacity increases, the situation becomes relatively more problematic due to mismatch of supply and demand (European Commission 2007). Installed wind power can change by a few hundred MW in less than an hour (Bullough et al. 2004), or 100% on a daily basis (APS 2010), and the absence of certainty in production rate is an ever-increasing problem. Thus, this problem is reduced somewhat by the fact that the net variation in power generation from wind groups is less than for individual wind turbines (OECD/ IEA 2009).

Wind parks using hybrid systems to produce hydrogen from excess energy produced, has become more popular the last decades. This technology is still in its R&D stage, though several minor test projects have been successfully implemented. An example is Hydro’s project on Utsira, a small island with 10 households, where two windmills are to produce enough power to supply the island. Excess energy produced was stored as hydrogen produced through electrolysis, in a tank on the plant. This was used to produce electricity when the wind power didn’t generate enough electricity relative to demand. Despite successful operation, the hydrogen energy storage project was decommissioned in 2010 due to high operational costs, though the two wind mills are still generating electricity to the grid.

As one of the fastest growing RE resource as of today (REN21 2010), this will be assessed in the case study in chapter 6. Through analyzing the issues of installing an ES facility in this mid-size wind park according to the main characteristics defined in the introduction, an assessment will be made of which technology is the best suited in this case. There are several prerequisites made for this case, especially the location issue is simplified. As one of the main challenges of renewable energy, introduced in chapter 2.3, it would give limitations for which technology was best suited. Yet, the location of the wind/ ES park analyzed in this thesis is assumed to be suited for all ES options.

2.3 Challenges of RE integration

There are a great number of aspects to consider when it comes to integration of renewable power generation in the market today. Technology, economy, politics and market-based issues all need to be assessed to determine to what extent renewable projects are sensible.

Concerns about the environmental prospective and desire for a sustainable future is an issue getting ever-more attention, and the main challenge to put out these concerns is the need of technology that allows satisfying and efficient utilization of these “infinite” resources. Apart from hydropower, the level of maturity on the RE market is low, and an ongoing development of technologies and solutions for utilization is in the spotlight (REN21 2010). For technologies already commercialized, as hydropower, the request for less expensive and more efficient solutions push R&D forward.

The main barriers of large-scale integration of renewables are economy and technology. Comprehensive research is ongoing, but most of technologies for implementing the renewables are yet too expensive or immature for commercializing. There are several practices and policies for governmental funding and support in the new energy sector, and different types of subsidies are used to finance projects within renewables and ES.

The principle for such support is *"the long-term economic, energy-security and environmental benefits they can bring"* (WEO 2010), given a certain degree of cost-effectiveness in this financing. In Norway the normal practice is financial support in the startup of a new power plant to overcome the high capital cost barrier, while in other countries policies like feed-in tariffs and green certificates are common. Germany, Denmark, Spain and at least 50 countries and 25 states/provinces have feed-in tariffs, a policy to support during operation to ensure income for the RE producers. The last years the development has boosted, and in 2010 more than 100 countries worldwide had some sort of policy target related to RE, compared to 55 in 2005 (REN21 2010). Table a) in Appendix A shows the national policies practiced in different countries.

Two technological challenges arise by use of renewables: location of resources and variability of generation. These have played an insignificant role in electricity generation from carbon-based energy. Major renewable resources are often located far from population centers, and the variability due to weather changes is significant compared to conventional resources (APS 2010). These are further noted as availability and intermittency respectively. They can be considered both as motivation for technological development to solve these problems, or as RE drawbacks.

2.3.1 Availability

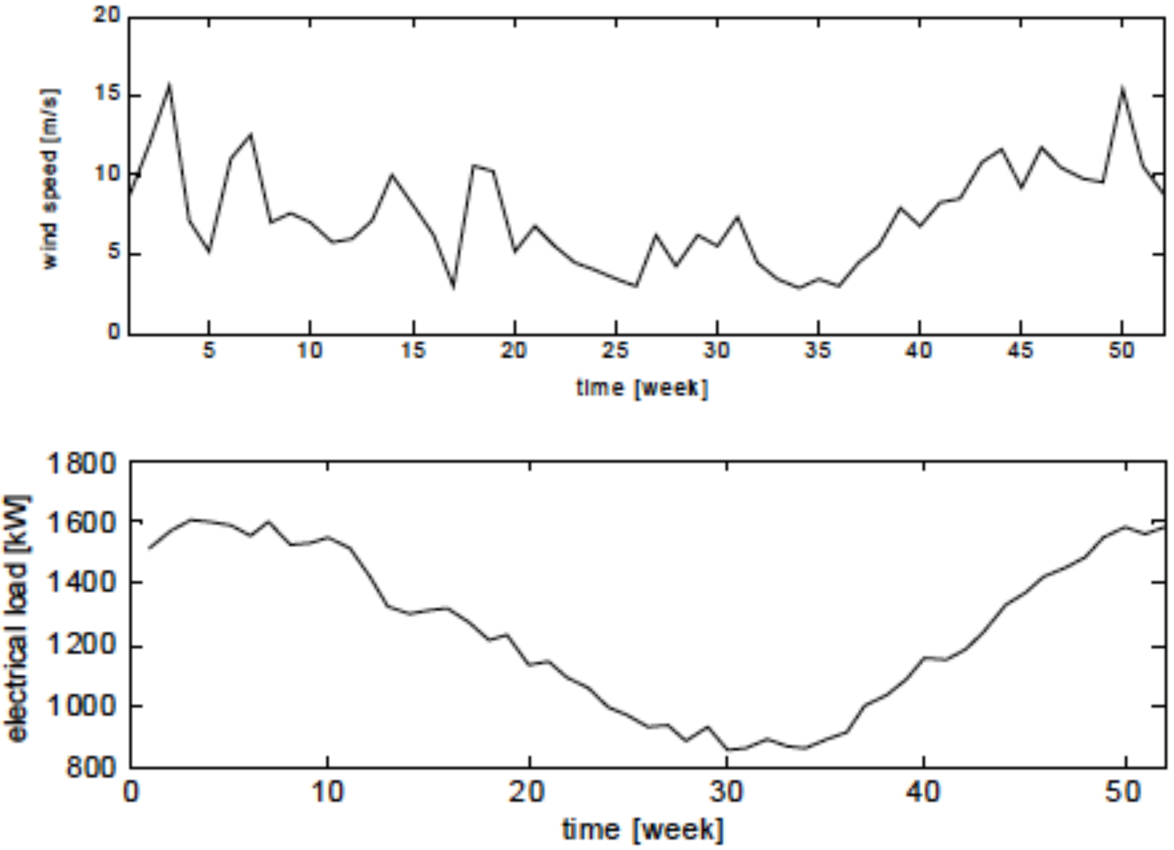
The challenge of mismatch between availability and demand of power potential is a common problem for renewables. Figure 8 illustrates this globally: the location of the two major power resources of wind and sun. It shows how the potential in these resources often are located in remote areas. Greenland has a very high annual average wind speed, but is not densely populated. To be able to utilize the energy potential supplied by the wind in this area, a comprehensive infrastructure of grid and transportation is required. This is complex and expensive, and results in high cost.

Figure 8. Global potential wind and solar power (www.3tier.com).

2.3.2 Intermittency

The renewables are intermittent, which is considered their most distinctive and challenging characteristic as an energy source. They produce energy in a stochastic manner, which causes uncertainty in energy production and supply, and both surplus and shortfall of energy can be the case in power generation. In periods where the potential power present at the plant exceeds the demand from the grid, energy is dissipated if not utilized or captured. To avoid this, energy storage is considered a solution, which will be explained in details in chapter 3. It gives the possibility to store this surplus energy available, and then use it in periods where demand exceeds the power generated at the plant. Also, it provides the possibility to control and regulate the electricity delivery much better than without ES.

The first graph in figure 9 shows the weekly average wind speed throughout one year. Despite a somewhat lower average speed during the summer period, there is a high degree of variance. The second graph illustrates the electric load during a year. There is also some degree of variance here, but in the same scale as the wind speed. This same trend applies on a daily basis, and underlines the importance of ES to stabilize the generated wind power.



Figur 9. Average wind speed (m/s) and electric load over a year (seasonal basis) (Korpås 2004).

2.3.3 Consequences and requirements of integration

The integration process of renewables is as of today not a major problem considering grid infrastructure and capacity. Yet, as the share of energy production increases in the favor of RE, the intermittent characteristic of these resources will be a problem considering grid capacity and energy delivery. Due to a higher share of stochastic energy generation, the need of additional regulation will raise. Estimations say that a fraction of > 20% of the load will require additional control resources for grid stability control (ULB 2010).

Another consequence is the difficulty in responding to market economy. The unpredictability in electricity generation makes difficult to response to the market conditions and to optimize profits (ULB 2010).

2.4. Future of renewables

There is high degree of uncertainty considering the future situation of the energy market. Attempts to predict the RE development and market share has been made through comprehensive scenario analyses, where low-, mid- and high-share scenarios are treated. Such analyses can help "exploring" the role of ES in the future of renewables (Martinot et al. 2007).

Low-share most often reflects the current situation, while high-share assume a policy-intensive scenario with significant increase in RE utilization. Europe for an example, defines a low-share scenario of 15-20% by 2030, and policy-intensive scenario of 30-40% by 2030. Several national and international high-share scenarios assume up to 50% share of primary energy and 50-80% share of electricity for renewables (Martinot et al. 2007).

Focus on climate and sustainable energy future becomes ever more important on the public agenda. National and international energy policies arise, and *"it will be governments, and how they respond to the twin challenges of climate change and energy security, that will shape the future if energy in the longer term"* (WEO 2010). The overall goal that applies for all of these policies is the wish and need for a future sustainable energy market. The objectives defined for to affect and promote the RE integration, comprise issues like emission constraints, technological development, and economy. On the UN conference in Copenhagen, December 2009, there was set a non-binding objective to limit the global temperature rise to 2 °C above pre-industrial levels. This seems to be obtainable in the western countries, but the prospects in the developing countries, especially in Asia, it seems more challenging to redeem. China, as one of the major and fastest growing energy consumers, is estimated to have an increase in energy demand of 75 % from 2008 and 2035 (WEO 2010), with an target of 16% share of primary energy from renewables by 2020 (Martinot et al. 2007). The main problem is that this increasing energy need is mainly covered by energy generated from conventional carbon-based energy resources.

In the longer term however, there are several other issues that may have a limiting impact on the RE development. Technical challenges, public acceptance, system integration and infrastructure constraints are some of these (SRREN 2011). As the renewables increase their share in the energy market, technologies and strategies are needed to solve the problem of intermittency in power generation. ES is one of the main strategies proposed to achieve this (NREL 2009), which allows energy to be stored for later use. This is discussed in chapter three, where different ES technologies and their benefits are introduced.

Ultimately, the adoption of renewables as a global energy resource will depend on cost effectiveness compared to the conventional energy sources. For the next decades, cost of RE will most probably decrease along with technological improvement, like the trend has been for the last decades. Fossil fuels on the other hand, will unavoidably experience higher costs in the future, due to depletion, internal conflict and environmental impact (Veziroğlu 2003), which most probably will favor renewables. R&D and governmental funding and subsidies are essential to move this integration of forth. Though, in prospective manners, some degree of renewable exploitation will independently be necessary to maintain the current level of energy consumption (which is also expected to increase significantly the next decades).

Chapter 3 - Energy storage technologies

"Electricity energy storage is any means of taking power directly from power plants or the electric grid and storing it for later use."(EPRI 2008).

3.1. The concept of energy storage

Increasing amount of research in the field of ES technologies, and the eager to find new solutions has several reasons. Concepts like hybrid vehicles and eco-friendly transport, smart grids and more efficient exploitation of renewables, are all important aspects affecting the effort put into this R&D process. There are numerous solutions that have proved or seem to have a potential within ES, supported by theory, experience and test-plants, and several are already introduced and established on the market.

Today there is a global installed storage capacity of 100GW, of which 99% is represented by pumped hydro (OECD/IEA 2009). Extensive, ongoing R&D is trying to find new and efficient solutions for ES. Predictions say that the amount of electrical energy produced will increase from 12% of the total global energy production in 2007 to 34% in 2025, where the share of RE will also rise. Hence, the need of more installed ES capacity is obvious (Ibrahim et al. 2007).

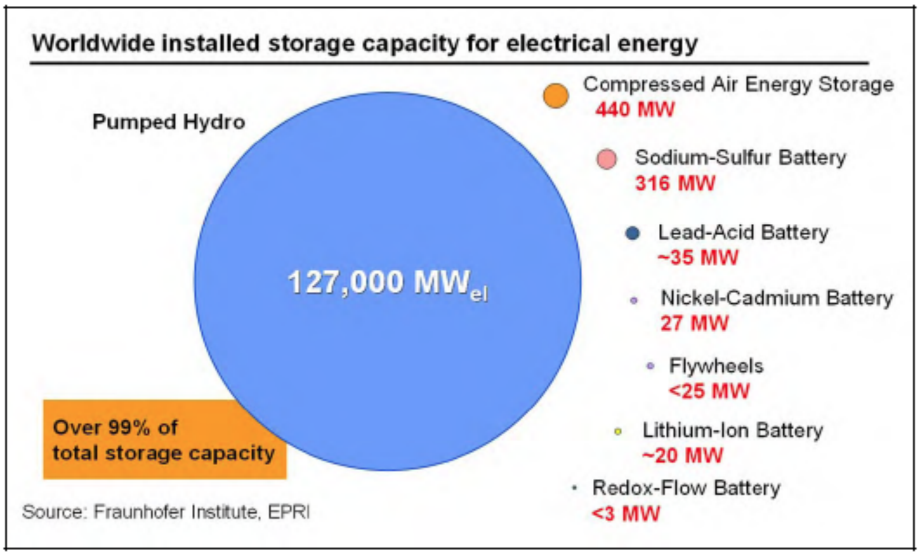


Figure 10. Storage capacity for electrical energy (EPRI 2010).

For large-scale integration of RE, its intermittent characteristic makes incorporation onto the electric grid more challenging. New and better technologies are required, to provide possibilities for control and regulation of the electricity generation, in addition to a general improvement of grid stability and reliability. This is why ES has become more important the last decades, as the energy market experience changes in favor of renewables. It allows these intermittent resources to "(…) *provide energy when it is needed, just as transmission provides energy where it is needed" (Gyuk 2008),* despite their stochastic power production. Due to high costs and technological barriers, conventional and reliable methods for power generation like fossil fuel are still preferred, but this seems to be heading for a new course.

There are several applications for which ES can be used, as illustrated in figure 11. These have generally been divided into five broad application categories: generation-related, ancillary services, transmission and distribution (T&D), end-user and renewable integration (Sioshansi 2010). In this thesis the main issue will be integration of renewables, as introduced in chapter 2, which requires somewhat large-scale ES (mostly in the range of MW). This is a very important ES application, as this principle is *"best thought of as enabling technologies..(….)..promoting a market change, such as the faster introduction of renewable energy resources."(Baxter 2005).* In chapter 3.4, the general benefits/values of ES will be assessed, focusing on this specific application.

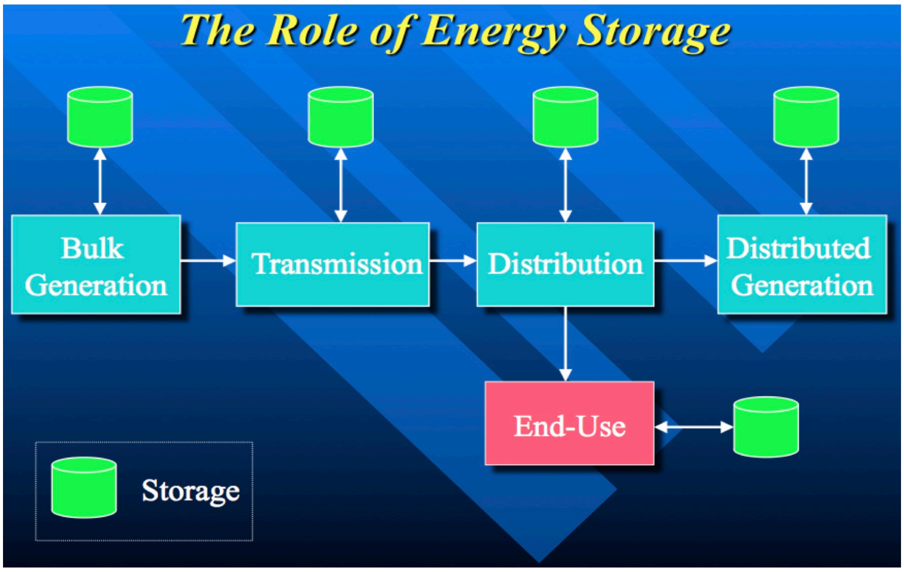


Figure 11. Roles of energy storage (SERG 2003).

Working on integration of renewables, ES could be used for several applications: match supply and demand, store surplus electricity generated on the plant, act as an electricity back-up when generation is not available, and smooth output fluctuations from the intermittent energy resources (Connolly 2010).

Figure 12 shows a simple structure of an ES system. With a controller monitoring the deviation of electricity demand compared to production, it can regulate the electricity output necessary from the storage device (discharge). If the demand falls below the production level, the storage unit will be charged.

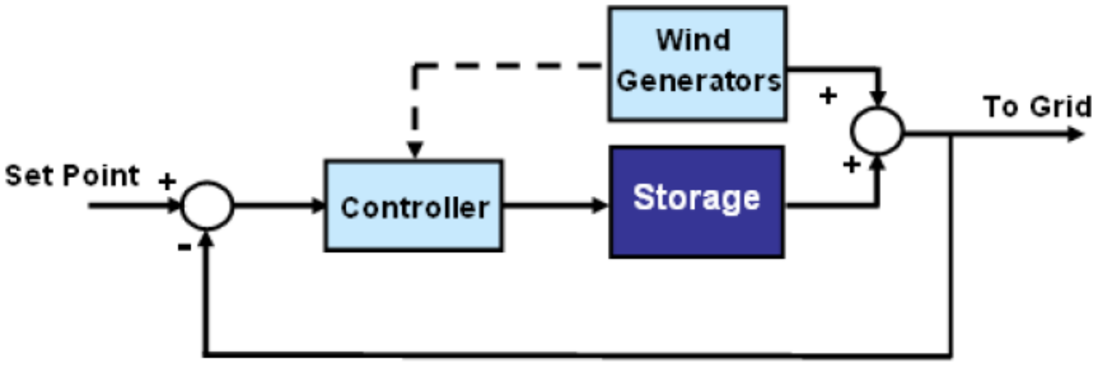


Figure 12. Structure of an ES system (EPRI 2008).

Several technologies can contribute to serve the applications mentioned. Some of the general characteristics and their ideal value of ES systems are defined as (SERG 2003; APS 2007):

- Quantity of energy stored (commonly kWh or MWh)
- Duration of discharge required (seconds, minutes, hours) → scalable
- Power level (kW or MW) → high power
- Response time (milliseconds to minutes) → fast dynamic response, flexible
- Frequency of discharge (number per unit of time, such as per day or year)
- Energy density (facility space and total ES capacity) → high energy density
- Cycle Efficiency (fraction of energy returned to the grid) → high conversion efficiency
- Cycle life → long lasting
- Footprint/compatibility with existing infrastructure → easy to integrate and implement
- Transportability → relocatable
- Cost → cheap

Considering these characteristics, they all in a varying degree describe the technologies introduced in chapter 3.2. The criterions from which ES is to be assessed in this thesis comprise the characteristics of cheap, flexible, scalable and high energy densities. All ES technologies have strengths and weaknesses, and it is important to choose the one *"best suited for a few related applications, where its technical capabilities can be leveraged for maximum economic benefit."*(Baxter 2005.)

Enabling renewables to be integrated into energy market has a high priority on the ES agenda (EPRI 2008), with the objective to solve the following problem of intermittency. For adequate ES capacity available, system planner need to include sufficient generating capacity to meet average demand rather than peak demands (Chen et al. 2009).

The basic principle of ES is to charge the storage device using off-peak and/or excess renewable electricity, and discharge through electricity production in periods of peak demand and high electricity price. How this cycle function is defined by the ES characteristics of the different technologies. The essential characteristics, which determines the cost of an ES facility, are (OECD/IEA 2009):

1. Storage properties: energy density, output density, energy storage efficiency, storage scale and charge/discharge times
2. Operation properties: start/ stop times, load response, partial load feature, lifetime, reliability
3. Surroundings/ circumstances: Location, construction time, safety and lead time/ market development

The significance of the above characteristics is decided by the scope of the project and storage application. A definition based on the latter separates the ES technologies into two groups, which will be accounted for in chapter 3.2. Also there, each technology will be introduced based on these properties. Figure 13 shows the distribution of the most common ES technologies based on the essential characteristics of discharge time and power rating.

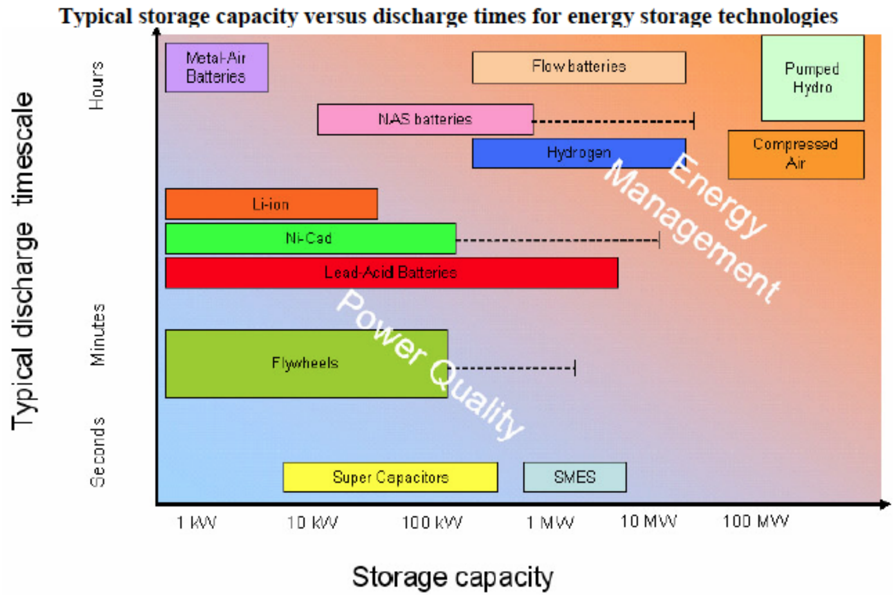


Figure 13. Storage capacity versus discharge time for ES technologies (European parliament (ESA) 2008).

3.2. ES technologies

"Large-scale electricity storage promises to be a game-changer, unshackling alternative energy." (REN21 2008)

There are currently six ES technologies that operate satisfying in different scales and manners, which seem to have a promising future (APS 2007). These include pumped hydro energy storage (PHES), compressed air energy storage (CAES), batteries, flywheels, superconducting magnetic energy storage (SMES), and electrochemical capacitors. One other, yet very early in its R&D stage, is hydrogen energy storage (HES), which also will be included as an alternative ES technology in this thesis.

The different technologies have distinct properties, strengths and application areas. Main diversities like storage capacity and discharge time, determines for what applications they are best suited. Based on this, they can be divided into two groups: power applications technologies and energy applications technologies.

Power applications require high power output for short periods of time (seconds to minutes), and usually have capacity to store only modest amount of energy per kW of rated power output (capacitors, SMES and flywheels, some batteries). Energy applications on the other hand, require large amount of energy and long discharge duration (minutes to hours). PHES, CAES, batteries (some types) and underground HES falls into this group (Sandia 2010; Chen et al. 2009). This contributes to determine which technologies are suited for ES in the electricity generation stage. Table 1 shows this division when looking at the storage capacity (kW → power applications; MW → energy applications).

Storage Technology	PHES	CAES	Batteries	Flywheels	SMES	Capacitors
Energy Storage Capacity	< 24 GWh	0.4-0.72 GWh	< 200 MWh	< 100 kWh	0.6 kWh	0.3 kWh
Duration of Discharge[6]	> 12 h	4-24 h	1-8 h	< 1 h	10 sec	10 sec
Power Level	< 2000 MW	100-300 MW	< 30 MW	< 100 kW	200 kW	100 kW
Respons Time	30 ms	3-15 min	30 ms	5 ms	5 ms	5 ms

Table 1. General characteristics of ES technologies[7] (APS 2007).

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[6] At maximum power level

[7] Hydrogen excluded due to its low cycle efficiency (35%).

The different technologies are found in different stages of their development, and table 2 shows a classification of their current maturity (LRI 2010). Many of the technologies are quite immature, but all found in their R&D stage.

Mature technology	Developed technology	New/less developed technology
Hydro-pump	CAES	Hydrogen/ fuel cell
Lead batteries	NaS batteries	Metal-air batteries
	Li-ion batteries	
	Flow batteries	
	SMES	
	Super condensator	
	Flywheel	

Table 2. Technological maturity of the storage technologies (LRI 2010).

3.2.1. Pumped Hydro Energy Storage - PHES

PHES is the most widespread and mature storage technology, and constitutes for 99 % of the global installed ES capacity, illustrated in figure 1. Its main applications are regulation, energy generation and delivery. The capacity and load cycle varies considerably, but they mainly regulate on a daily or seasonal basis with a capacity up to several thousand MW (Pembina 2008). The worldwide PHES capacity makes up for roughly 3 % of the global electricity generation (Baxter 2005).

Conventional pumped hydro uses two water reservoirs, separated vertically. During off-peak hours water is pumped from a lower-level reservoir to an upper-level reservoir. When required, the water flow is reversed to generate electricity. It has a fast response time on demand changes, measured in seconds to minutes (Pembina 2008). Figure 14 (Connolly 2010) shows the structure of PHES systems.

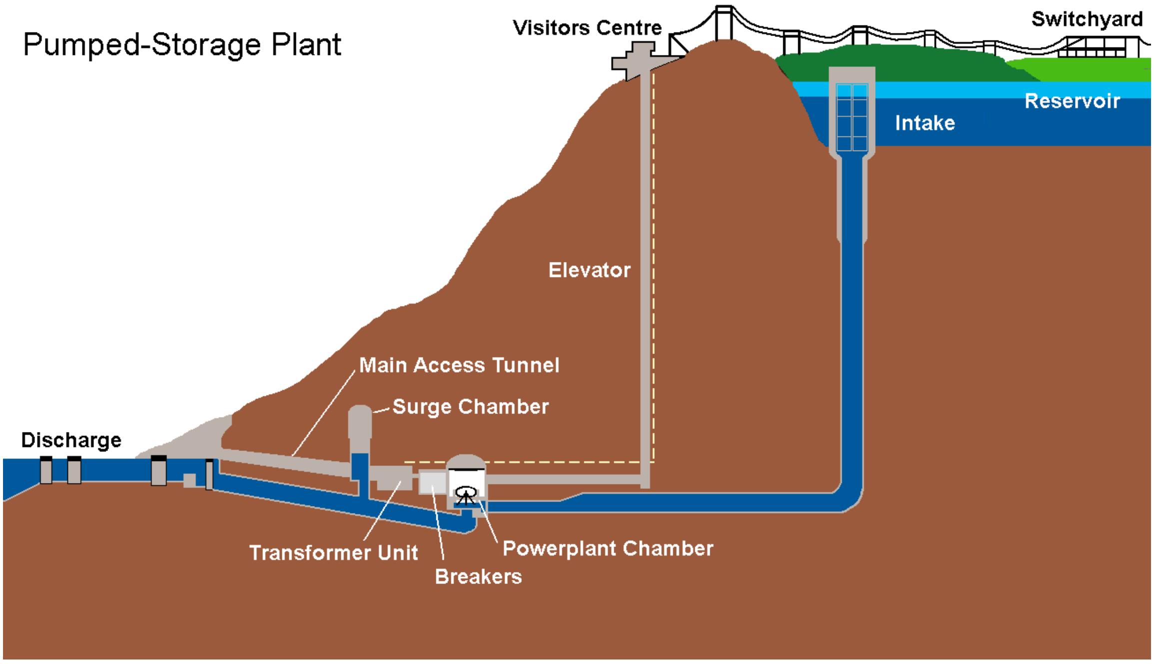

Figure 14. General structure of a PHES facility.

Pumped hydro was first used in Italy and Switzerland in the 1890's, and was the only commercial available ES technology for utility scale applications up until the 1970s (Baxter 2005). By 1933 reversible pump-turbines with motor-generators were available. Adjustable speed machines are now being used to improve the overall efficiency.

Pumped storage plants are characterized by high capital expenditure, low maintenance costs, long lifetime, long construction times (determined by site), permitting, and associated environmental impact (Pembina 2008). Table 3 shows a summary of general properties of pumped storage plants.

Description	Value
Efficiency	65-85 %
Time of discharge	hours to days
Power capacity	< 4GW
Lifetime (years)	40-50
Advantages	High power capacity Very high energy capacity Lower O&M cost
Disadvantage	Site restrictions Low efficiency (variable) High capital cost

Table 3. Summary of PHES values (LRI 2010; Pembina 2008; Connolly 2010).

Underground pumped storage is also an alternative, using flooded mine shafts or other cavities/caverns with a good opportunity for using existing infrastructure. This gives significantly more freedom considering sites, and also reduced environmental impact. Still, it also means that the head of the system must be significantly higher due to reduced water volume. Open sea can also be used as the lower reservoir. Seawater pumped hydro plant was first built in Japan in 1999 (Yanbaru, 30 MW). Upgrading existing PHES facilities, as with variable-speed drivers, advanced turbines and control systems, is also one of the main focuses for development of this technology (Baxter 2005).

Very large-scale storage as pumped hydro still has some unexploited potential, where geographic considerations and other factors such as public acceptance allow installation. Still, site limitations have already been felt, and the growth in hydropower development has slowed down the last 10-20 years compared to other storage methods (Renewable energy 2007).

3.2.2. Compressed Air Energy Storage - CAES

CAES uses off-peak or surplus electricity to compress air, which is stored in a reservoir, either an underground cavern or aboveground pipes or vessels. To produce electricity, the compressed air is heated, and released through a conventional turbine generator. Figure 15 shows a general set up for a power station with a CAES facility. This shows the main storage principles; underground cavern storage, off-peak electricity in/ peak electricity out, compressor for air in, turbine and generator for air out. As for pumped hydro, CAES also depends on suitable sites and geological formations, though not limiting in the same degree as for the first.

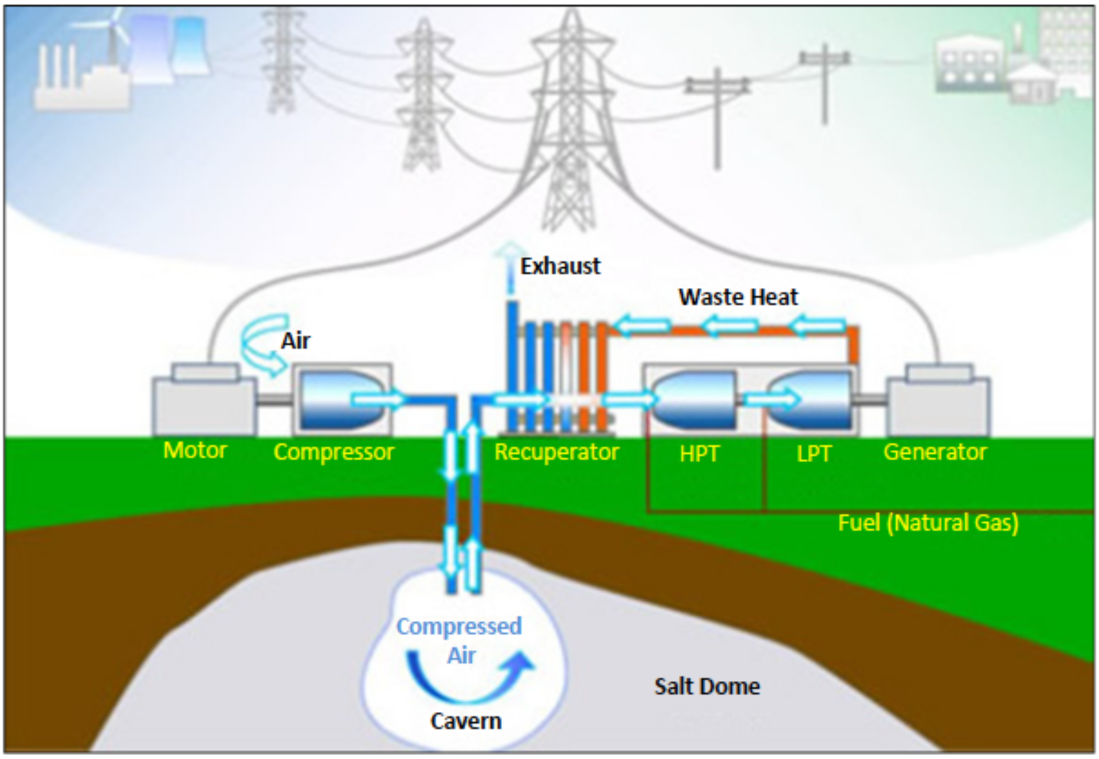

Figure 15. General structure of a CAES facility.

This is classified as developed technology, and is accounted the only bulk ES technology apart from pumped hydro that can be operated at reasonable costs in the wholesale power market at present time (LRI 2010; Baxter 2005). It is also the most cost effective with storage capacities up to hundreds of MW and discharge time up to 24 hours (APS 2007).

Despite successful operation, there are only two commercial large-scale CAES running today. Located in Hundorf, Germany, there is a 290 MW plant, built in 1978. The second is a 110 MW plant in McIntosh, Alabama, built in 1991. They both use underground caverns formed from dissolved salt domes for storing the compressed air. There are also planned projects, where two are mentioned in table 4. The largest ever planned is in Norton Ohio, with a capacity of 2700 MW. This 9-unit plant will compress air to 1500 psi in an existing 9.6 million cubic meter limestone mine, some 2200 feet under ground.

Name	Huntorf (Germany)	McIntosh (USA)	Adele (Germany) planned	Norton (USA) planned
Type	Conventional	Conventional with recuperator	Advanced-Adiabatic	N/A
Capacity	290 MW	110 MW	200 MW	2,700 MW
Year of commission	1978	1991	2013	N/A

Table 4. Existing and planned CAES facilities (LRI 2010).

One of the current disadvantages using CAES, is the need of fuel (natural gas) to run the turbine. This causes CO_2- emissions from the combustion, which is not a desired result of ES. Still, a plant with CAES uses less than one third of the natural gas used in pure gas electricity generation without compressed air, and hence produces three times the electricity for the same amount of natural gas/ emission (Pembina 2008; Baxter 2005). Recent development has come up with a new technology, AA (advanced adiabatic)-CAES, which operates without a combustion chamber and need of fossil fuels, and offers significant improvements in the cycle efficiency (OECD/IEA 2009; Bullough et al. 2004). It's being developed through the "AA-CAES" (Advanced Adiabatic – Compressed Air Energy Storage) Project, funded by the European Union. Other improved properties offered by a second-generation CAES are lower installation costs, higher efficiency, and faster construction time (EPRI 2010).

Description	Value
Efficiency	max 70%
Time of discharge	hours to days
Power capacity	hundreds of MW (< 1GW)
Lifetime (years)	30
Advantages	High power capacity High energy capacity Lower cost
Disadvantage	Geological restrictions Gas connection --> emisisons

Table 5. Summary of CAES values (LRI 2010; Pembina 2008; Connolly 2010).

3.2.3. Battery energy storage - BES

The battery is a well-known principle, delivering electricity at high round-trip efficiency, with the capability of being reloaded. It is used in basically all mobile electronic equipment that does not have access to an electrical grid, and are also used for backup in case of power failure, like in hospitals, where this could cause fatal consequences. Today, it is mainly used for small-scale energy storage, but experiencing ongoing and increasing R&D. Its advantages include high efficiency, relatively compact size, and flexible location, while its main constraint is high cost (Yang and Williams 2009).

Along with hydropower, batteries are the oldest and most mature storage technology. They generally produce electricity through a chemical process, so-called redox reactions. The last decades several different types of batteries have been developed with distinct usage properties. They have broad range of applications, from very small-scale storage up to tens of MW-scale.

For ES there are three more important types of solid batteries: Lead-acid (LA), nickel-cadmium (NiCd) and sodium-sulphur (NaS). Though, recent R&D shows that NaS is the only major contender for future large-scale storage, while LA and NiCd will be used primarily for their current applications (Connolly 2010). NaS, along with flow batteries are the most promising types of batteries for large-scale ES, and they are all competing in the renewable energy market. Their future will be determined by upcoming demonstration results (Yang & Williams 2009).

Batteries are not yet commercialized as large-scale storage (>50MW), and it will require big volumes to provide this power-scale. Still, the technology is constantly developing, and there are several ideas for batteries as storage for large amounts of energy. As of today, their cost is about 3 to 12 times higher than the one for conventional PHES, but with a continuing development their operating costs will approach that of pumped hydro (Poonpun & Jewell 2008). Japan is taking the lead in use of batteries for large-scale storage, with more than 55 installations of BES (APS 2007).

Batteries are often denoted by a modular nature, especially the solid ones, due to production in standard units. Multiple units are often connected in "battery-networks" to achieve greater power and energy levels, with a discrete increase (APS 2007). Flow batteries are more adjustable considering energy and power level, yet their complexity is the reason why conventional batteries are still more popular (Connolly 2010).

3.2.3.1. Lead-acid battery, LA

Lead batteries originated in the 1860s, and are today the most commercially mature rechargeable battery technology in the world (EPRI 2010). Their conventional uses are in motorized vehicles and for backup in electricity grids. Compared to other batteries they are the low-cost option, up to 8 times less expensive than Li-batteries and up to 13 times less than Ni-batteries (European parliament 2008). Still, they are generally not used for large-scale storage, due to the battery size required and the replacement costs occasioned by their short cycle of life (EPRI-DOE 2004).

Despite new, competitive types of batteries, LAs will remain an important ES technology in several market applications in the foreseeable future (Baxter 2005). The R&D is ongoing, and new advanced lead-acid batteries are being developed for usage in peak shaving, frequency regulation, wind integration, photovoltaic smoothing and automotive applications (EPRI 2010). They are recognized by improved lifecycle, durability and response time.

Considering the expanding role of large-scale ES in the future, LA batteries have a limited potential due to its short lifetime. It causes a considerable increase in maintenance costs, which makes it hard to compete with the lifetime of new battery technologies when these are commercialized. As LA is a highly mature technology, the possibility of a major improvement in lifetime is small, despite further R&D (Baxter 2005). Also competing storage solutions and growing environmental concerns about lead will restrain deployment of LA batteries.

Description	Value
Efficiency	80-85 %
Time of discharge	seconds to hours
Power capacity	< 50 MW
Lifetime (years)	5.
Advantages	Mature technology Low cost
Disadvantage	Short lifetime Small potential of further development

Table 6. Summary of LA battery values (LRI 2010; Pembina 2008; Connolly 2010).

3.2.3.2. Sodium sulphur battery - NaS

Sodium-sulfur is cylindrical electrochemical battery, consisting of a molten-sulphur positive electrode separated from the molten-sodium negative electrode by a solid ceramic electrolyte, shown in figure 15.

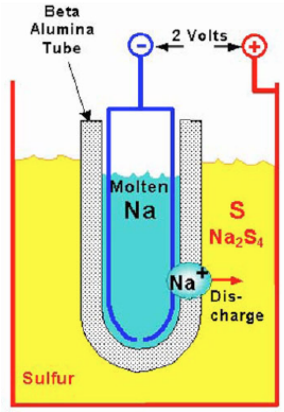

Figure 16: Standard NaS-battery.

It is a commercial storage technology, developed over the past 25 years, with applications within electric utility distribution grid support, wind power integration, and high-value service applications on islands (EPRI 2010). The technology is well received, specially utilized in Japan where several large installations are operating (Baxter 2005). The largest single NaS-installation is a 34 MW/ 7h wind stabilization project in Rokkasho, Japan, operating since August 2008. Total installed capacity is anticipated to reach 606 MW (3636 MWh) by 2012 (EPRI 2010).

NaS has high energy density - about three times the one of LA batteries (Connolly 2010), and a good round-trip efficiency (Baxter 2005). Its disadvantages are limited lifetime (<3000 cycles), temperature sensitivity and very high initial costs for large-scale batteries (Pembina 2008).

For the application of RE integration, NaS has a MW scale storage potential by combining battery modules, and is considered the only conventional battery technology with good opportunities in the large-scale ES market (Connolly 2010).

Description	Value
Efficiency	80-90 %
Time of discharge	Second to hours
Power capacity	< 50 MW
Lifetime (years)	10
Advantages	High efficiency Medium power and energy capacity High power density
Disadvantage	Higher initial cost Temperature sensitivity

Table 7. Summary of NaS battery values (LRI 2010; Pembina 2008; Connolly 2010).

3.2.3.3. Flow batteries: Vanadium-redox battery -VRB

Flow batteries are rechargeable batteries in which energy is stored and released through a reversible electrochemical reaction between two separate tanks of electrolyte. The electrolyte flow through a redox cell, converting chemical energy directly to electricity. The main difference from ordinary solid batteries are that the chemical species used for producing the electricity are supplied externally, instead of stored inside. This allows flow batteries to be scaled up independently of the battery in itself, while the solid battery is limited by the amount of active material that can be stored inside it. Thus, power and energy are separated and independent of each other, as power output depends on the fuel cell and energy storage capacity depends on the electrolyte tanks (Gyuk 2008; European parliament 2008). Many variations of energy storage and power capacity are possible, determined by the size of the tanks and type of electrolyte.

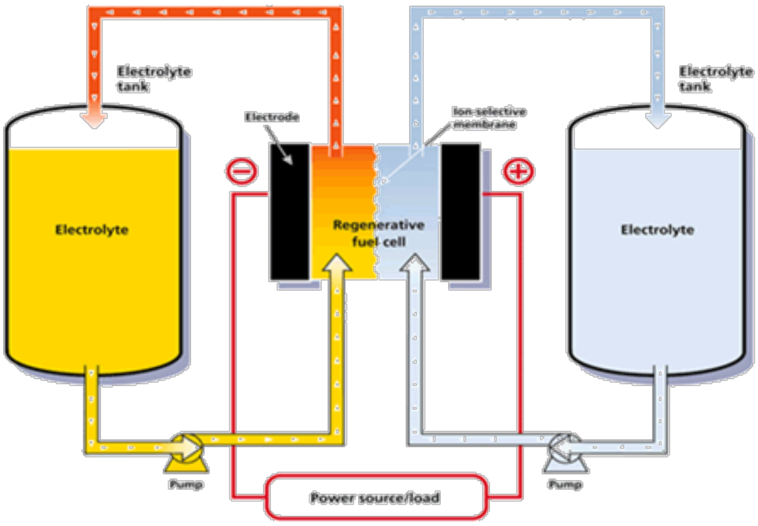

Figure 17. General Flow battery.

Some great advantages of flow batteries are their simplicity in replacing the electrolyte when degraded (despite the battery complexity) (Sandia 2010). Also, as the same chemical reaction is taking place during charging and discharging, the charge/ discharge ratio is 1:1 (Connolly 2010).

The four leading flow battery technologies, either in production or very late stage of development, are polysulfide bromide (PSB), zinc bromine (ZnBr), hydrogen bromine (H-Br) and vanadium redox (VRB) (Pembina 2008). VRB is lately the most mature and popular of the flow battery systems available (EPRI 2010), and appears to have great potential for future deployment in wind power projects and more widely in the electricity networks (European parliament 2008).

VRB is charged and discharged through a reversible process, and tests have confirmed that it's capable of more than 10 000 charge/discharge cycles without reduced efficiency (Pembina 2008). It has a MW-scale power and energy potential, which gives them a possibility in large scale ES (Connolly 2010). Appropriate design can provide energy for more than 8 hours, and the lifespan of these batteries is not strongly affected by the rate of cycling. Suppliers of these batteries inform that the lifetime of the cell stack is over 15 years, and the cycling capability exceeds 10000 cycles at 100% discharge. The electrolyte requires large volumes to supply energy for utility-scale, and these systems therefore tend to be large. They are also easy to upgrade at low incremental cost, and recognized by low maintenance costs (Pembina 2008).

Description	Value
Efficiency	70-90 %
Time of discharge	Second to hours
Power capacity	< 3 MW (MW scale potential)
Lifetime (years)	10
Advantages	Flexible
Disadvantage	Complexity Large volume of electrolyte for high energy capacity

Table 8. Summary of VRB values (LRI 2010; Pembina 2008; Connolly 2010).

3.2.4. Hydrogen Energy Storage - HES

Hydrogen is the ES technology with the widest application area. Due to its ability of also replacing the fossils in the transport sector, it has a competitive advantage compared to other storage technologies. The expression "hydrogen economy" was first used in the energy crisis of the 70s, to describe "an energy infrastructure based on hydrogen produced from non-fossil primary energy sources." (Dutton et al. 2005). This principle is illustrated in figure 18.

Today this is not yet the reality, although a lot of effort is put into R&D to create viable technologies. Estimates vary, but a large-scale hydrogen economy not expected before 2030 (European parliament 2008). The main barriers of implementation are currently very high costs and a non-efficient technology, and further technical and economic development is necessary to commercialize deployment of hydrogen as ES (Ete 2009).

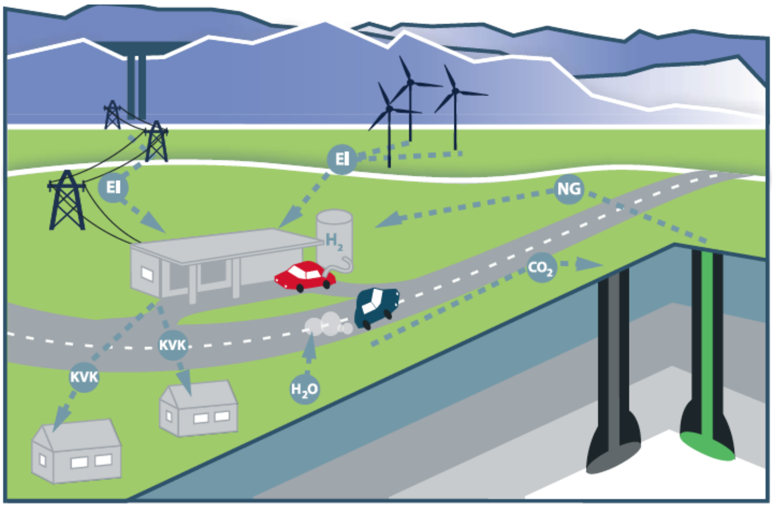

Figure 18. An ideal hydrogen infrastructure.

Beside CAES and PHES, hydrogen is the known ES technology with the largest theoretical storage capacity, yet also the most immature. The possibility of serving all three main sectors within the energy system: electricity; heat; and transport, and also allow a higher level of interaction between these, makes this a very attractive technology (Connolly 2010).

Hydrogen has two main applications areas being developed today; fuel for transport and storage of electricity. There are several milestones set for this development, as for example The European Union aims for hydrogen to represent 2% of the total transportation fuel by 2015 and 5% by 2020 (OECD/IEA 2005). In this thesis, the application of electricity storage will be the main issue.

There are several sources of hydrogen production: fossil fuels, nuclear energy and RE. This can be done by a number of processes, such as water electrolysis, natural gas reforming, gasification of coal and biomass, water splitting by high-temperature heat, photo-electrolysis, and biological processes (Roads2Hycom 2011). Here, the main issue is production from renewables through electrolysis.

The general equation for the reaction in an electrolyze is:

Cathode: $2H_2O + 2\,e^- \rightarrow H_2 + 2\,OH^-$

Anode: $2\,OH^- \rightarrow \frac{1}{2}\,O_2 + H_2O + 2e^-$

Overall reaction: $H_2O \rightarrow H_2 + \frac{1}{2}\,O_2$

Water is simply split into hydrogen and oxygen. The hydrogen may then be stored in distinct phases using different methods (Kruse et al., Bellona, 2002):

1. Compressed hydrogen gas in a pressure tank or underground cavern
2. Cooled hydrogen in liquid state, kept cold in a properly insulated tank
3. Hydrogen bound to a solid compound, a so-called hydride.

To produce electricity, the equation for electrolysis is simply turned, as it works as a reversed electrolysis reaction. Figure 19 shows a PEM electrolyzer and a general fuel cell. Despite separately well-established technologies, where both electrolyzers and fuel cells are commercialized with efficiencies of approximately 70-75% and 50% (optimistic values) respectively, the combined cycle efficiency becomes at best around 35% (APS 2007; NREL 2009). Yang & Williams (2009) state that even if the cost of both electrolyzer and and fuel cell were zero, HES would still not be competitive to batteries due to its very low efficiency.

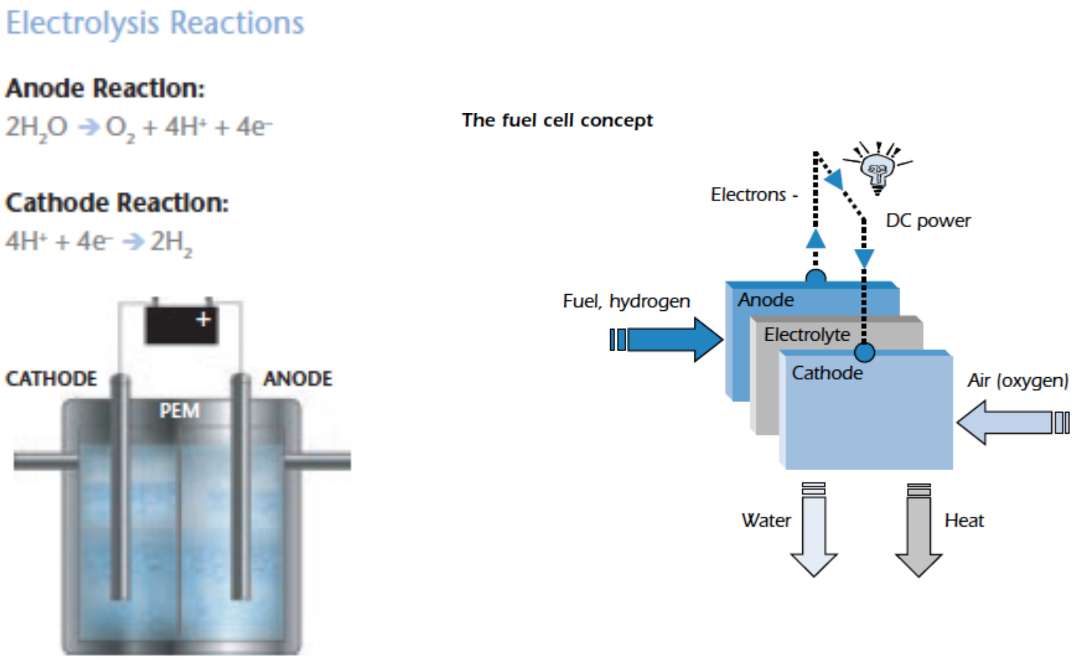

Figure 19. PEM electrolyzer and a fuel cell

The roundtrip efficiency of the hydrogen ES depends on which method of storage are chosen and its application (Vazquez 2010), and for large-scale storage, underground-pressurized storage is the most beneficial in economic manners (OECD/IEA 2005). There are basically four formations allowing storage; empty reservoirs, aquifers, caverns/mines and empty cavities in salt formations. The costs vary depending on geological formations, but it is found to be the cheapest method at all production rates and storage times due to low capital cost of the cavern (Amos 1998).

One of the barriers in implementing hydrogen as a commercial storage option is the difficulty treating the substance itself. It is the smallest existing atom, and is therefore hard to isolate within a tank. High energy content compared to weight is a benefit, but low energy content compared to its volume is a drawback. Table 9 shows these values for hydrogen and some other common fuels. Hydrogen requires higher storage pressure, which results in higher capital and operating costs (Garrett 1989).

Fuel	State	Energy per mass (MJ/kg)	Energy per volume (MJ/m^3)
Gasoline	liquid	47.4	34.9
LNG	liquid	50	ca 230
Ethanol	liquid	29.9	23.6
Liquid H_2	liquid	141.9	10.1
H_2	gaseous	141.9	0.013
Natural gas	gaseous	50	0.040

Table 9. Energy density per unit mass and volume for common fuels.

Demonstration projects for hydrogen storage have been successfully implemented (in technical manners); yet they cannot indicate commercial viability, as partly or entirely funded by governments (Yang and Williams 2009). The world's first stand-alone hydrogen system was installed at the small island Utsira in Norway, and was funded by governments. Two wind mills producing energy for 10 households using hydrogen storage as back-up in low production periods. Periods of full autonomy were proven, but also a portion of interaction with mainland electrical grid was necessary. Despite satisfying technological results, the hydrogen storage unit was decommissioned in 2010 due to high operative costs and low efficiency (Ulleberg et al. 2009).

Description	Value
Efficiency	< 35 %
Time of discharge	As needed
Power capacity	Very large scale potential (underground)
Lifetime (years)	10--> 20
Advantages	Potential for several applications High energy per mass No restrictions but cost and technoloy
Disadvantage	Very low efficiency Low energy per volume High cost

Table 10. Summary of HES values (LRI 2010; Pembina 2008; Connolly 2010).

3.3. ES implementation and operation

The electricity value chain has a traditional division into five links: source, generation, transmission, distribution and end-user. Energy storage is now being reckoned as the sixth link, supplying energy when and where it's needed (Chen et al. 2009), which is becoming ever more important in the energy market.

Considering large-scale energy storage, PHES is the only commercialized method as of today. Despite developed technologies of both CAES and several types of batteries, these are not yet implemented as common large-scale ES in electricity generation. Earlier analyses have shown that CAES is the only large-scale ES system, apart from PHES, with benefit/cost ratios at approximately 2 for all applications. For batteries, both solid and flow, the ratio is mostly below 1 for all applications. (EPRI-DOE handbook 2004). For hydrogen produced through electrolysis, the benefit/cost ratio is from 0.45-0.78, which indicates the least cost-effective ES.

The ES technologies are introduced as individual technologies, operating according to their own technical characteristics like reaction time, storage capacity and discharge time. To build an ideal ES facility, which can react fast when energy supply is needed, but also keep energy supply running for a certain time (discharge time), a technological combination can help to solve this. This is roughly illustrated in figure 24 where a combination of battery and PHES can offer both a very quick reaction time and a long discharge time.

Significant differences in their possible independence gives the technologies distinct requirements for operation. NaS and flow batteries has the advantage of acting both as energy management and power quality, due to their fast reaction time and ever-growing storage capacity. The CAES on the other hand, needs some help to handle the short-term voltage fluctuations, due to its relatively long reaction time (European parliament 2008). In the case study in chapter 6, the ES alternatives are considered as individual storage options. With only one charge/ discharge cycle during a day (24 h), the time for start-up is ignored as a major problem.

3.4. Benefits of ES

ES is accompanied by several benefits denoting aspects that increase revenues and reduce or remove costs. Environmental and economic aspects are important, and also energy diversity benefits: reduction of power plants, cutting cost of power failures, enabling renewable energy etc. (APS 2007). The technologies may have somewhat different benefits, but in this case the ones resulting from the application of *integrating renewables into the grid* will be evaluated.

3.4.1. Introduction

Benefits are very important in promoting ES technologies, as most of them are not yet profitable in terms of economy. Since many of the technologies are rather immature, understanding the actual benefits of these projects can be difficult. The conventional view of assessing an energy project includes project finance and technical perspectives. But the additional benefits such a project offers are important to recognize, to enhance the possibility of an investment (APS 2010).

These inconclusive benefits are another obstacle that has prevented commercialization of ES devices (Connolly 2010). It can be hard to give an exact value of ES benefits, and thereby hard for customers, investors and operators to understand the total value of installing ES. Skepticism and ignorance enhanced by high capital cost, stops ES projects from being implemented. Large-scale storage is still in its infancy, where limited knowledge and a cautious approach remain when looking for potential benefits from pilot, one-off projects, to large-scale deployment on the grid (APS 2010).

In 2010 Sandia released a framework prepared for *"making first-cut or high-level estimates of benefits for a specific storage project ()...() the intended audience includes ()..() electric utility planners and researchers"* (p 1). Estimates included in the report indicate the PV of the respective benefits for a 10 years period, with 2.5% inflation and 10% discount. Although calculated based on the U.S. energy market, the estimates give a good indication of which benefits may be consider most profitable for different applications. Several other attempts turning these benefits into numbers have been made (EPRI 2010; Sandia 2010; NREL 2008), based on different suppositions and mostly to indicate their actual value.

The benefit sector may be divided into three groups:

1. Economical benefits of ES
2. Technical benefits (comparative aspects)
3. Non-market value (passive) benefits

The energy industry is complex, and the benefits do not always fall in favor of only one part. Exemplified, operational benefits can also be profitable for others than the owner (Baxter 2005). Also, the types of benefits are not necessarily mutually exclusive, and both operational and environmental benefits can provide economic benefit, hence are divided between the system “participants” (CPUC 2010).

When evaluating benefits resulting from ES applications it is important to separate use and value. While application is a type of use, benefit connotes a value (Sandia 2010). Benefits, as with costs, are desired quantified in terms of a monetary value to easily compare the net present value (NPV) of a project (explained in details in chapter 4).

Benefits can generally take two forms (Sandia 2004):

1. Additional revenue received by the storage owner/operator (energy sales, capacity, ancillary services)

2. Cost avoided by the storage owner/operator (avoided cost) (avoided need of T&D, higher power capability).

Accurate revenue can be hard to find, and long-term benefits are difficult to identify and estimate. Primary benefits, which enfold the direct results of an ES installation, are most easy to identify and common to evaluate. Still, several secondary and tertiary benefits are also generated, for which it is more difficult to find a present value (APS 2010). A new energy infrastructure will affect so many different parts of the society, but yet too early to identify the long-term impact in the surroundings.

There are some general benefits that somewhat-to-very apply to all the ES technologies, including increased energy sustainability, reduced emissions and improved regulation and stability on the grid. Here, the economical and so-called passive (non-market value) benefits (no 1 and 3 in the benefit division above) will be introduced, as general benefits of ES. Technical benefits like efficiency, flexibility and storage capacity are assessed in chapter 5, in a more comparative manner to evaluate the different technologies.

3.4.2. Economical benefits

In this chapter the *economic benefits of ES for the application of RE integration* are assessed. Values of using ES in the generation phase of the electricity are evaluated, and the magnitude of each of these benefits will be discussed. The main issues are: competitiveness, time-shift, capacity firming, defer grid improvements, improved regularity and reliability. They are all described below, with an indication whether to be considered as additional revenue or avoided cost.

- **Competitiveness:**
  Allow renewable power sources to compete in power (wholesale) markets, such as offering day-ahead guaranteed contracts and selling at high price

  → Additional revenue

  This is the main benefit of ES for this application, allowing renewables to penetrate the market with the ability of competing with the conventional power sources and attain a high market share.

  With sufficient storage capacity, the owner of renewable energy power plant will be able to guarantee power delivery a day ahead. Fully charged ES unit, either from surplus energy generated at the plant or low-price electricity from the grid, will increase its capability of competing on the wholesale market. The electricity can be sold on the market in high price peak-demand hours, independent of the production rate at this time. This is somewhat limited by the storage capacity, but owners will have to take this into consideration when estimating the necessary capacity to run the plant power supply this way.

Wind power generation is a key issue considering the global move towards renewable integration, and seems to be having some undesirable impact on the electricity grid (Sandia 2010). To follow up this development in the market, ES is one of the best technological supports offered today. Through R&D, this support will also be improved, thus the drawbacks from intermittency can be reduced, allowing the renewables to be competitive.

- **Capacity firming**

→ Avoided cost

“Filling in” energy from the storage device so that the output power becomes somewhat-to-very constant, guaranteeing a minimum output, is known as capacity firming. This is done to avoid/reduce the need of generation equipment, like need of additional ancillary services and energy reserve support requirements, and hence improve the economy of the ES installation (Sandia 2004/ 2010). Renewables capacity firming is especially valuable during peak demand periods (OECD/ IEA 2010).

The intermittency can cause rapid changes in power output, also known as ramping. Capacity firming is a process, where “filling” in amounts of energy is done to avoid deviations in demand and supply caused by these changes, and hence provides a somewhat-to-very constant output. The benefit provided by this process may be in the range of modest to significant, depending on how often the storage is discharged.

The power rating of the storage unit only needs to be a small portion of the system total power rating, often just 20% of the plant (wind park) size (Baxter 2005).

- **Time-shifting**

→ Additional revenue, avoided cost

The basic principle of time-shift is charging the ES unit/system with low valued energy (off-peak hours; low price) and discharging with valuable energy (peak demand hours; high price), with the overall goal of enhancing the energy value. Hence, the benefit of time-shift highly depends on the difference between on- and off- peak electricity price (Sandia 2010). It may also be considered avoided cost, as the need of fuel or energy purchase during peak demand hours to generate electricity supply is reduced/eliminated.

When discharged, energy can be used by owner, sold at wholesale market, or sold under terms of a purchase contract ("power purchase agreement")(OECD/ IEA 2010; Sandia 2010). Still, if costs of system wearing, storage losses and charging energy exceed the value of benefit, this application will not be operated.

To illustrate the time-shift principle, the annual wholesale prices in California in 2009 are listed in table 11. Sale profit minus charge cost and storage losses gives the net time-shift benefit (system wearing is left out in these calculations; negliable). These benefit values can be used to calculate the total value of time-shift during 2009. Figure 20 shows graphically how energy sale is transferred from low-value to high-value period of time.

	Month=>											
Hour	1	2	3	4	5	6	7	8	9	10	11	12
12:00 P.M. - 5:00 P.M.	85.1	74.5	77.6	94.6	100.3	118.0	148.2	163.1	142.5	99.1	104.5	105.9
1:00 A.M. - 6:00 A.M.	-51.8	-44.4	-46.2	-61.2	-42.7	-35.2	-55.1	-69.7	-77.0	-61.3	-61.5	-72.9
Storage Losses*	-10.4	-8.9	-9.2	-12.2	-8.5	-7.0	-11.0	-13.9	-15.4	-12.3	-12.3	-14.6
Net Time-shift Benefit	23.0	21.1	22.1	21.1	49.1	75.7	82.1	79.4	50.1	25.5	30.7	18.4

Table 11. Wholesale energy prices in California 2009 (Sandia 2010).

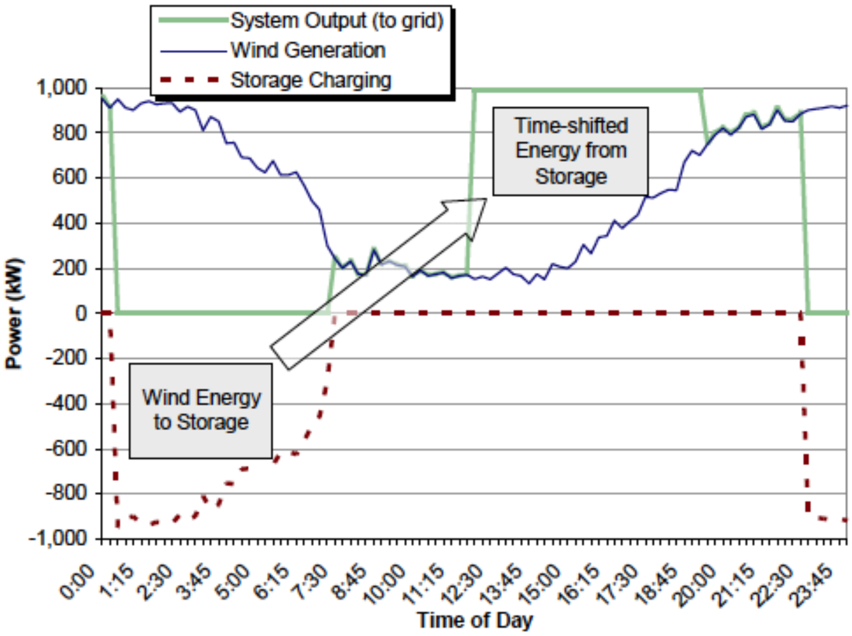

Figure 20. Time-shift illustration (Sandia 2010).

This benefit is one that also applies for ES in general, then mostly noted as arbitrage. The main difference is the energy used for charging, where for renewables it is mostly energy produced at the plant in off-peak hours, while for arbitrage it is low-price energy from the grid. Also is does not necessarily follow the normal daily buy/sell trend like time-shift, but follows the market only.

- **Improved regulation ability**

→ Additional revenue

The ability of electricity supply regulation from renewable power generation is one of the main benefits considering ES. Large-scale production of intermittent energy arise the problem of unpredictability in amount generated. If surplus energy is stored when production rate is high (exceeds demand), this “back-up” energy gives the ability to regulate the power output with respect to demand, independent of production (assumed sufficient storage capacity).

Improved regulation improves the possibility of certain and stable delivery, which is a clear advantage and necessity for renewable integration. This property is especially important to improve as the share of renewables in the electricity grid increases, because so far a shortage of regulation capacity is anticipated (OECD/IEA 2009).

- **Improved reliability**

→ avoided cost

Reduced financial losses associated with improved electrical reliability denotes the value of this benefit (Sandia 2004). The economic consequences in case of an outage are mostly user-specific, as utilities are not responsible for covering financial damages if operation has followed standard practices. Still, it might be the case that they have to cover the losses, and it could then constitute a great cost.

Reliability cannot yet be proven for the new ES technologies entering the market, in the lack of sufficient testing data (DOE 2011). For mature systems as PHES and LA reliability can be estimated with high degree of certainty, and PHES is assumed most reliable among large-scale ES technologies (IEA 2009).

- **Reduced need of new transmission and distribution (T&D) capacity**

  → Avoided cost

  Power plants are often located in remote areas with high energy potential, and where the impact on surroundings is minimized. Installing sufficient storage capacity, ES can be used to maximize utilization of existing T&D resources, thus reduce the need of new and improved grid connection and transportation abilities. *"The value of T&D upgrade deferral varies greatly by location and is driven by the population density of the area, terrain, geology, weather, and the type and amount of T&D equipment involved."* (CPUC 2010). In any case, this can contribute to avoided costs.

  ES allows remote areas to function as autonomous power systems, or energy can be transported at rates adjusted the existing grid. Thus, if the connection is limited, the supply may be distributed over time so that the energy amount fits the grid capacity.

- **Allow renewables to integrate "site-independent"**

  Location of renewables has been considered challenge so far in the RE sector. ES gives the probability to run an RE power plant in a more controllable manner, it helps to handle this problem. As explained in chapter 2, the availability of these resources is not proportional to population density and energy demand, and they are often remotely located. By storing the energy, a suitable infrastructure allows this to be used when and where it's needed, either though grid or by transportation.

Several attempts to find general value estimates of these economical benefits of ES have been made (Sandia 2010; EPRI 2010). Table 12 gives an overview over the present values (PVs) of some of these benefits. It is stated that these values are not additive, but must be modeled together in an integrated fashion (EPRI 2010).

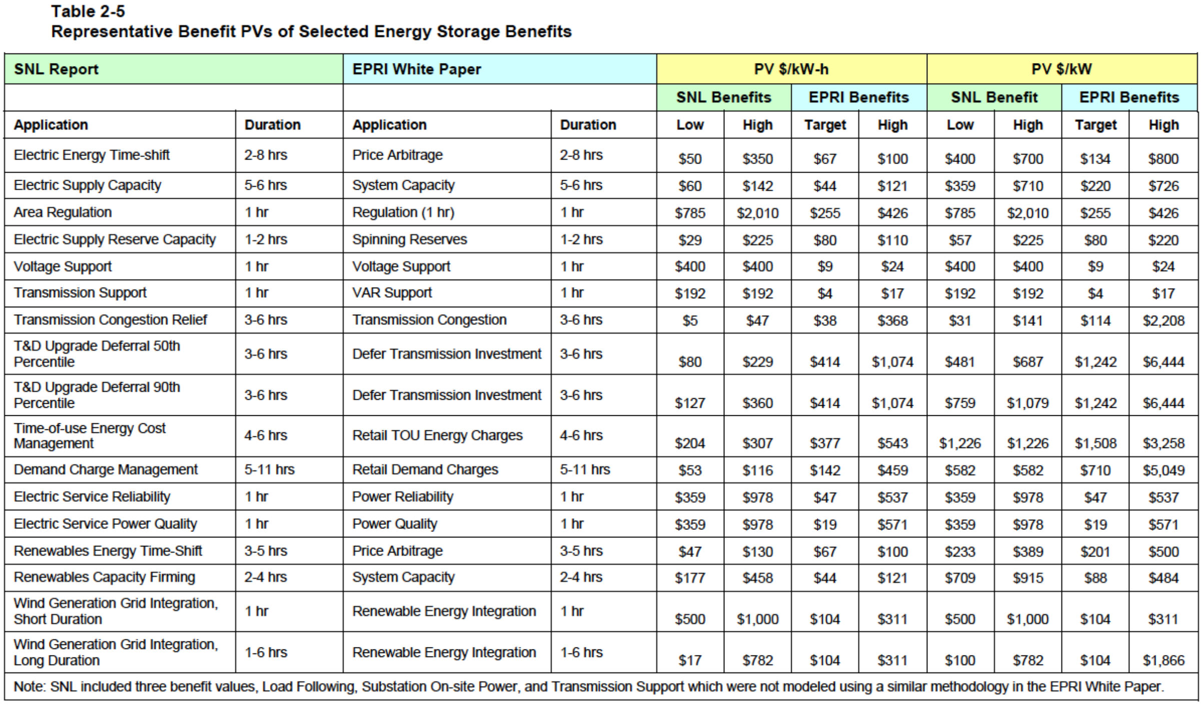

Table 2-5
Representative Benefit PVs of Selected Energy Storage Benefits

SNL Report		EPRI White Paper		PV $/kW-h				PV $/kW			
				SNL Benefits		EPRI Benefits		SNL Benefit		EPRI Benefits	
Application	**Duration**	**Application**	**Duration**	**Low**	**High**	**Target**	**High**	**Low**	**High**	**Target**	**High**
Electric Energy Time-shift	2-8 hrs	Price Arbitrage	2-8 hrs	$50	$350	$67	$100	$400	$700	$134	$800
Electric Supply Capacity	5-6 hrs	System Capacity	5-6 hrs	$60	$142	$44	$121	$359	$710	$220	$726
Area Regulation	1 hr	Regulation (1 hr)	1 hr	$785	$2,010	$255	$426	$785	$2,010	$255	$426
Electric Supply Reserve Capacity	1-2 hrs	Spinning Reserves	1-2 hrs	$29	$225	$80	$110	$57	$225	$80	$220
Voltage Support	1 hr	Voltage Support	1 hr	$400	$400	$9	$24	$400	$400	$9	$24
Transmission Support	1 hr	VAR Support	1 hr	$192	$192	$4	$17	$192	$192	$4	$17
Transmission Congestion Relief	3-6 hrs	Transmission Congestion	3-6 hrs	$5	$47	$38	$368	$31	$141	$114	$2,208
T&D Upgrade Deferral 50th Percentile	3-6 hrs	Defer Transmission Investment	3-6 hrs	$80	$229	$414	$1,074	$481	$687	$1,242	$6,444
T&D Upgrade Deferral 90th Percentile	3-6 hrs	Defer Transmission Investment	3-6 hrs	$127	$360	$414	$1,074	$759	$1,079	$1,242	$6,444
Time-of-use Energy Cost Management	4-6 hrs	Retail TOU Energy Charges	4-6 hrs	$204	$307	$377	$543	$1,226	$1,226	$1,508	$3,258
Demand Charge Management	5-11 hrs	Retail Demand Charges	5-11 hrs	$53	$116	$142	$459	$582	$582	$710	$5,049
Electric Service Reliability	1 hr	Power Reliability	1 hr	$359	$978	$47	$537	$359	$978	$47	$537
Electric Service Power Quality	1 hr	Power Quality	1 hr	$359	$978	$19	$571	$359	$978	$19	$571
Renewables Energy Time-Shift	3-5 hrs	Price Arbitrage	3-5 hrs	$47	$130	$67	$100	$233	$389	$201	$500
Renewables Capacity Firming	2-4 hrs	System Capacity	2-4 hrs	$177	$458	$44	$121	$709	$915	$88	$484
Wind Generation Grid Integration, Short Duration	1 hr	Renewable Energy Integration	1 hr	$500	$1,000	$104	$311	$500	$1,000	$104	$311
Wind Generation Grid Integration, Long Duration	1-6 hrs	Renewable Energy Integration	1-6 hrs	$17	$782	$104	$311	$100	$782	$104	$1,866
Note: SNL included three benefit values, Load Following, Substation On-site Power, and Transmission Support which were not modeled using a similar methodology in the EPRI White Paper.											

Table 12. PV of selected ES benefits (EPRI 2010).

3.4.3. Challenges in monetizing ES benefits

Benefits can as mentioned be intricate to quantify. Due to presently insufficient experience with several new technologies (< 10 years of operation), their total influence on the surroundings is still unknown. Passive benefits are indirectly connected to the technology itself (non-operative), and their values are reflected in how they affect their surroundings (excluding market and operation). This comprises issues of environmental and social impact from ES, where the monetary values are not directly measurable. The valuation process of these benefits may be considerable affected by subjective opinions and judgments. The key question is then whether these values are truly informative, despite the subjectivity added (OECD 2006).

To reduce the subjective impact on benefit valuation, methods like contingent valuation method[8] (CVM) has been developed. It is a somewhat-to-very comprehensive research on peoples willingness-to-pay (WTP) (alternatively willingness-to-avoid (WTA)) for the

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[8] This is a stated preference approach for measuring the use and passive use benefits of ES, and has been developed during the last decades to find these estimates (Pearce et al. 2006). As a subjective evaluation, it requires a high number of participants to obtain an empiric representative value.

benefits following an ES project. The WTP values are evaluated to put a value on the respective benefits. It is beyond the scope of this project, where the discussion of these passive benefits is mainly qualitative.

3.4.4. Passive benefits: environment and society

These benefits may be considered in terms of avoided environmental costs following carbon-based energy, and they have to be highlighted to emphasize the importance of clean energy. Many are non-market value benefits, as explained in 3.4.3, but investors need to take these into account when assessing a possible project, to make environmental and socially optimal investments.

3.4.4.1. Reduced emissions

For the application of integrating renewables on of the main benefits is most often considered to be reduced emissions, which can be considered both an environmental (less pollution in the nature) and social (cleaner air; less health problems) benefit. This may be appraised a benefit of the RE itself, and not directly a result of ES. But as these technologies are a prerequisite for future large-scale integration of renewables, it may also be assessed as a benefit of ES (Connolly 2010).

Figure 21 shows the anticipated annual CO_2 emissions from 2007-2035, in both the OECD and non-OECD countries. It illustrates the argument mentioned in chapter 2: the different situation in the energy markets around the world. For the developing countries to maintain the rate of development seen today it will require a great amount of energy, much more than emerging RE installations can provide. Thus, here the amount of emission is not expected to stagnate as seen in the OECD countries, but anticipated to increase approximately as shown in the figure.

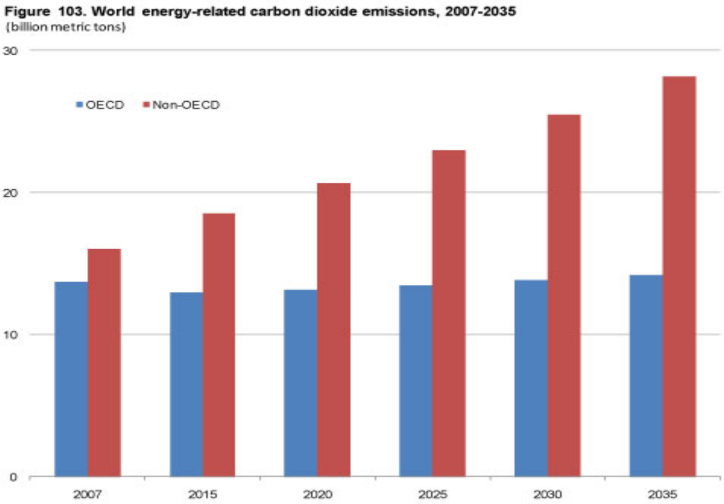

Figure 21. World energy-related CO₂ emissions 2007-2035 (IEO 2010).

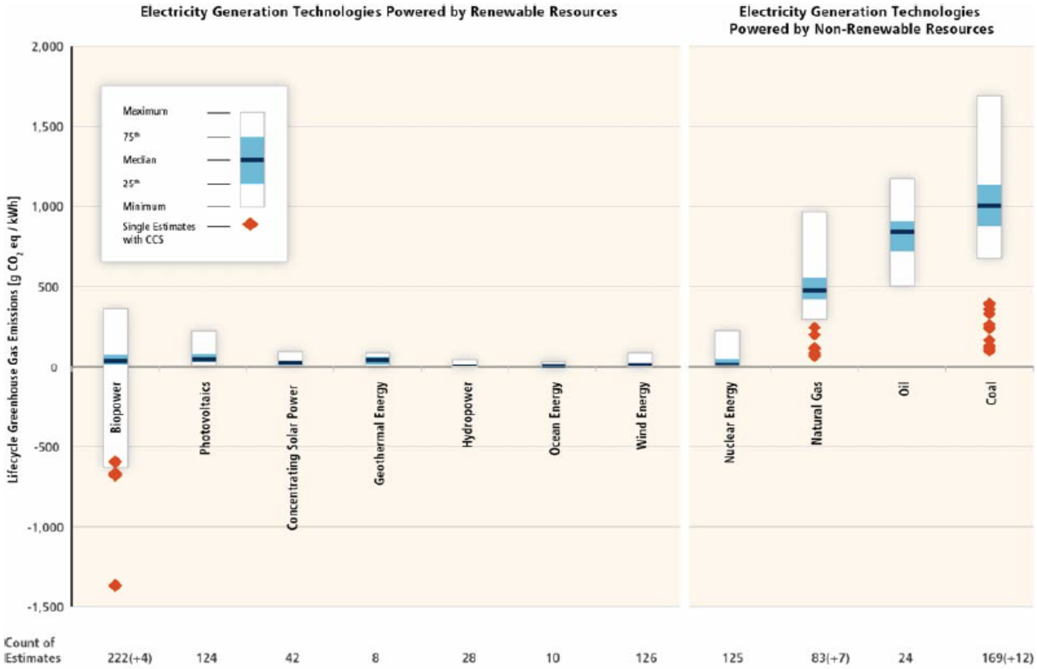

Figure 22. Lifecycle Greenhouse Gas Emissions (SRREN 2011).

Figure 22 shows the lifecycle GHG emissions from different power sources in electricity generation, where the numbers are much higher for the fossils. This underlines one of the main arguments to put stakes on renewables: to avoid these amounts emissions.

This benefit can to a certain extent be measured as a direct value, based on reduced governmental emission taxes. Yet, people in general (end-users) may also appreciate reduced pollution, but the value of improved air quality is not as easy to estimate. CVM mentioned in the previous section may be used to find the price increment per kW customers is willing to pay for a certain amount of reduced emission. The total monetary value of this benefit will then comprise the reduce fees and increased income.

CAES is one of the ES technologies causing direct emission during operation. To run the combustion engine, natural gas is often used as fuel. Still, compared to a pure natural gas power plant it reduces emission by 2/3, which is explained in more detail in the chapter of CAES. This has been one of the main issues of CAES, as it does not represent an entirely preferable technology considering environment. Therefore, new solutions for CAES are being developed, including the AA (advanced adiabatic)-CAES, which removes the need of a combustion engine operated on natural gas.

There are several, in different degree severe, health consequences from emissions, and health organizations all over the world express strong concerns. In the western areas, there has already been made an effort to develop solutions to reduce these problems. In developing countries on the other hand, the consequences are often more severe. In India, 40,000 people die each year as a result of air pollution in urban areas (Kruse et al., Bellona, 2002).

Although this thesis evaluates the large-scale storage benefits, small-scale use within transport can also be mentioned, which had a 28% share[9] of the global CO_2 emission in 2007. As one of the main goals within the energy sector is reducing fossil fuel consumption, the transport sector also needs changes. Both batteries and hydrogen can play a significant role, where the ideal environmental objective is to run the transport sector completely without fossils.

Electric vehicles have lately gotten a lot of attention and in the transport sector. Several successful test projects have been completed, which have proven that these alternative vehicles will be able to obtain a certain market share. Though, they are not yet comparative to conventional vehicles, due to relatively low discharge time of batteries and low engine power.

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[9] http://ec.europa.eu/energy/publications/doc/statistics/ext_co2_emissions_from_transport_by_mode.pdf

3.4.4.2. Avoid social and nature intervention

One of the most controversial issues considering new power plants is intervention. Nearby inhabitants are often reluctant to these projects, where their opinion says this will damage their surroundings, both the visual aspect and the local wildlife. Avioding this may be considered both a social and environmental benefit.

The problem of remotely located RE resources, which can be solved using ES, can also help to avoid social intervention. As ES allows a higher utilization of these distant energy resources, the need of central power plants is reduced, and the degree of intervention becomes lesser. The impact of the ES facility itself varies, and the technological alternatives will cause diverse visual impacts. The bulk of the power plant itself determines how much of this "damage" is to blame the ES facility. Nevertheless, the ability of moving the power plants to distant locations makes this an obvious benefit considering reduces social intervention.

Regardless of location, nearby wildlife of a power plant will experience a certain degree of intervention. Although the plants are moved further away from populated areas, there is wildlife in its surroundings. This is not an issue to be solved from ES, but in a comparative manner, the additional interference from the ES facility (versus no ES) may often be considered insignificant.

Chapter 4 - Methodology

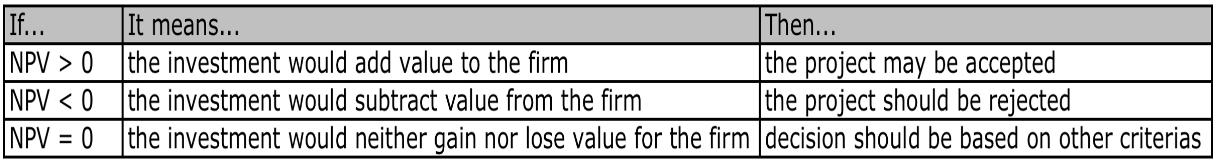
There are several methods to analyze a potential project, but the common superior objective is to determine whether it should be implemented or not and whether it would be profitable. Considering ES, where most of the technologies are still found in their R&D stage, it requires thorough research to perform economic analysis. For a technology to get support for a certain (test)project, it is important that the type of analysis used is familiar and accepted among economists. Two methods will here be used to evaluate the costs:

- Net Present Value (NPV)
- Scenario analysis

4.1. Net present value

When assessing the cost of a project, it is desirable to find a reliable estimate for its present value, including both current and future cash flow. The cost part includes capital cost, operation and maintenance cost and possible decommissioning costs. Unforeseen costs can also appear, but can be hard to account for. Methods have been developed to account for some of these uncertainties, one which is the scenario analysis presented in chapter 4.2. Trying to find the project net present value, this allows evaluation of several possible scenarios for diverse values of these uncertainty factors.

To find the net present value (NPV) of a project, the most common method is to find its net present cost (NPC) and withdraw this from the net present benefit (NPB), and positive result thus indicates a profitable project. Table 13 shows the basic principle. NPVs are good first-cut estimates for whether to invest in a storage system or not (EPRI 2010).



If...	It means...	Then...
NPV > 0	the investment would add value to the firm	the project may be accepted
NPV < 0	the investment would subtract value from the firm	the project should be rejected
NPV = 0	the investment would neither gain nor lose value for the firm	decision should be based on other criterias

Table 13. The Net Present Value decision principle.

To find the net values of both these, it includes both current cost/benefits and future cash flow (out/ in). An essential factor for this calculation is the discount rate, which estimates the present value of future cash flow through discounting. This is a risk-adjusted rate, depending on the degree of uncertainty related to the potential project/investment and on what profit owners/investors expect to get. The situation is often: higher high risk and uncertainty, the higher discount rate.

As mentioned in chapter 3.5, some benefits related to ES are difficult/hard to valuate. Some methods are mentioned for how this can be done, though beyond the scope of this thesis. Here, only the PV of costs will be estimated: NPC. This includes capital, O&M and possible decommissioning costs. Benefits introduced in chapter 3 are somewhat-to-very common for all of the ES technologies, and cost will most often be the crucial decision factor.

The capital cost appears in year 0 of the project life, and the PV will be equal to it actual cost. For the future cash flow C in year t, the general equation to estimate the total PV (C_t) for a period T years of operation is:

$$NPV = \sum_{t=1}^{T} \frac{C_t}{(1+r)^t}$$

C_t - cash flow (cost)
t - time of the cash flow
T - project lifetime (years)
r - discount rate

A discount rate of 10% is used in the case study of wind/ES. This is a common value in several other ES analyses (NREL 2009; EPRI 2010; Sandia 2010).

4.2. Scenario analysis:

The principle of scenario analysis is to assess a future event (project) and its alternative outcomes (scenarios). When evaluating the NPV, introduced in 4.1, uncertainty is a common problem. Scenario analysis allows this to be somewhat accounted for, through analyzing different future situations based on variations in critical factors (parameters). It is an important method in projection, as it does not give a narrow picture of the outcome, but a wide spectrum of possible developments, dependent on certain analysis-parameters.

To predict the future of ES technology includes a high degree of uncertainty, which often has been underestimated in earlier attempts of forecasting the future energy situation (Martinot et al. 2007). To account for this uncertainty and the unpredictability, scenario analyses are often used to consider several alternatives scenarios. This is an important tool for dealing with complexity and uncertainty of development.

Scenario analysis can be based on different parameter, for instance: population, demand, fuel costs, technology cost and degree of policy actions (Martinot et al. 2007). Here, the parameter used is cost, including capital and O&M costs. Two scenarios will be analyzed: Low and high cost scenario, and both will include both the existing cost pessimism and optimism concerning technology development (OECD 2006). The extreme values of the cost ranges in table 15 will be used, maximum cost in the high cost scenario, and minimum cost in the low cost scenario. This means that it is the extreme outcomes of project development that are found, but the realistic value is often found in between these. The width of these cost ranges reflects the uncertainty and variance of the estimates, and is often higher among the new, less mature technologies.

Chapter 5 - Comparative analysis of ES technologies

5.1. Comparative characteristics

ES technologies are characterized by different properties, which they operate according to. Some of these are (APS 2007):

- Quantity of energy stored (commonly kWh or MWh)
- Duration of discharge required (seconds, minutes, hours)
- Power level (kW or MW)
- Response time (milliseconds to minutes)
- Frequency of discharge (number per unit of time, such as per day or year)
- Energy density (facility space and total energy storage capacity)
- Cycle Efficiency (fraction of energy removed that is returned to the grid)
- Cycle life and/or calendar life
- Footprint/compatibility with existing infrastructure
- Ease of implementation
- Transportability
- Cost

Some are more crucial than others, and will often be weighted more in an ES comparison. In the introduction, 3 important criterions were defined: cost, flexibility and storage capacity. These are also reckoned in this list of properties, and are here accounted as the more “heavy-weighted” properties of ES for the application of RE integration. Further, these will be assessed to compare the ES technologies introduced in chapter 3.

These questions addressed in this chapter are:

1) What are the costs of ES?
2) What is the potential storage capacity of these technologies, and what possibilities/ limitations do this cause?
3) How flexible are the technologies? Are there any requirements for flexibility?

Several cost analyzes have been performed to prove the most cost efficient[10] technology for different ES applications. Here, the main criterions for ES to appear as a profitable and competitive technology are introduced, followed by a case study in chapter 6, where these are evaluated for a specific wind park project. Considering costs, numbers from earlier research and projects will be transferred and adapted to this thesis. Due to high degree of variance and complexity considering power plant projects, cost estimates appears to be controversial within the industry (APS 2007) and will not give estimates of high accuracy. They are used mainly for a rough comparison of the technologies.

5.2. Challenges of a comparative analysis

To assess costs there are several challenging issues (Mariyappan et al. 2004):

- availability of data
- distinguish between actual current cost and projections
- difficulty of being generic, e.g. batteries

As the different systems considered in this thesis are in somewhat-to-very different stages of their development, some fully matured while others in their infant stage, the data availability for estimation/ valuation of costs can be very limited. Also the issue of being generic is sometimes a problem. Costs are very situation and application dependent, and can therefore be hard to generalize. This analysis will therefore focus on identifying the costs following integration of renewables, and perform a mostly qualitative analysis of how these may affect the economic result of the project. In the

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[10] Highest possible/ optimal production or profit in an efficient and economic manner.

part concerning costs, a cost table will be estimated for the technologies, gathered and adapted from earlier research. In the benefit chapter, there will be mentioned methodologies that can be used to quantify these.

For hydrogen, which is still found in early in its R&D phase, there are few accurate numbers for costs estimations. In earlier reports on ES (EPRI 2010; Chen et al. 2009; Sandia 2003), where the technologies mentioned in chapter 3 have been assessed, hydrogen is often left out as an alternative. With an overall maximum efficiency of 35% for both geologic and aboveground storage (APS 2007; NREL 2009), this is far below the efficiencies of the other technologies and therefore not considered an alternative. While PHES, CAES and batteries are placed within the high efficiency group of 60-90%, hydrogen is within the low efficiency group (Chen et al. 2009). Most of the reports on hydrogen as an ES technology focus on hydrogen only, with a more prospective view.

The common character of the technologies being analyzed is their ability of being used for the application of RE integration. Although hydropower is the only mature large-scale method, CAES and some batteries are also commercialized (EPRI 2010). Still, CAES is the only technology except from pumped hydro that can store above 100 MW with single unit (Chen et al. 2009), while batteries today needs to be implemented as a "storage grid" (several battery units connected) to obtain this storage capacity.

Using the ES technologies mentioned above in integration of wind power as the renewable energy resources, will give an insight in integration of RE. Although wind power represents only one of the renewables available, the same principles also apply for the rest of these. The main focus is not on the energy source itself, but the intermittent property and need of storage to utilize the energy available.

As the profitability of ES projects is often low as of today, the environment and argument of a sustainable future is used in gathering finance when establishing new renewable power plants with storage capacity. These are also important arguments to be agreed public support, and are used to promote these new storage technologies. This was explained in more details in chapter 3, and is accounted as more general arguments in the promotion of ES. Here, the diverse properties of the technologies are in focus, which are more crucial in the decision of *which ES is best suited for the project assessed.*

5.3. Costs

Depending on the degree of maturity, general costs of a storage technology can be difficult to estimate, especially for those found in their R&D stage (Sandia 2003). Cost calculations have to be made based on research, conversation with the producers/developers, and analysis of earlier and existing (test) projects. Indications can be found in similar project, but usually there are several factors defining previous cases that in varying degree differ from the present case. Thus, exact costs can be difficult to find, and the bandwidth of the uncertainty will depend *"on the status of the technology. Based on the maturity of its components, cost and performance estimates scaling up from pilot to demonstration to commercial are difficult to estimate"* (EPRI 2009). Hence, mature technologies like hydropower and batteries give reliable numbers for the price per kilowatt electricity produced, based on broad experience. This can be illustrated by a "learning-curve", which shows that over the years, as the technology develops, the cost varies (falls) drastically. Figure 23 shows price development per watt for solar and wind power plants as the cumulative global capacity of these resources increases, where the common trend is price fall when the knowledge increases.

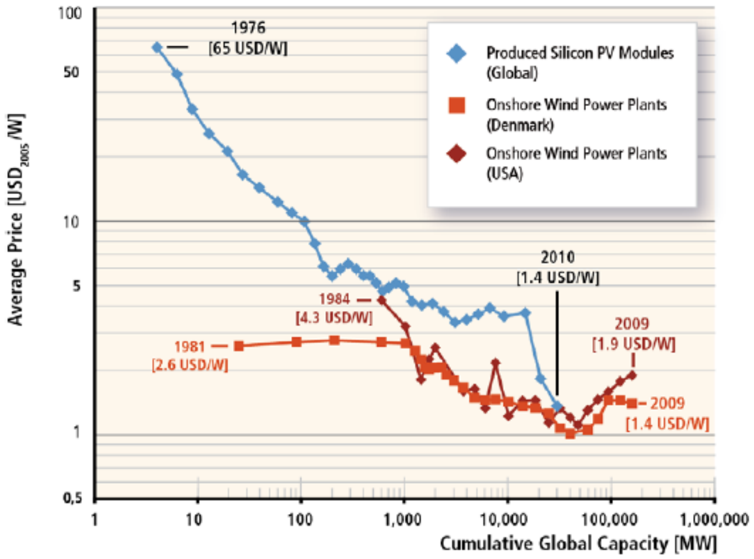

Figure 23. Learning curve - Average price versus Global capacity (SRREN 2011).

Cost of an ES system includes the costs of installation, operation and maintenance, and replacement (if needed). Capital cost for ES represents the main expense for the system, and the cost of the storage medium often constitutes for half the cost of the entire facility (Baxter 2005). O&M costs also have somewhat-to-very great significance for the total costs, especially for technologies with short lifetime and significant replacement costs (variable O&M). Technological properties as efficiency and lifetime are essential cost factors. The non-market value costs associated with ES installations include those expressed in more environmental manners. As one of the objectives of using ES is to avoid these environmental costs of energy production, they are not assessed as costs, but as possible benefits (explained in chapter 3).

For potential utility owners, cost is most often the decisive factor, as economic viability is a prerequisite for business. Time of occurrence is also important, especially when it comes to O&M costs, which are more unpredictable than capital cost (considering variable O&M). In total, costs depend heavily on system design.

For a fair comparison of the alternatives, it is important to find a comparative metric. Both kW and kWh are good metrics when comparing technologies targeting the same application (Baxter 2005), and the most commonly used metric to estimate the costs of

ES technologies are either $/kW or $/kW-h (noted levelized cost[11] : cost to own and operate one kW capacity for one hour) (Sandia 2003; NREL 2009). To evaluate the lifecylce cost of an ES system, two basic “components” need to be assessed: capital cost and O&M (fixed and variable) costs, often summed up into levelized cost. This is a useful metric for a fair comparison of technologies with different characteristics as efficiencies, lifetime and capacity (EPRI 2010). These are most often measured in $/kW-yr, presenting how much one kW of capacity costs to own and operate for one year (CPUC 2010).

Technologies used for energy management applications often get a significantly lower cost per kW than the storage technologies used for power applications, due to their large storage capacity. It is therefore important to ensure that the technologies being compared are all suited for the storage application evaluated. The cost per unit energy should also be divided by the storage efficiency, to obtain the cost per output useful energy (Chen et al. 2009).

Cost of hydrogen as a storage solution is often left out in technological comparisons. Due to low efficiency, high costs and its degree of maturity, it is not yet considered a possible ES technology. Several successful demonstration projects have been installed the last decade, with Utsira (Norway) and West Beacon farm (UK) as the largest examples. Despite satisfying technical results, economy does not allow for this technology to commercialize. Still, analysis of the future energy situation, comparing hydrogen to fossil fuels, shows that hydrogen ES systems could be preferable in economic manners for distant locations (Ulleberg et al. 2009).

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[11] ”The levelized cost of energy represents the cost of an energy generating system over its lifetime; it is calculated as the per-unit price at which energy must be generated from a specific source over its lifetime to break even. It usually includes all private costs that accrue upstream in the value chain, but does not include the downstream cost of delivery to the final customer; the cost of integration; or external environmental or other costs. Subsidies and tax credits are also not included.”(SRREN 2011)

5.3.1. Capital costs

3.3.1.1. Cost

The capital cost of ES technologies varies significantly, but in most cases it represents the main cost in a project lifecycle. Considering large-scale storage, a project requires a high initial investment to build a facility with sufficient storage capacity. The related O&M costs tend to go the other way, with lower $/kW(h) for large storage solutions (explained in details in chapter 5.3.2).

ES facilities comprise three primary components (Connolly 2010):

- Storage medium
- Power conversion system (PCS)
- Balance of Plant (BoP)

The storage medium denotes the "chamber" of storage: the cavern in the case of CAES; the dam in the case of PHES; and the electrolyte in the case of flow batteries. PCS is the unit(s) converting the stored energy into electricity. The complexity of this is determined of how the energy is stored: mechanically, chemically or potentially. BoP is the surrounding "support" system, and comprises the housing of the equipment, the environmental control system of the storage facility, and the electrical interconnection between the PCS and the grid (transformers, electrical interconnection, protection device and control systems, facility shelter etc.) (Connolly 2010). Its value is typically proportional to energy storage (Sandia 2003), but also by far the most variable cost component of an ES facility (Baxter 2005).

To compare the capital costs, they can generally be summed up as the total cost of these three primary factors (Sandia 2001):

$$\text{Cost}_{\text{CapitalTotal}}(\$) = \text{Cost}_{\text{PCS}}(\$) + \text{Cost}_{\text{Storage}}(\$) + \text{Cost}_{\text{BoP}}(\$)$$

$Cost_{PCS}(\$) = UnitCost_{PCS}\ (\$/kW) \cdot P\ (kW)$

$Cost_{Storage}(\$) = UnitCost_{Storage}\ (\$/kWh) \cdot E\ (kWh)$

$Cost_{BoP}(\$) = UnitCost_{BoP}\ (\$/kWh) \cdot E\ (kWh)$

As the efficiency is a decisive factor considering amount of output energy provided by an ES system, it is often included in the cost estimations. The storage capacity is then divided by the efficiency; hence the cost estimated is per unit of useful energy (Chen et al. 2009):

$Cost_{Storage}(\$) = UnitCoststorage\ (\$/kWh) \cdot (E\ (kWh)/\eta\ dis)$

The relation between cost and efficiency is discussed in 5.3.1.2.

Cost estimates of storage possibilities are often calculated for several scenarios, depending on the technology flexibility. For CAES, both tank and underground solutions are often considered, within capacity limits. Especially hydrogen, with its unique adaptability as ES medium, gives several storage opportunities with somewhat-to-very differing economy. Underground versus above ground, rock formation versus tank, compressed gas versus liquid etc. Several scientists have done this, proven that underground cavern storage is the most beneficial solution for hydrogen BES (NREL 2009; Korpås 2004). Hydrogen as ES also provides a unique possibility to combine electricity and fuel production. Optimizing energy utilization through balancing the production of stored energy and fuel gives the opportunity to reduce the levelized cost of energy (NREL 2009).

Several technologies that are proven to function satisfying in technical manners are prevented from commercializing due to high capital cost, and price needs to drop significantly before they will reach widespread use. Through R&D this can be solved, as technology maturity provides cost decline, which offers a possibility of economy of scale and thereby commercializing (Baxter 2005). However, the economic justification also needs to take other issues into account, including all the benefits following ES. Thus, cost-benefit analyses show that ES is economically justified in some cases (Poonpun & Jewell 2008).

5.3.1.2. Efficiency

High efficiency affects the total cost of an ES project, and the formula in 5.3.1.1 shows that the cost of storage increases as efficiency decreases. Hence, increasing efficiency reduces cost, and the total value of a project will increase. This trade-off illustrates the importance of the efficiency factor (Chen et al. 2009), which is one of the main criterions of success for ES technologies. Here it is included in the cost criterion, due to their close relation.

In a comparative manner, technologies with high efficiency are the most tempting considering reduced cost. Technologies discussed here, all have an average efficiency between 70-90 %, except from hydrogen with an overall efficiency of 35 % (Sandia 2001; Connolly 2010; Chen et al. 2009; APS 2007) at best. This is much lower than the others, and the reason why hydrogen often is left out of reports and articles on ES. A significant improvement in efficiency is required before hydrogen can become competitive.

PHES	70-85
CAES	65-80
LA	70-90
NaS	70-90
VRB	60-85
H tank	<35
H underground	<35

Table 14. Efficiency range (%) of the ES technologies

5.3.2. Operation and management costs

O&M comprise all the costs related to the ES facility, which is not included in the capital cost: energy costs to charge the system, fixed costs (not dependent on how often the system is charged/discharged) and variable costs (of which the bulk is replacement costs) (CPUC 2010). These costs run annually, and for a storage system they vary greatly depending on technology and application. Fixed costs include the operation of the system and annual preset maintenance, while the variable costs are the ones unforeseen or the ones occurring with different time space. An example is battery replacement, which for batteries is predicted approximately every 5-15 year, depending on lifetime of the different types (Sandia 2008). This cost is not unforeseen, but not an annually fixed cost.

Several public analyses have estimated capital cost, both general and project specific ones, but the O&M costs are more difficult to find (CPUC 2010). To estimate the present value (PV) of the O&M costs occurring during the lifetime of the storage system, both an escalation and inflation rate have to be assumed. There are good predictions and estimates for these considering a certain market. In this wind park scenario, a rate of 2.5% and 10% are set for escalation and inflation, respectively.

Often capital cost is the main factor within costs evaluation, as this most often represents the initial and larger cost for ES systems. For emerging technologies in their R&D stage, O&M costs are more difficult to estimate and are often assigned less time for analysis and estimation. After one or just a few test projects, there is still no basis to generalize these costs for a technology (Chen et al. 2009). On the other hand, for mature solutions as pumped hydro and some common batteries, it is possible to make good general estimates for O&M costs per kWh stored.

5.3.3. Cost table

Table 15 shows cost numbers found in different reports on ES technologies from the last decade (Connolly 2010; NREL 2009; Chen et al. 2009; EPRI 2008; Sandia 2008). The year of release is given, though the numbers are adapted, and presented in $2010. Given wide ranges for some of the estimates, there will be used a scenario analysis in chapter 6, to get both a pessimistic and optimistic view of the ES cost.

$2010	Capital cost					O&M	
Technology:	**Power cost($/kW)**		**Energy cost ($/kWh)**		**BoP($/kWh)**	**Fixed ($/kW-y)**	**Replacement($/kWh)**
	low	*high*	*low*	*high*			
PHES	600	2000	0	20	4	2,5	
CAES	400	800	0	10	50	2,5	
LA	175	600	150	500	50	15	250
NaS	150	3000	250	500	40	20	230
VRB	200	1800	150	1000	30	20	300
Hydrogen, tank	1500	1500	20	20		10	
Hydrogen, underground	500	500	1	1		10	

Table 15. Cost of ES technologies.

5.4. Storage capacity

Whilst the economical benefits are somewhat-to-very general for all the energy management/BES application technologies, the operational benefits differ some more. At the same time, these values also have a certain impact on the economical benefits. The storage capacity determines the total benefit of time-shift, while the flexibility may affect the capacity firming with its ability to adjust the ramping.

For large-scale storage, some technologies are currently highly more beneficial than others. Possible storage capacity of PHES and CAES are in the scale of hundreds of MWh, whilst for batteries most current projects operate in the range of kWh, although several MWh projects have been installed recent years (EPRI 2010). Hydrogen, with its high energy density will in theory have the possibility to overcome both PHES and CAES in storage capacity.

As mentioned, this operational benefit also influences the economical benefits of ES. With a good kW profit in time-shift, the storage capacity will determine the total value of this benefit depending on the amount of power being time-shifted. If this had been considered an issue of cost, it would be mentioned that it increases the capital energy storage cost when the efficiency degree is included in the estimations.

Comparing hydrogen to CAES, which is the most similar technology in operation, hydrogen has a much greater storage potential than CA. The energy density of a hydrogen system is estimated to be 170 kWh/m^3, compared to a CAES reservoir with energy density of 2.4 kWh/m^3 (Crotogino and Huebner, 2008 via NREL 2009). For a drymined salt cavern this will give a cost of 0.02 $/kWh ($2008) for hydrogen and 1.20 $/kWh ($2008) for CAES.

5.5. Flexibility

> *"In broad terms, flexibility can be defined as the degree to which and the rate at which adjustment to changing circumstances is possible. More specifically, flexibility may provide the means to respond adeptly to uncertainty."* (Sandia 2010)

ES allows renewable energy power plants a much higher ability to adjust to changes in its circumstances, especially production rate and demand. This is a very important property of ES technologies, as intermittency is the greatest challenge of RE. It is highly circumstance-specific (Sandia 2010), but for the application of RE integration considered in this thesis, it is of high importance.

As explained in chapter 3 of storage technologies, the technologies considered here are the ones suitable for energy management applications, where one of the main characteristics is somewhat slow reaction-time in the need of electricity generation. Batteries are the one technology with the shortest reaction time, in range of ms, while CAES is relatively slow, using several minutes to obtain 100% operation. PHES, offering the largest storage capacities as of today, may go from 0 to 100% in power output in less than two minutes, which proves a somewhat good reaction compared to power capacity (APS 2010; Bullough et al. 2009).

Significant variance in the assumed reaction time (flexibility) of the different technologies opens for the idea of technology combination. Figure 24 illustrates how the combination of batteries and PHES co-operate to obtain I high flexibility and long discharge time.

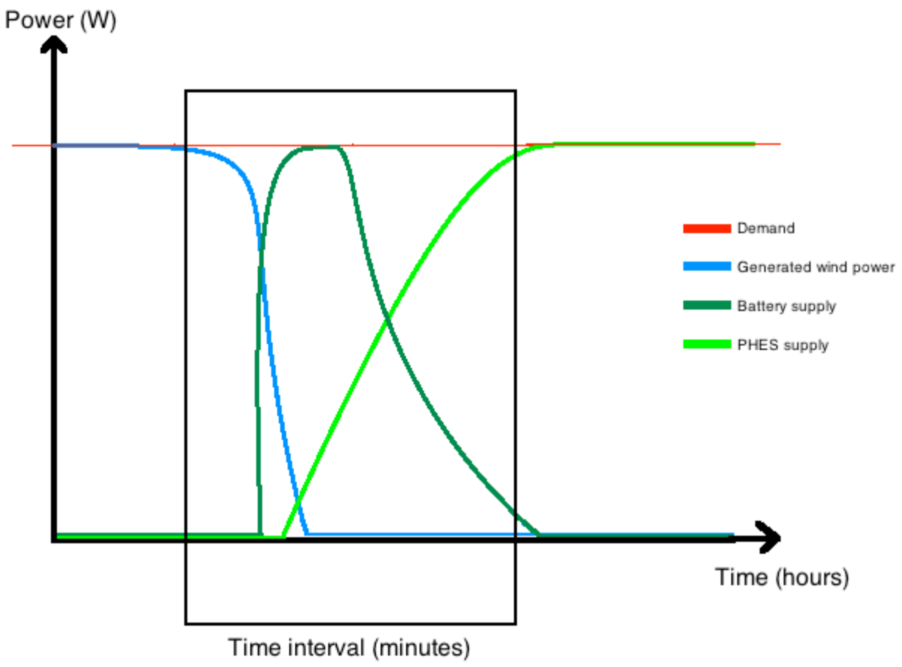

Figure 24. Combination of ES technologies for high flexibility and long discharge time.

The importance of flexibility varies, depending on the power plant where the ES facility is installed. Intermittency is a common factor of the renewables, though the rate at which this intermittency occurs is different for the energy sources. Chapter 2.2.2 describes the variation in wind power generation, which is one of the renewable resources with highest degree of intermittency.

5.6. Summary

This chapter has evaluated come the competitive characteristics of ES technologies. As shown in the chapter 5 introduction there are also several other criterions to consider when assessing an ES project. The ones explained in details are the ones considered more crucial for large-scale storage.

As the technologies develop and both knowledge and experience increase, the natural consequence is an improvement in all these characteristics: costs are reduced (as shown in figure 23), efficiency is improved, storage capacity may increase and flexibility may improve. The magnitude of the last two is more difficult to predict, but these technical properties have a certain potential of development.

Chapter 6 – Case: Wind/ES

The goal of this study is to determine which storage technology is profit maximizing and best suited in conjunction with modest size wind farms, in terms of the characteristics introduced in chapter 5.

6.1. Case

The case settings used in this analysis are adopted from a report on cost sensitivity of different ES technologies (NREL 2009). It concerns is a mid-size ES facility, connected to a remotely located wind power plant with a limited grid connection. It has a storage capacity of 300 MWh, operating on a daily basis, where charged in its off-peak hours (18 hours per day on weekdays and all day on weekends) and discharged at an average rate of 50 MW per hour for peak hours (6 hours a day on weekdays). It is assumed that the system is fully utilized, meaning that power is purchased from the grid when off-peak wind generation is insufficient to completely charge the storage media.

The lifetime of the plant is set to 30 years, which means that replacement costs of battery technologies also need to be accounted for. Replacement adds a significant cost factor into the lifecycle of batteries, and needs to be taken into account if the plant-life exceeds 10 years (or less, if that is the case) (Sandia 2003). Despite variation in battery lifetime, a general life of 10 years is assumed. (EPRI 2008; Sandia 2003).

Considering location, it is assumed that the site is suitable for installation of all the technologies considered. This is to avoid assessment of possible arrangement costs, which is circumstance-dependent and varies significantly.

6.2. Scenarios

Costs will be evaluated for the technologies mentioned in chapter 3, and both tank and underground storage will be considered for hydrogen. ES costs shown in table 15 are used to calculate the total lifetime cost of the technologies. These cost estimates are gathered from existing reports and literature from the last years based on somewhat-to-very the same settings as this case. An inflation rate of 2.5% have been used to find the 2010$ value. A discount rate of 10 % is used to calculate the PV of the future O&M and replacement costs. The settings are summarized in table 16.

Parameter	**Value**
Service life	30 years
Charge	18 h
Discharge	6 h
Charge/discharge cycle	24 h
Annual operating days	260
Deflation rate	10 %
Escalation rate	2.5%

Table 16. Settings for the Wind/ ES plant.

Two scenarios are used for case assessment: low cost (optimistic) and high cost (pessimistic). As costs estimates are characterized by uncertainty (varies mainly according to technology maturity) and situation-dependence, and given in term of ranges, a scenario analysis is a suitable method for cost estimation. Two possible outcomes are found for this project.

6.3. Technology comparison

6.3.1. Cost

Battery costs estimates are found from relatively small-scale storage systems (< 50 MW). Batteries do not yet experience the economy of scale principle when increasing storage capacity (linear cost increase, explained in chapter 3). This makes it a somewhat-to-very linear relation between storage capacity and cost. And as costs are given in the metric $/kW, it can be used for estimation independent of the storage capacity considered.

Several reports on cost estimations present the estimate as range of values instead of accurate numbers. The uncertainty in the estimates, depending on maturity, complexity and flexibility of the technologies, determines the size of the range.

Fixed O&M costs are included in the total cost estimate, while variable ones are left out. These often insignificant compared to capital and fixed costs for most technologies, except from batteries. Here, replacement represents the main variable O&M cost, which has a significant impact on the total cost due to relatively short lifetime. It is therefore included for all the batteries.

For this case study, it would be preferable near-by location of the storage unit. The battery-location flexibility is an obvious advantage, but also hydrogen tank-storage offers this flexibility. Both PHES and underground storage (CAES and hydrogen) are more site-specific, which makes these the determining factor for plant site. This is an obvious drawback, as wind power potential is the main issue.

6.3.2. Storage capacity and flexibility

With a storage capacity of 300 MWh, this is a relatively large bulk of energy. For batteries this size has not yet been implemented, but are assumed to have this potential

(Connolly 2010).

Production that changes by a few hundred MW in less than an hour (Bullough et al. 2004), or 100% on a daily basis (APS 2010), describes a highly intermittent power resource. Wind power is not easy to predict and with drastic changes like these, flexibility is an important property.

With a significant variation in reaction time of these technologies, where batteries are the obvious winner considering reaction for charge/discharge, it is somewhat difficult to compare the flexibility of these technologies. Yet, for this project the main purpose is to generate electricity for 6 hours (peak), and then charge for the remaining 18 hours of the day. These relatively large charge/discharge time intervals (assuming constant charge and discharge) make the reaction time of the storage facility less significant. For power application technologies, this will be more important, as their applications often requires several charge/ discharge cycles a day. So, despite a reaction time up to several minutes for PHES and CAES, it is not considered a problem in this case, where only 2 switch-processes per 24 hours.

6.4. Project evaluation

6.4.1. Net present cost

From using the cost estimates in table 15 in chapter 5.3.3, net present cost (NPC) of the two scenarios is found. Figures 25-27 show the NPC of the all the ES technologies, and includes:

- Capital cost
- O&M (fixed)
- Replacement

As mentioned earlier, these are found for comparison purposes only. These estimates take the cost range into account, showing total cost for both the low cost and high cost scenario. The efficiency on the other hand, which also is represented in terms of ranges in table 14, is assumed to be high. Its influence on capital cost is illustrated in chapter 6.3.2.

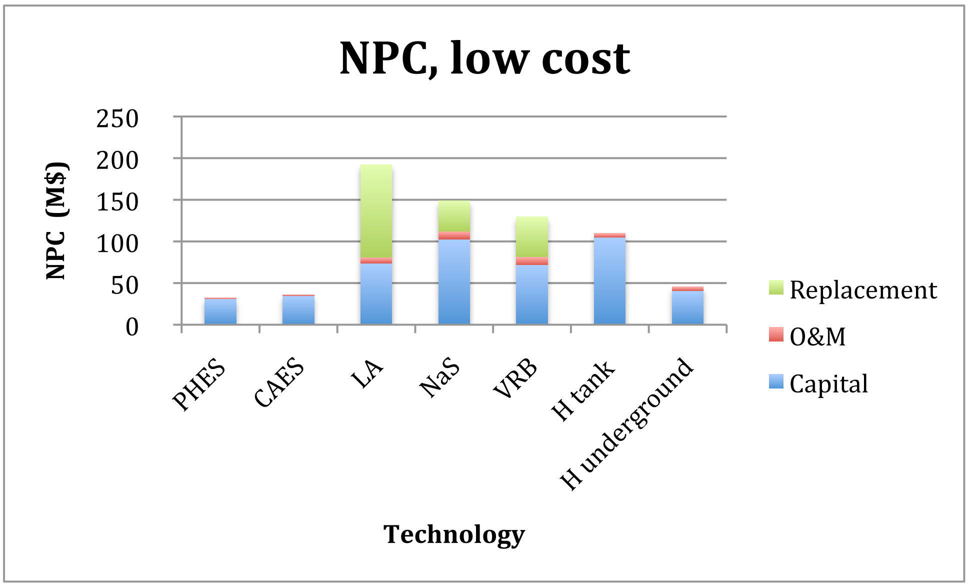

Figure 25. Net present value of the project cost for the Low cost scenario.

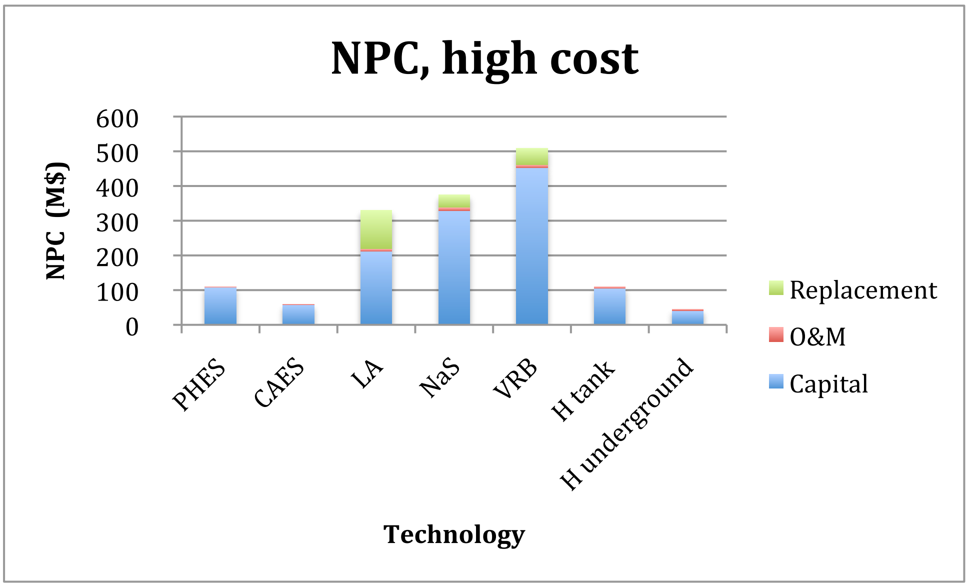

Figure 26. Net present value of the project cost for the High cost scenario.

The cost of electricity used for charging, and for natural gas in the case of compressed air, is not included in these cost estimates. Earlier research shows that the sum of these is approximately of the same size (NREL 2009), and excluded in this case as it is mainly a comparative analysis. The remaining cash flow of O&M costs, including replacement for the batteries lead-acid (LA), sodium-sulphur (NaS) and vanadium redox battery (VRB), are shown in table 17. These are the discounted values during the 30 years of lifetime for this facility.

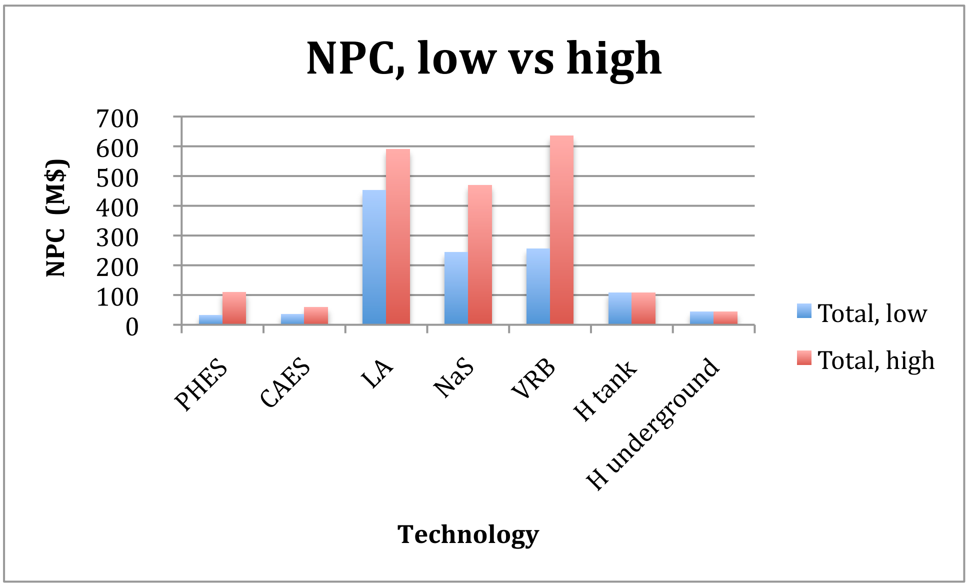

Figure 27. Net Present Cost comparison, Low versus High cost scenario.

This comparison shows that PHES, CAES and HESS have a significantly lower NPC in this case. This is an expected result considering the present situation of these technologies, as these are considered the bulk ES technologies as of today. Despite the fact that CAES is only has a few installations; the technology is developed and well-known (though, not placed within the mature-group in chapter 3). Also its low capital cost based on the low cost storage medium (underground cavern, rock formation etc.) has a crucial influence on the total cost.

PHES, although the most mature technology, can be more expensive than CAES and HESS. The capital cost of building the dams (levels) are often high, with a significant variation. In this case, one of the prerequisites for the facility was that the site was suited for all the storage technologies, so that this wouldn't be a problem. Still, sites are the main limitation of PHES (along with water availability), and could affect the cost of installation significantly if facility installation becomes more comprehensive.

All batteries have a very high NPC, many times that of the three other technologies. One major drawback is the replacement costs of the BESS. For a project lifetime of 30 years, several replacements are needed (depending on battery lifetime), causing a considerable increase in total cost. In the low cost scenario, replacement constitutes a much larger share of the costs. Especially LA batteries, where a lifetime of 5 years is assumed, experience very high replacement costs. LA was mainly included for the purpose of illustrating this battery drawback, as it is not considered a future alternative for large-scale storage, but assumed use primarily for its current applications (Connolly 2010).

This project has a relatively high power and energy capacity considering batteries, and there are no BESS of this size installed today. Though, the principle of combining several battery units to achieve higher power and storage capacity is in its R&D stage, and would give the opportunity of accomplishing this. Their flexibility considering sites, which is always an issue installing ES facilities, is also batteries benefit.

Underground hydrogen storage shows a relatively low present value of total cost, at the same level of PHES and CAES. This will in theory be the future case, due to its high storage potential. Yet, as mentioned earlier, it is difficult to find reliable cost estimates for this technology as it is often left out of general ES cost analyses. They often need to be found in separate reports on hydrogen only (or as main issue), which operates from a more prospective and theoretical view. Positivism in technology analysis may therefore influence the estimates made for this technology, which gives a less realistic value of total cost.

This result indicates that PHES and CAES are the economically feasible ES technologies as of today (the low NPC of hydrogen storage explained in the previous section). But the battery-technologies in their R&D phase, needs further development before available for this application. The future of hydrogen as energy storage medium, supported in theory and by present research and project results, has good prospects. The decisive factor in the ES future is the effort put into R&D and investments made in these projects.

Year	PHES	CAES	LA		NaS		VRB		H tank	H underground
	Fixed O&M	*Fixed O&M*	*Fixed O&M*	*Replacement*	*Fixed O&M*	*Replacement*	*Fixed O&M*	*Replacement*	*Fixed O&M*	*Fixed O&M*
1	113 636	113 636	681 818	0	909 091	0	909 091	0	454 545	454 545
2	103 306	103 306	619 835	0	826 446	0	826 446	0	413 223	413 223
3	93 914	93 914	563 486	0	751 315	0	751 315	0	375 657	375 657
4	85 377	85 377	512 260	0	683 013	0	683 013	0	341 507	341 507
5	77 615	77 615	465 691	46 569 099	620 921	0	620 921	0	310 461	310 461
6	70 559	70 559	423 355	0	564 474	0	564 474	0	282 237	282 237
7	64 145	64 145	384 869	0	513 158	0	513 158	0	256 579	256 579
8	58 313	58 313	349 881	0	466 507	0	466 507	0	233 254	233 254
9	53 012	53 012	318 073	0	424 098	0	424 098	0	212 049	212 049
10	48 193	48 193	289 157	28 915 747	385 543	26 602 487	385 543	34 698 896	192 772	192 772
11	43 812	43 812	262 870	0	350 494	0	350 494	0	175 247	175 247
12	39 829	39 829	238 973	0	318 631	0	318 631	0	159 315	159 315
13	36 208	36 208	217 248	0	289 664	0	289 664	0	144 832	144 832
14	32 916	32 916	197 498	0	263 331	0	263 331	0	131 666	131 666
15	29 924	29 924	179 544	17 954 404	239 392	0	239 392	0	119 696	119 696
16	27 204	27 204	163 222	0	217 629	0	217 629	0	108 815	108 815
17	24 731	24 731	148 384	0	197 845	0	197 845	0	98 922	98 922
18	22 482	22 482	134 894	0	179 859	0	179 859	0	89 929	89 929
19	20 438	20 438	122 631	0	163 508	0	163 508	0	81 754	81 754
20	18 580	18 580	111 483	11 148 272	148 644	10 256 410	148 644	13 377 927	74 322	74 322
21	16 891	16 891	101 348	0	135 131	0	135 131	0	67 565	67 565
22	15 356	15 356	92 134	0	122 846	0	122 846	0	61 423	61 423
23	13 960	13 960	83 759	0	111 678	0	111 678	0	55 839	55 839
24	12 691	12 691	76 144	0	101 526	0	101 526	0	50 763	50 763
25	11 537	11 537	69 222	6 922 200	92 296	0	92 296	0	46 148	46 148
26	10 488	10 488	62 929	0	83 905	0	83 905	0	41 953	41 953
27	9 535	9 535	57 208	0	76 278	0	76 278	0	38 139	38 139
28	8 668	8 668	52 008	0	69 343	0	69 343	0	34 672	34 672
29	7 880	7 880	47 280	0	63 039	0	63 039	0	31 520	31 520
30	7 164	7 164	42 981	0	57 309	0	57 309	0	28 654	28 654
Sum	1 178 364	1 178 364	7 070 186	111 509 722	9 426 914	36 858 897	9 426 914	48 076 823	4 713 457	4 713 457
Total O&M cost	*1 178 364*	*1 178 364*	*118 579 907*		*46 285 812*		*57 503 737*		*4 713 457*	*4 713 457*

Table 17. NPC of operation, maintenance and replacement for the ES technologies.

6.4.2. Efficiency and capital cost

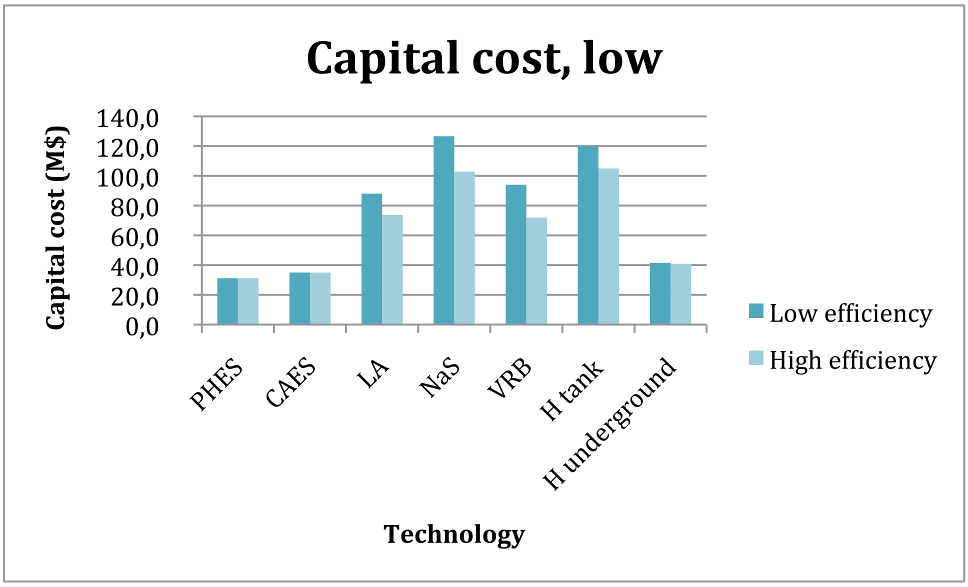

Figure 28. Total cost for the Low cost scenario.

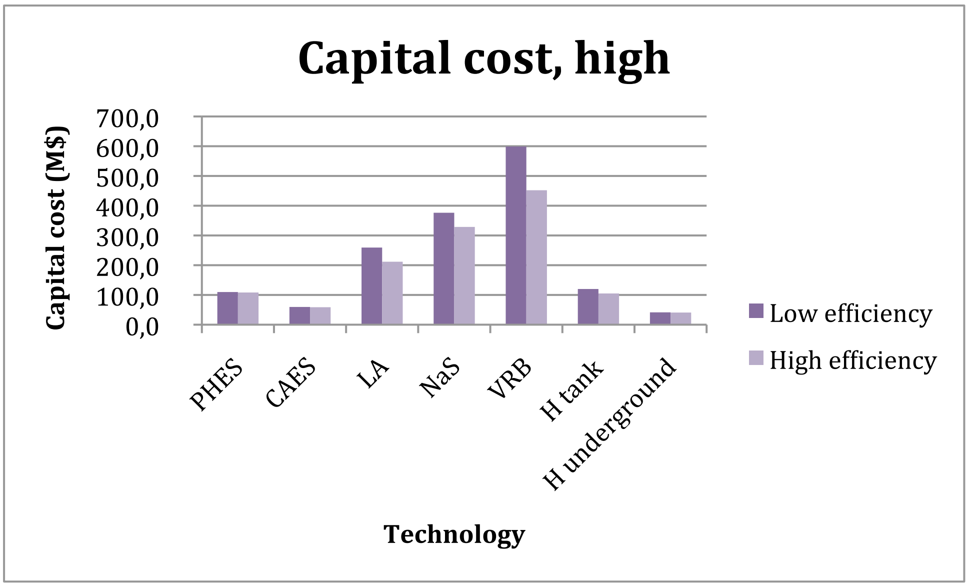

Figure 29. Total cost for the Low cost scenario.

Figures 28 and 29 show the impact of efficiency on capital cost. As explained in chapter 5, efficiency is included in the cost of storage, which is illustrated above. For both underground storage (CAES and HESS) and PHES, the impact of efficiency is somewhat insignificant, due to their low storage medium cost.

For the batteries and hydrogen tank storage, the efficiency impact on capital cost is more significant. This is due to expensive storage medium and a somewhat proportional relationship between storage capacity and cost. The efficiency factor will therefore play a bigger role for these technologies.

Chapter 7 - Conclusion

First, there is a short conclusion to each of the sub-questions. In 7.5 there is an overall conclusion to the main research question.

7.1. How is the current energy market, and what are its future prospects?

The current energy market is dominated by fossil fuel, as reliable resources providing energy when and where it is needed. Though, a future increase in renewable energy utilization is inevitable, as the conventional energy sources dominating the market today are limited. Ever more of the damages caused by fossil energy become identified and reported, which also cause environmental and social concerns.

With the development experienced in the energy sector the last century, and the future prospects established through research, it is quite obvious that the energy market experience somewhat-to-very significant alterations. There will be no drastic changes, and fossils will remain the dominant energy supplier for several more decades, though a steady move towards a higher share of clean energy on the market is necessary. As this becomes the situation, new strategies are required to keep up a steady and reliable energy generation, and one of the primary strategies is considered to be energy storage (NREL 2009).

7.2. What is energy storage, and how can these technologies benefit RE integration?

ES is defined as absorbing/harvest surplus or low-cost energy when available, storing it for peak demand hours or in case of power generation deficit (high demand or low renewable generation). It has a broad spectrum of applications, and the technologies introduced in this thesis offers a broad range of operation characteristics, which can be adapted to different applications. ES are used in all stages of the energy "lifecycle": from generation to end-user (illustrated in figure 10). Every stage/application has own requirements for how an optimal storage unit is to operate. Implementation in the generation phase gives a unique opportunity for renewables to offer steady and reliable energy supply.

Economy and technology are the current main obstacles for ES commercializing, with only a few exceptions reckoned as mature technologies. Yet, promoting this as a solution to the challenges of intermittency and availability and also a necessity to obtain a cost-efficient large-scale RE implementation, these opportunities and benefits could work as motivation for further ES R&D.

In this thesis ES has been portrayed as a prerequisite for integration of RE. Yet, this is not the case for small-scale RE power generation, where the intermittent characteristic are somewhat negligible. Though, for large-scale integration assessed in this thesis, ES will play a significant role.

7.3. How are the ES technologies positioned according to the main operation characteristics?

The main ES characteristics for the energy management application (RE generation) were reckoned as cost, efficiency, storage capacity and flexibility in this thesis, and the technologies are positioned differently relative to these.

In general, ES in terms of pumped hydro, compressed air, and underground hydrogen are the least expensive large-scale storage technologies, offering relatively low operation and maintenance costs over their long lifetime. Hydrogen ES is presented based primarily on theoretical results from test project and research reports, but there are no commercial facilities installed yet. Its future potential is what makes this an interesting alternative. For batteries there are currently two which is assumed to have a future in the RE integration application: Sodium- sulphur (solid) and vanadium-redox (flow) . These are at a much higher cost level than the three technologies mentioned above, but they are assumed to evolve in the direction of higher storage capacity and lower cost.

As for the storage capacity, the situation is somewhat the same as above. Pumped hydro, compressed air, and underground hydrogen have very high storage potentials (in the scale of GWh), due to their technological infrastructure (large dams and underground caverns). Their storage capacity experience the economy-of-scale principle, due to storage medium cost somewhat independent of the total storage capacity. Batteries on the other hand, have a proportional relation between cost and storage capacity. Due to their modular production, a distinct increase in storage capacity (additional battery units) will give the same $/kWh as for the existing capacity.

The criterion of flexibility does not favor the same three technologies. The importance of flexibility is highly application-dependent, but always a crucial factor. It is somewhat less important for the energy management applications than for the power application technologies, yet always desirable that a storage facility is able to react quickly to changes in power generation to avoid power deficit in the transient periods of source shift. Batteries are the most flexible technology, while compressed air, which needs several minutes for start-up, is the "slowest". Pumped hydro and hydrogen vary, but are usually found somewhere in between these.

7.4. How are the ES technologies suited for supporting a 50 MW wind power plant?

High degree of intermittency in the electricity supply from wind power generation in somewhat illustrated by figure 9, and applies both on a daily and seasonal basis. In this case, the cycle of charge/discharge was 24 hours (daily basis).

Estimated total cost of the technologies is shown by figures in chapter 6.4, and confirms the cost assumptions based on maturity and characteristics. Pumped hydro and underground storage show a superior cost advantage in comparison to batteries. These are ES technologies meant for the purpose of large-scale storage for a longer time (hours → seasonal), and will be favored in the wind/ ES case analyzed here. Battery storage, which yet is early in its development as large-scale storage, experiences a great disadvantage considering cost. The main drawback is the replacements, which represents a high share of the total cost, higher the lower the capital cost is. The benefit of high flexibility becomes somewhat insignificant compared to this disadvantage. This case is currently outside their range of operation, but a realistic prospective situation for battery storage.

Combining wind and energy storage has become ever more popular, and to choose ES technologies requires thorough consideration. Apart from cost, it depends mainly on the storage purpose: bulk of storage, cycle of charge duration, and degree of flexibility needed. As illustrated in figure 22, the ideal situation can often be a combination of technologies, where each of these can promote their main advantages in favor of the storage system as a whole. Then again cost will be the main issue.

7.5. Summary

The share of renewables on the global energy market has experienced a significant increase the last decades, both due to new technology and governmental and public support. Challenging issues like intermittency and availability will influence the scale of further integration (SRREN 2011). Hence, ES can play an important role in large-scale integration by reducing/solve these challenges. Additional factors like new and improved infrastructures in the electricity grid are also essential.

Both technological development and cost reductions are prerequisites for a higher use of ES. Mature technologies as pumped hydro and lead acid battery, which already has an acceptable cost level and operates as competitive alternatives on the market, also have limitations like site-dependence and low storage capacity respectively. Emerging ES alternatives in their R&D stage can solve these, but their further development and future commercialization highly depends on governmental funding and subsidies. Thus, not only cost reduction and technological development will be crucial, but also decisions of business managers, policy-makers, and households will affect their future (Martinot et al. 2007).

Fossils will still dominate the energy market for some decades, but the more long-term prospects for renewables are established through several national and international policies and agreements, to ensure a market development towards clean energy. This is to a certain extent in inevitable due to limited carbon-based resources. Though, the extent of development and usage in the future can not be predicted by high certainty, but several optimistic scenarios in favor of RE and ES on the energy market have been established based on thorough research.

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Appendix

Country	Feed-in tariff	Renewable Portfolio Standard/quota	Capital subsidies, grants, rebates	Investment or other tax credits	Sales tax, energy tax, excise tax, or VAT reduction	Tradable RE certificates	Energy production payments or tax credits	Net metering	Public investment, loans, or financing	Public competitive bidding
EU-27										
Austria	X		X	X		X			X	
Belgium		(*)	X	X	X	X		X		
Bulgaria	X		X						X	
Cyprus	X		X							
Czech Republic	X		X	X	X	X		X		
Denmark	X		X	X	X	X		X	X	X
Estonia	X		X		X		X			
Finland	X		X		X	X	X			
France	X		X	X	X	X			X	X
Germany	X		X	X	X			X	X	
Greece	X		X	X				X	X	
Hungary	X		X	X	X				X	X
Ireland	X		X	X		X				X
Italy	X	X	X	X	X	X		X	X	
Latvia	X				X				X	X
Lithuania	X		X	X	X				X	
Luxembourg	X		X	X	X					
Malta			X		X			X		
Netherlands			X	X	X	X	X			
Poland		X	X		X	X			X	X
Portugal	X		X	X	X				X	X
Romania		X			X	X			X	
Slovakia	X			X	X				X	
Slovenia	X		X	X	X	X			X	X
Spain	X		X	X	X	X			X	
Sweden		X	X	X	X	X	X		X	
United Kingdom	X	X	X		X	X			X	
Other Developed/Transition Countries										
Australia	(*)	X	X			X			X	
Belarus									X	
Canada	(*)	(*)	X	X	X			X	X	X
Israel	X				X					X
Japan	X	X	X	X		X		X	X	
Macedonia	X									
New Zealand			X						X	
Norway			X		X	X			X	
Russia			X			X				
Serbia	X									
South Korea	X		X	X	X				X	
Switzerland	X		X		X					
Ukraine	X									
United States	(*)	(*)	X	X	(*)	(*)	X	(*)	(*)	(*)

Country	Feed-in tariff	Renewable Portfolio Standard/quota	Capital subsidies, grants, rebates	Investment or other tax credits	Sales tax, energy tax, excise tax, or VAT reduction	Tradable RE certificates	Energy production payments or tax credits	Net metering	Public investment, loans, or financing	Public competitive bidding
Developing Countries										
Algeria	X			X	X					
Argentina	X		X	(*)	X		X		X	X
Bolivia					X					
Brazil				X					X	X
Chile		X	X	X	X				X	X
China	X	X	X	X	X		X		X	X
Costa Rica							X			
Dominican Republic	X		X	X	X					
Ecuador	X			X						
Egypt					X					X
El Salvador				X	X				X	
Ethiopia					X					
Ghana			X		X				X	
Guatemala				X	X					
India	(*)	(*)	X	X	X	X	X		X	
Indonesia	X			X	X					
Iran				X			X			
Jordan					X			X	X	
Kenya	X			X						
Malaysia									X	
Mauritius			X							
Mexico				X				X	X	X
Mongolia	X									X
Morocco				X	X				X	
Nicaragua	X			X	X					
Pakistan	X							X		
Palestinian Territories					X					
Panama							X			
Peru				X	X		X			X
Philippines	X	X	X	X	X		X	X	X	X
Rwanda									X	
South Africa	X		X		X				X	X
Sri Lanka	X									
Tanzania	X		X		X					
Thailand	X				X				X	
Tunisia			X		X				X	
Turkey	X		X							
Uganda	X		X		X				X	
Uruguay		X								X
Zambia					X					

Governmental policies for renewable energy financial support (REN21 2010).