IIIEE Theses 2011:19

Thermal Energy Storage in Sweden and Denmark

Potentials for Technology Transfer

Michael Harris

Supervisors

Philip Peck

Mikael Backman

Thesis for the fulfilment of the
Master of Science in Environmental Management and Policy
Lund, Sweden, September 2011

© You may use the contents of the IIIEE publications for informational purposes only. You may not copy, lend, hire, transmit or redistribute these materials for commercial purposes or for compensation of any kind without written permission from IIIEE. When using IIIEE material you must include the following copyright notice: 'Copyright © Michael Harris, IIIEE, Lund University. All rights reserved' in any copy that you make in a clearly visible position. You may not modify the materials without the permission of the author.

Published in 2011 by IIIEE, Lund University, P.O. Box 196, S-221 00 LUND, Sweden,
Tel: +46 – 46 222 02 00, Fax: +46 – 46 222 02 10, e-mail: iiiee@iiiee.lu.se.

ISSN 1401-9191

Acknowledgements

First a thank you to the Öresund Group, without support and interest in this research this report would not have been possible. In particular Casper Harboe, Anders Brix-Thomson and Maja Baungaard, for their easy-going attitudes and for taking the time to explain important parts of the meetings in English for me.

My supervisors, Mikael and Philip. Mikael the man of many connections, thank you for making sure that I was put in touch with the right people to make this work possible. To Philip, for a willingness to drop everything to meet with me whether that was in your office or on your summerhouse patio.

I would like to send a special thank you to Marie Fossum, VP of New Business at Fortum in Stockholm. You took time for a student and introduced around your office like I was an old friend. I hope to one day become one.

Thank you to my father Brian for investing hours of time even on a sunny Saturday reading and editing my work. Thank you for holding me to a high standard and not letting me get away with sloppy writing. I appreciate it and look up to you as a father and a writer.

Finally to the rest of my family who have been my tireless supporters though everything I have done, regardless of what it is or where. Having a home base of support, and always knowing that I have a safe place to return to if things went awry has made it possible for me to venture.

Abstract

Management of intermittent renewable energy sources (RES) such as wind and solar is a significant issue for countries with interconnected electricity markets. Increasing amounts of electricity from intermittent RES increases the variability of electricity supply, causing electricity prices to become highly sensitive weather conditions. Unpredictable prices have a negative effect on new infrastructure investment both for renewables and for existing combined heat and power (CHP) production. Storage of electricity to alleviate that variability is costly and problematic. Storage of heat, however, is possible, and electricity can be efficiently turned into heat. Where there is a demand for district heating, Thermal Energy Storage (TES) can offer CHP /district heating operators the flexibility to produce heat from fuels, or with stored heat generated from 'excess' intermittent electricity. TES systems have evolved in different jurisdictions; if TES systems are to become mainstream, greater use of both existing technologies and applicable ones from other jurisdictions is necessary. Ensuring public understanding and acceptance of new ways of using electricity for heating (via heat pumps) is critical. Sweden and Denmark have developed independent strategies for TES: Aquifer and Borehole TES in Sweden, and Pit TES in Denmark. This paper identifies the path-dependent evolution of the Swedish and Danish energy systems that influenced the TES technologies that each developed. Opportunities for TES technology transfer between these countries and potential roles for government, businesses and regional planners are explored.

Keywords: Thermal Energy Storage Sweden Denmark Renewable Integration

Executive Summary

Energi Öresund: The Öresund region, shared between Sweden and Denmark, is rapidly becoming an international centre for business, education, and technology. While the two countries have long shared regional ties, the opening of the Öresund Bridge in 2000 ushered in a new era of cooperation. Greater linkages and mutual interests has led to integration of technical systems and increased the potential for services and knowledge exchange.

Energi Öresund, a group drawn from Danish and Swedish municipalities, energy companies, universities, and energy-agency planners in Öresund region, was created to help coordinate regional energy planning. In addition to sharing information on energy technologies and improving inter-country communication, the group aims to identify cross-border economic opportunities for businesses in recognition that greater interaction between the countries can be beneficial for both.

Research Problem: A key topic for the group is thermal energy storage (TES), which is one method to address the challenge of integrating the intermittent generation of renewable energy into the common electricity grid. Energi Öresund has noted that the specifics of how TES technology could be used to achieve this integration is not well understood by all members of the group. Understanding and acceptance is key to the success of any technology exchange between the countries, and thus addressing this cognitive gap one of the group's key priorities.

Research Questions: The task of this research project has been to address this cognitive gap by: 1) clarifying the case for using TES, 2) describing the historical differences in use and attitudes of TES between Sweden and Denmark, 3) identifying the potential for technology transfer between these countries, and 4) offering some insight into how technology transfer can occur. These questions are answered under the context of the main research question: "How can greater interaction between Denmark and Sweden in the area of Thermal Energy Storage help to integrate intermittent energy in an energy system increasingly based on renewable sources?"

To accomplish this research, a comprehensive literature review and a series of personal interviews with both Swedish and Danish energy professionals were conducted. Path Dependency theory was used to categorize the historical evolution of the Danish and Swedish energy systems, and Technology Transfer theory used to structure the section on how TES systems used in each country could be transferred to the other.

The research identified four key findings:

1. There is a strong case for using TES: Both Sweden and Denmark share a grid connection and buy and sell electricity on the Nord Pool electricity spot market. Currently, wind generated electricity in Denmark at times exceeds domestic demand. This excess electricity is exported on the Nord Pool market, which causes considerable price fluctuations. This fluctuation is compounded by heat-bound combined heat and power (CHP) generation during cold months, which adds more electricity and further volatility to the grid. Common weather patterns across Nord Pool states mean that as all members add projected amounts of intermittent renewables (notably from wind) market prices will become increasingly dependent on weather conditions and increasingly volatile.

Unpredictable energy prices have a negative effect on the investment climate for new energy infrastructure and place additional pressure on the operators of traditional sources (CHP) to adjust their power generation rapidly to meet unpredictable demand.

Traditionally Swedish and Norwegian hydropower has been available to balance some of the intermittent wind supply. However, as Nord Pool members all increase their generation from intermittent RES and climate change affects the predictability of wet and dry years, traditional buffering sources may not be able to dampen the volatility of electricity supply. Increased transmission to markets in nearby countries may ameliorate the situation somewhat but similar wind generation plans and similar weather patterns will likely reduce the effectiveness of this option.

Better management of domestic electricity use could reduce the problems of volatile supply. Smart grid technology, battery electric vehicles, or electricity storage measures are three potential solutions, however none currently exist at a volume capable of making a significant impact on volatility.

However, some of the electricity could be used to power heat pumps for CHP / district heating at times when it would otherwise be exported (and thus depress electricity market prices). This is a market ready option that could help stabilize volatile prices and reduce demand for heat generated from combusting fuels. Heat pumps, which are far more efficient than direct electric heating, offer increased heat output per unit of electricity. However, heat demand is not constant throughout the year, and this is where TES can help.

Storing heat in large tanks can moderate daily fluctuations in district heating demand and are already in use in much of Sweden and Denmark. However long-term storage requires different methods and technologies that can store thermal energy from season to season.

2. Sweden and Denmark each developed independent technologies for TES: In Sweden, seasonal storage mostly occurs at the building level where heat is stored underground using Aquifer Thermal Energy Storage (ATES) and Borehole Thermal Energy Storage (BTES). In Denmark, seasonal storage is used at the district heating level, above ground in large, water filled pits (PTES). Neither technology is used to a great extent by the other country.

3**. The path dependant history of each country's energy system had a strong impact on the TES technologies developed for generating and storing heat and electricity**: Sweden since the 1980s was characterized by an abundant supply of electricity from hydropower and nuclear power. Inexpensive electricity encouraged the development of heat pump technology at both the building and district heating level. Sweden's extensive mining and geotechnical capacity aided the installation of shallow geothermal heat pumps. Development of TES technologies such as Borehole TES and Aquifer TES built on this experience and used similar techniques to store heat. Although mostly used at the building level, ATES and BTES can be used at the district heating level as well. In Sweden using electricity for heating has long had widespread public acceptance – in the past using direct electricity heating, more recently in a range of heat pump technologies.

In Denmark, without hydro or nuclear power, CHP electricity from burning fossil fuels has historically been expensive. Government requirements for heat consumers to connect to district heating or natural gas heating reduced individual heating options. Investment in renewable energy helped establish wind power and solar thermal district heating, and Pit TES developed as a method of storing solar heat from summer to winter. Government discouragement of the use of electricity for heating contributed to low use of heat pumps and poor public understanding and acceptance of this use of electricity despite the high efficiency of heat pumps.

4. Technology transfer is possible and beneficial: In the future, renewable energy sources will contribute an increasing proportion of electricity generation. TES is one technology to manage the intermittency of these energy sources, and holds significant opportunity for international cooperation and technical exchange.

According to technology transfer theory, successful technology transfer involves not only the physical components (hardware) but also the knowledge of how to use them (software) and a third component (orgware), which ensures explicit laws and implicit societal rules are also conducive to the new technology.

From an economic perspective, implementing TES entails investment costs as well as risks associated with a new technology. The installation costs may be allocated between public and private actors in proportion to the benefit received. In some cases, TES may be considered a "public good," because using heat from a TES may reduce some CO2 emissions and help stabilize electricity market prices, both of which are desirable outcomes for the public. Consequently there may be a role for government policy makers to either help finance TES installation projects or, more coercively, mandating them.

Conclusions: Increasing amounts of intermittent RES increases the variability of electricity supply. For a variety of reasons, storage of electricity to alleviate that variability is problematic. Storage of heat, however, is possible, and electricity can be efficiently converted to heat with heat pumps and then stored. Sweden and Denmark have developed different technologies for TES, and some of the best examples of each country's technologies can be found in the Öresund region. Thus there is opportunity for inter-country transfer of TES technologies. Fundamental to successful TES technology transfer however is public understanding and acceptance of using electricity for heating, largely absent in Denmark. Greater interaction between the countries can help address this issue, and Energi Öresund can help facilitate this interaction. This report concludes with some recommendations for governments, businesses, and Energi Öresund to enhance the acceptance for using electricity for heating.

Table of Contents

List of Figures

List of Tables

Abbreviations

TES: Thermal Energy Storage

RES: Renewable Energy Sources

IEA: International Energy Agency

EU: European Union

BTES: Borehole Thermal Energy Storage

ATES: Aquifer Thermal Energy Storage

PTES: Pit Thermal Energy Storage

DONG: Danish Oil and Natural Gas company

COP: Coefficient of performance

GS Heating: Ground Source Heating

Glossary:

Demand-Side Heat Management: Managing heating and cooling 'demand' at the home or building level

Supply-Side Heat Management: Managing heating and cooling 'Supply' district heating level.

Shallow geothermal: Less than 300m in depth

1 Introduction

1.1 Rise of the Öresund Region

The Öresund[1] region, a shared territory between eastern Denmark and southern Skåne area in Sweden has a long intertwined history. Named after the stretch of Baltic Sea that separates the two countries, for centuries the Öresund region was a battleground between Sweden and Denmark. Sweden only established permanent sovereignty over Skåne after the Treaty of Roskilde in 1658 (Scania, 2006).

Despite its bloody history, more recently the Öresund region has become an example of inter-country cooperation. The year 2000 marked the completion of the Öresund Bridge, the first fixed-link connection between the two countries. The new transport link opened the region to trans-border business and labour markets, particularly in the two major cities of the region, Copenhagen in Denmark and Malmo in Sweden.

Figure 1-1 'Öresund Region of Denmark and Sweden; Öresund Bridge'

Source: (Trendens Öresund, 2011)

During the past decade the region has experienced substantial economic and population growth. Since 2000 over 180,000 new inhabitants moved to the Öresund region, which now accounts for 26% of the combined GDP for the two countries (Trendens Öresund, 2011). Increased economic importance has encouraged political integration. The recently created Öresund Committee aims to reduce administrative boundaries between the two countries (Oresunds Regionen, 2011).

Integration between Sweden and Denmark also extends to the energy sector. Both countries are connected to the Nord Pool Spot market, a common electricity trading market also including Norway, Finland, Estonia and Northern Germany (Nord Pool Spot, 2011).

This linkage of the Swedish and Danish electrical systems enhanced the security of supply and price transparency, but also created a host of new challenges. A key issue facing the sector is the integration of the increasing percentages of intermittent Renewable Energy Sources (RES), such as solar photovoltaic (PV) and, in particular, wind generated electricity. In 2011 Denmark satisfied 25% of its electricity demand with wind. In Sweden the proportion is much smaller

---

[1] As this thesis is published in Sweden, the Swedish spelling Öresund has been chosen for consistency. However the Danish spelling, Øresund, is equally valid.

(2%) but growing rapidly (European Wind Energy Association, 2011). Intermittent renewable electricity is challenging for electricity grid operators to ensure constant supply because of its inconsistency – high production on windy and sunny days and low production on calm and cloudy days.

In the highly interconnected energy system between Sweden and Denmark, integrating intermittent RES while ensuring that the system remains capable of delivering reliable, predictable electricity, is in the best interest of both countries. It is this recognition, and that in a world of trans-national grid connections successful energy planning must occur at the trans-national level, that Energi Öresund was created.

1.2 Energi Öresund:

Energi Öresund is an international project for knowledge sharing between Sweden and Denmark which recognizes that greater interaction between both countries can have positive social and economic benefits for each. It represents a collaborative forum where Danish and Swedish municipal planners, energy companies, universities, and other private industry stakeholders from the Öresund region meet to exchange information on energy issues and to identify opportunities for improving cross boarder trade. (A list of Energi Öresund partners can be found in Appendix A).

The group is funded with European Union Interreg IV project financing. Interreg is an arm of the European Regional Development Fund, whose mandate is to reduce the barriers of national borders and strengthen economic, social and cultural cooperation between member states (INTERREG IV, 2011).

The Danish and Swedish energy systems are significantly different in how each generates electricity and heat. For example, Sweden has nuclear and hydropower, and a prevalence of heat pumps for individual and district heating, while Denmark relies primarily on fossil fuel combustion in Combined Heat and Power (CHP) plants, wind, and district heating. Members of Energi Öresund recognized that these differences represent opportunities for information sharing and the potential for technology exchange (C. Harboe, Personal Communication, 10 May, 2011).

One key topic that the group has identified is Thermal Energy Storage (TES), a method of integrating intermittent renewable energy into the current energy system.

1.3 Thermal Energy Storage

TES refers to technologies and methods of storing energy. TES has been used for centuries – there is evidence of civilizations in biblical times storing winter ice for summer cooling (Dincer & Rosen, 2011). In this paper, TES most often refers to the storage of heat. TES has a variety of uses and time spans. It can be used to better manage building heating and cooling needs, to store solar heat from summer until winter, or to hold hot water in district heating plants between periods of low and high demand, (Dincer & Rosen, 2011);(SOLARGE 3, 2005); (Petersen & Aagaard, 2004). TES can also be used as a method for integrating intermittent RES into an established energy system (Togeby et al., 2009); (Larke & Lund, 2008).

As mentioned, one of the challenges of renewable energy is that the amount of electricity generated is not constant. This can result in times when wind or solar generated electricity is produced in excess of domestic demand, which is exported and drives down spot market prices. Exporting the excess electricity can cause technical and economic problems as explained in Chapter 2. If energy producers could use some of that electricity domestically to produce heat, some of the problems with electricity export could potentially be alleviated. However, heat demand is not constant either. TES technologies offer methods to store heat from the time it is generated to when it is needed. Several of the largest examples of Danish and Swedish TES technologies were developed and exist in the Öresund region, and several researchers have identified that TES can play an essential role in integrating renewables in the area (Togeby et al., 2009); (Vad Mathiesen & Lund, 2004); (Lund, Sanner, & et al, 2004).

1.4 Problem Definition

Öresund is emerging as an integrated region technologically and economically. Its energy systems are already connected physically through the Nord Pool electricity market, and consequently what happens in one country can affect the electricity supply and prices in the other (and other member counties).

The Region already has a high deployment of intermittent RES, currently coming primarily from wind electricity generation in Denmark. However both Sweden and Denmark plan to increase the proportion of wind energy in their respective systems. As the percentage of intermittent electricity generation rises, the challenge will be to integrate that electricity into traditional systems and will soon be an issue for both countries.

Energi Öresund has identified Thermal Energy Storage, as a method for integrating intermittent renewable energy, as a key topic for the group. However, they found that the TES technology is not well understood by all group members or the public. In fact, the understanding and acceptance of TES differs markedly on the Swedish and Danish sides of the sound. Lack of understanding is a significant barrier to any potential for technology transfer. Energi Öresund thus made addressing this cognitive gap one of their main priorities.

1.5 Problem Statement

Energi Öresund has identified a significant cognitive gap in the uses and implications of TES on Danish and Swedish sides of the sound. The manner in which TES can contribute to increased integration of renewables, and the benefits to their respective energy systems is not well understood. A clear understanding of current TES technology and the reasons why they came into use in each country is necessary before there can be technology transfer between countries.

1.6 Research Questions

Reflecting the identified needs, and the problems listed above the following questions have guided this work:

Overarching Research Question: How can greater interaction between Denmark and Sweden in the area of Thermal Energy Storage help to integrate intermittent energy in a future energy system increasingly based on renewable sources?

Sub Question 1: How can TES help facilitate the integration of intermittent RES?

> **Task:** Conduct literature review to clarify the case for using heat storage in a future Danish and Swedish energy system increasingly built on intermittent sources.

Sub Question 2: How do Sweden and Denmark currently generate heat and electricity and how is energy stored in each country?

Task: Conduct literature review and personal interviews. Describe the Swedish and Danish use of both energy generation and storage. Identify TES technologies that are used on one side of the sound only.

Sub Question 3: How did Sweden and Denmark each arrive at the energy systems and storage technologie they have?

Task: Conduct literature review and interviews. Identify a technical theory/conceptual framework to assist categorization of key developments that influenced the historical evolution of the Swedish and Danish energy systems and how that gave rise to the respective TES technologies.

Sub Question 4: How could mutually beneficial technology transfer occur between Sweden and Denmark, using TES technology as an example?

Task: Identify a social theory to assist the explanation of how technology exchange between the two counties could be accomplished.

1.7 Methodology

1.7.1 Selection of Topic:

Part of Energi Öresund's agreement with Interreg is facilitation of M.Sc. level thesis work for students from the partner universities writing on topics related to the group's mandate. Thus, a client – consultant relationship was established, with Energi Öresund providing the initial topic to be researched. TES was suggested as a key area where group knowledge was incomplete and could fulfil one of the group's goals to exchange technology. The thesis work was proposed by the author to address this gap.

TES technologies are intricately linked to each country's energy system, and Sweden and Denmark have fundamentally different electricity generation. Thus, an integral part of the research became to determine not only how TES was used in each country, but to understand how each system evolved to reach the technologies in use.

TES has many applications, but one of the most relevant for Energi Öresund is the potential for incorporating intermittent renewable energy sources (RES) into the current energy system. Thus, the topic was expanded to clarify how TES can play a role in greater RES integration.

Finally, it was important to both the author and Energi Öresund that the topic be applicable beyond the Öresund region. As implementation of renewable energy expands around the world, methods for facilitating its incorporation become globally relevant. Both Denmark and Sweden are facing the situation of a large percentage of fluctuating renewable electricity earlier than many other countries, and lessons learned here may be relevant elsewhere. Thus, the topic has potential to contribute to a growing world body of knowledge for renewable energy management.

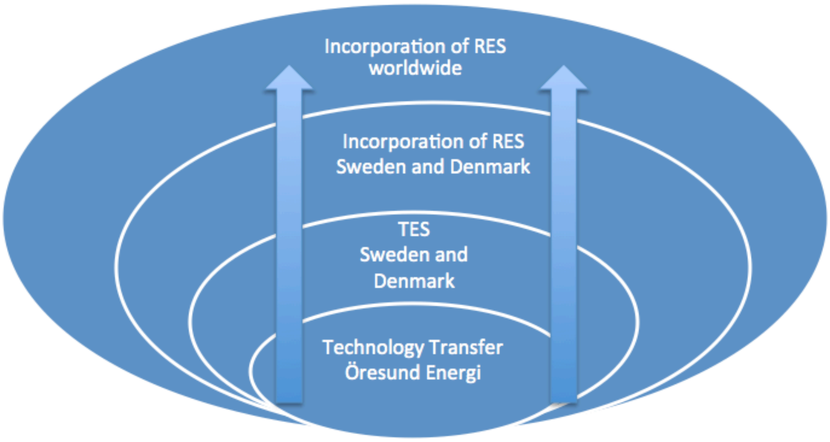


Figure 1-2 'Research position within the technological field'

Source: 'Author'

1.7.2 Selection of Analytical Frameworks

Initial interviews with Energi Öresund members and preliminary literature review indicated two areas where analytical frameworks could prove useful for this work: 1) Understanding the historical evolution of each countries energy system, and 2) Understanding how technology can be exchanged.

1) To structure the research on the historical evolution the Swedish and Danish energy systems, several social theories were considered. Institutional Persistence theory (North, 1990) and Resource Accumulation theory (Helfat, 1994) each offer some insight into how initial conditions affect later system outcome. However, Path Dependency theory (Arthur, 1989); (David, 1985) was selected because it included not only the influence of initial conditions, but also how decisions taken along the system path by institutional actors can shape choices later available, which was felt to better fit the Swedish/Danish case. A full description and literature review of Path Dependency theory and its application to the evolution of the Swedish and Danish energy system is found in Chapter 4.

2) To structure the section on technology exchange, social theories regarding technology and society were reviewed. These included Technological Innovation theory (Bergek & Jacobsson, 2002) and Techno-Economic Paradigm theory (Perez, 1983) each of which offered some insight into how new technologies develop. However Technology Transfer theory (IIASA, 2006) offered an uncomplicated way to categorize the main aspects of technology transfer, termed "Hardware" – the physical components, "Software" – the knowledge of how to use them, and "Orgware" the institutional settings required. A full description and literature review of Technology Transfer theory and its applications for Danish and Swedish TES technologies is found in Chapter 5.

1.8 Data Collection

1.8.1 Secondary Data: Literature review

Research for Chapter 2 required an understanding of the challenges of RES intermittency and the various methods and technologies available to address them. TES technologies are largely energy system dependant, thus each technology could not be studied in isolation, but in association with current applications. A world overview TES was undertaken first. Once a basic understanding of 'world' case for using TES had been established, the focus was narrowed to Sweden and Denmark and the different technologies and used for TES. For a purely technological overview, a wide variety of secondary sources were used from around the world. Much was from engineering and thermo-dynamic university papers and textbooks, as well as academic papers, conference proceedings, company reports and government agency reports.

Research for Chapters 3 and 4, current and historical background of the energy systems of Sweden and Denmark, included sources from the Swedish and Danish energy agencies, International Energy Agency, the European Union, academic journal articles, history textbooks as well as company reports.

1.8.2 Primary Data collection: Interviews

Primary data collection consisted of a series of interviews. Interviewee selection began with a process of stakeholder mapping conducted with direction from thesis supervisors. An abbreviated stakeholder map can be found in Appendix B.

Once relevant stakeholder groups were identified, individuals within these groups were contacted by phone and email. Interviews were semi-structured due to the wide variation in knowledge areas but conducted in a similar fashion. Interviews were conducted individually and primarily in person or occasionally by phone. The project background and research questions were first explained, and interviewees were allowed to ask clarifying questions. The interview progressed in a conversational format, based around themes provided by the two theoretical frameworks and the individual knowledge area of each interviewee.

From these initial interviews, other stakeholders were identified in the 'snowball method.' The number of interviews was decided in two ways. Once a relatively balanced number of both Swedish and Danish stakeholders had been achieved, and secondly, the 'law of diminishing returns' – when the useful new information supplied by each new interviewee began to decrease. A list of interviewees and dates contacted can be found in Appendix C.

1.9 Limitations and Scope

The goal of this work is primarily informative. It aims to clarify the case for using TES, understand how Sweden and Denmark each developed and use TES, and identify potentials for technology transfer within Energi Öresund. While some recommendations are offered, the work has been focused to provide insight to Energi Öresund, the prime audience. The specific technical requirements for each technology, their specific costs and how to modify government legislation, where or if required, are beyond the scope of this paper.

The theme of this paper is renewable energy integration. There are many methods for addressing the challenges of intermittent RES employed around the world. Some include:

- Greater grid interconnection: allowing intermittent electricity can instantly be routed across borders from where it is generated to where it is needed
- Smart grids: which manage electricity supply and demand efficiently – for example by turning appliances on and off in accordance to wind and solar supply
- Electric Vehicles: which can store electricity in their car batteries
- Electricity storage: such as large batteries or stored hydro-electric power

A range of such methods is discussed briefly in Chapter 2. However this paper is focused on energy storage. Energy can be stored as electricity or heat (Vartiainen et al, 2011). An overview of the main electricity storage methods used around the world can be found in

Appendix D. An exhaustive description of all methods for RES integration, however, is beyond the scope of this paper. This work will focus solely on the use of TES.

TES has a variety of applications and has developed in different ways around the world depending on the energy systems established and uses for heat. A description of some of the main TES technologies used can also be found in Appendix D. However as Energi Öresund is the intended audience, the geographic scope of this work is Sweden and Denmark. As such, this research is focused on the technologies in use there.

2 The Case for Thermal Energy Storage

2.1 Part 1: The Issue of Intermittent Renewable Electricity

In the absence of storage, electricity must be used when it is produced. This requires a system that is constantly able to balance electricity generation with electricity demand (Swedish Energy Agency, 2010). Excess supply of electricity in the grid will cause the voltage and alternating frequency to rise above the safe level causing electricity "surges," too little supply and there will not be enough electricity in the grid for demand, causing shortages or "brown-outs" (CESPOS, 2009).

In an energy system based on relatively constant supply such as nuclear power or hydropower, demand can be estimated and planned for. Even in an energy system with a small percentage of intermittent RES supply fluctuation can be addressed similar to demand fluctuation, and utilities can generally absorb small changes without difficulty. As the amount of intermittent renewable energy increases as a proportion of the total supply, however, fundamental changes in how supply and demand is managed become necessary (Larke & Lund, 2008).

Denmark already faces this situation. Due to a variety of policy and public choices (addressed in Chapter 4), Denmark has one of the highest percentages of intermittent RES of any society on the world. In 2010, 25% of its electricity demand was provided by wind, and is on track to have between 37% and 47% by as early as 2020 (European Wind Energy Association, 2011).

In addition to wind, Denmark has a high percentage CHP production, which provides the country with heat for its district heating systems as well as electricity. The fundamental problem created by this combination is that wind generated electricity is not always in sync with demand, and it does not provide heat. Heat demand is met by CHP but is difficult to adjust in response to varying wind supply, as it takes time to ramp up or down combustion / steam cycle based generation system turbines (Munster & Lund, 2003). Consequently a situation can occur where CHP will continue to provide heat and electricity, even though wind is already sufficient to meet electricity demand, a situation referred to as called Heat-Bound electricity production (Larke & Lund, 2008) (for more information on CHP, see Appendix D).

Thus far, Denmark has been able to use the Nord Pool electricity market as means of accessing Norwegian and Swedish hydropower to balance out its supply and demand of electricity, and as a place to sell any excess (above domestic demand) wind electricity. An assumption for the future has been that combination of hydropower balancing and increased interconnection between large neighbouring electricity consumers such as Germany, will absorb any excess wind energy (EWEA, 2005). However, as all bordering countries increase their production of RES, neither of these solutions may be adequate to ameliorate the fluctuating supply (Pöyry, 2011); (Eurolectric, 2011).

2.1.1 The Nord Pool Spot electricity market

The Nord Pool Electricity Market consists of Norway, Denmark, Sweden, Finland, Northern Germany and Estonia. Electricity markets function via electricity providers such as wind turbine operators, CHP operators and hydropower dam operators, agreeing to provide a certain amount of electricity to the grid at price agreed upon by electricity sellers, companies that distribute and sell electricity to the end customer (Nord Pool Spot, 2011).

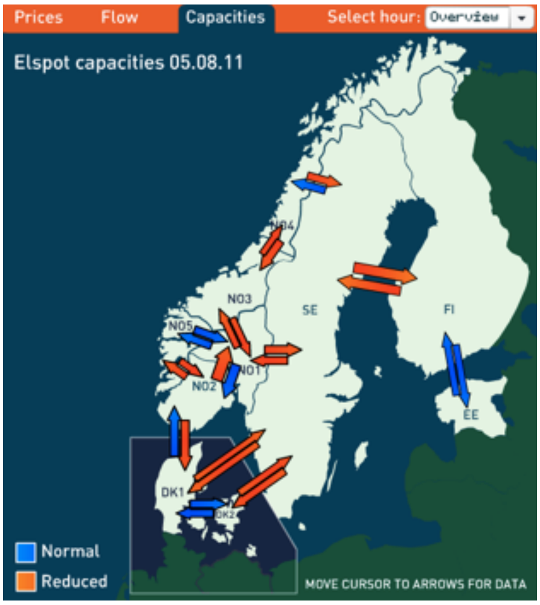


Figure 2-1 'Nord Pool Spot Market showing transmission capabilities'

Source: (Nord Pool Spot, 2011)

Interconnection with other countries allows Denmark to sell its excess wind electricity on the spot market such that, in theory, on windy days Sweden and Norway can conserve their hydropower resources and buy Danish wind power, and when the wind abates, release some of their hydropower to sell to Denmark (Togeby et al., 2009).

However, the future capacity of Sweden and Norway to provide this balancing service with their hydropower may be reduced for four reasons:

2.1.2: Wind may increasingly exceed export transmission capabilities
2.1.3: As Sweden and Norway increase wind generation themselves they may have less balancing capacity for other members
2.1.4: Hydropower in Norway and Sweden is also variable, dependent on annual precipitation
2.1.5: Expanding transmission capacity to areas with high demand may be more difficult than expected

2.1.2 At high rates of wind transmission capabilities may be exceeded

The ability to export excess electricity is limited by the transmission capabilities to do so. Larke and Lund note that in in 2006 and 2007, when Danish wind production only accounted to approximately 15% of electricity generation, there were several occurrences when extremely heavy winds generated electricity volumes that exceeded not only domestic demand but the capacity of transmission lines to export it. A critical over-supply situation was avoided only by shutting down CHP production and 200MWs of turbines (Larke & Lund, 2008). As Denmark is now at 25% wind generation, and will likely be nearing 40% by 2020, there is potential for this situation to become more common.

2.1.3 Norway and Sweden may increasingly use hydropower for themselves:

Sweden and Norway both have a high percentage of hydropower in their electricity grid. Having hydropower has, until recently, reduced the perceived pressure for Sweden and Norway to invest in wind technology. However, both Sweden and Norway are now rapidly expanding domestic wind capacity, which may affect how much hydropower each country makes available for balancing. In 2009 the Norwegian Government unveiled plans to leverage its offshore oil and gas experience into offshore wind power, where it hopes to become a leader in large-scale turbines (Enslow, 2010). Sweden, as is discussed in Chapter 4, also had a slow start to wind power. Recently, however, Sweden has had one of the highest rates of wind turbine installation in the world. According to the European Wind Energy Association, Sweden is on track to reach as much as 18% wind generated electricity by 2020 (2011). As both Sweden and Norway acquire significant wind power, they may wish to use their hydropower resources to balance their domestic electricity grid first, leaving less hydropower to resources available for other Nord Pool members (CESPOS, 2009).

In addition, in a market system no longer controlled by a central government, hydropower operators have an incentive to sell electricity, not hold it. It cannot be assumed that in the future they will be content to, "wait for the wind to die down" (A.Nylander, Personal Communication, 4 July, 2011).

2.1.4 Hydropower in Norway and Sweden is variable

Hydropower capacity varies with annual precipitation levels. In 'wet' years, such as 2005, 2007 and 2008, the melting heavy snowpack fills lakes and reservoirs. In 'dry' years, such as 2003 and 2006, however, low levels of precipitation failed to refill hydropower reservoirs. With too much precipitation, dams must release water regardless of wind, too little precipitation and they have less water for balancing (CESPOS, 2009); (The Economist, 2011). Climate change is expected to increase variations in precipitation levels, thus unpredictability in Nordic hydro supply levels will likely make long term planning for RES balancing in Denmark more challenging (Lafferty & Ruud, 2008).

2.1.5 Increased transmission capabilities to larger markets likely more difficult than expected

Germany has a population over three times that of the entire Nordic region and is heavily industrialized with a high demand for electricity, particularly in the south (Fröhlingsdorf, 2011). In theory, greater interconnection with larger markets such as Germany could absorb any excess Nordic RES electricity supply. This assumption may prove untenable for three reasons. First, Germany is already facing a situation where transmitting their own domestic wind generated electricity from the northern part of the country (near Denmark) to the south is reaching capacity of their high-tension transmission lines and thus may have little transmission capacity to spare for imported Danish (or Swedish) electricity (Munster & Lund, 2003). Second, utilities are encountering strong public resistance to building new transmission lines in Germany. For technical reasons, high voltage power lines are typically overhead (Wassenber, 2009). Installing these lines face a strong "Not In My Backyard" response from citizens concerned about the visual impact and from environmental groups opposed to transmission lines crossing protected nature areas. (Fröhlingsdorf, 2011). German law requires that public concerns be addressed before large infrastructure projects can proceed, causing long delays. Finally, building transmission lines to Germany or any other neighbour country is expensive. In 2003, Munster & Lund studied the costs for future ways of avoiding excess supply of wind electricity for Denmark and found increasing transmission lines to be by far the most expensive option (2003).

2.2 Consequence: Electricity prices on the spot market will become increasingly volatile

The Nord Pool network has worked well for balancing as different generation methods were able to complement each other. However, as each partner country pursues a renewable energy strategy, electricity supply in each country becomes more similar and prices are increasingly linked to weather conditions (Pöyry, 2011). Geographical proximity also means when it is windy or sunny in Denmark it is often the same in Sweden and northern Germany, and RES generation increases at the same time. Thus across the Nord Pool countries sun and wind can cause the market price for electricity to drop, and when the wind stops or sky clouds over, prices then spike. This volatility will likely increase as more intermittent RES is added (Pöyry, 2011); (Larke & Lund, 2008).

Already, significant intermittent wind electricity from Denmark causes large price fluctuations on the Nord Pool Spot price for electricity at todays level of RES. Figure 2-2 demonstrates the inverse correlation between wind generation in Denmark and electricity prices on Nord Pool for one week in 2007. Figure 2-3 shows the levels of intermittent RES today what is expected by 2030:

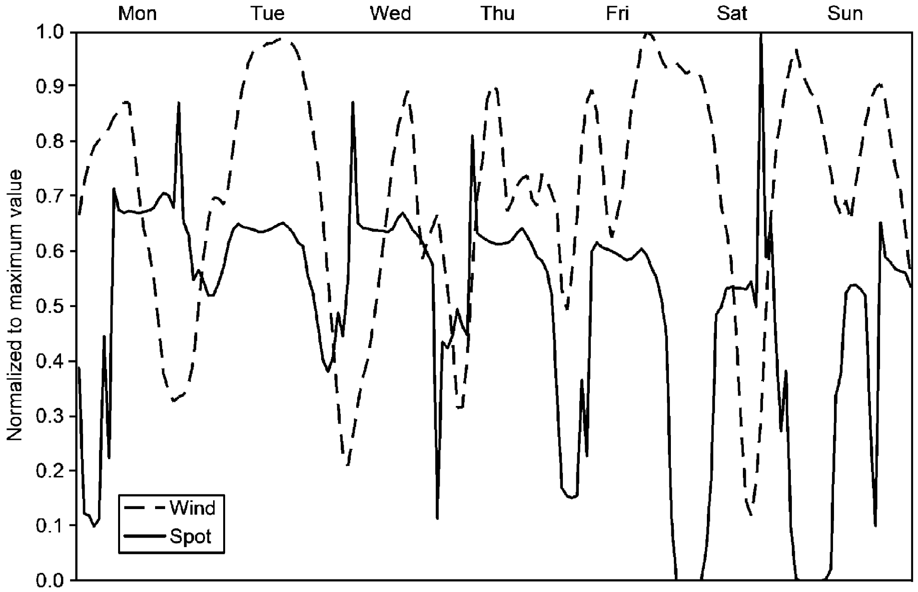
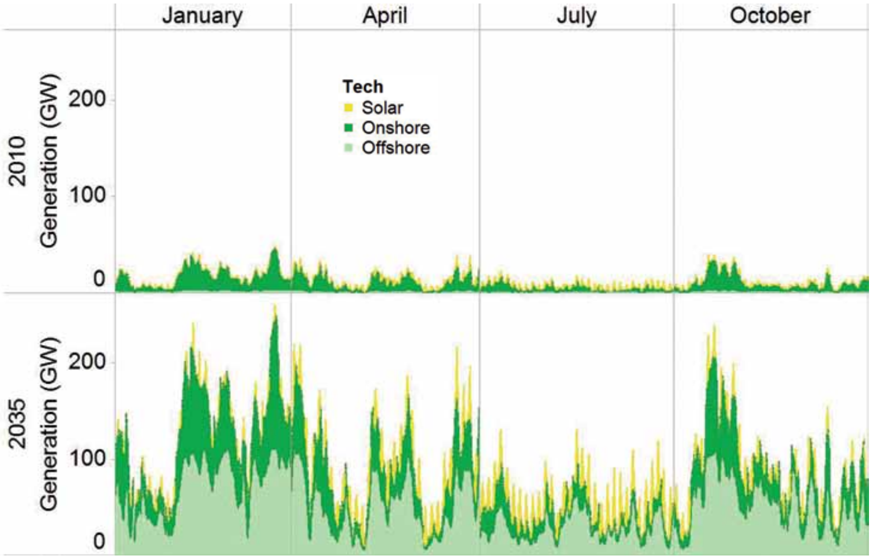


Figure 2-2 'Wind generation Denmark and Nord Pool electricity price'

Source: (Larke & Lund, 2008)



Aggregate hourly output across North Europe for four months (GWh)

Figure 2-3 'Current and expected RES generation for Northern Europe'

Source: (Pöyry, 2011)

2.3 Effects of increased volatility:

2.3.1 Long term forecasting difficult

Increased volatility and extended periods of low or even negative electricity spot prices due to high amounts of intermittent RES are situations that do not favour CHP or wind turbine operators. Increased volatility makes it increasingly difficult to make financial forecasts or calculate pay back periods for investors or utilities looking to expand or upgrade facilities – CHP or wind. In many cases this can drastically reduce profitability (Eurolectric, 2011).

2.3.2 Heat-bound electricity production lowers CHP profit

In Denmark, virtually all thermal electricity production is CHP. Many small CHP plants located in Denmark operate with a prime function to supply district heating – not electricity. These small distributed plants regulate production according to heat demand not electricity demand (Munster & Lund, 2003). Yet, they are still required to sell the electricity they produce on the spot market. Consequently, in the wintertime, a period of usual high wind electricity generation, is also a time when heat demand is high. Thus CHP plants are run to produce heat – and in many instances the electricity can be considered a "by-product" which is exported. This heat-bound electricity production is unavoidable and thus contributes to driving already low electricity prices further downwards (CESPOS, 2009).

Danish regulations allow CHP operators to make a profit from electricity generation but not from the heat generation component, which must remain non-profit. Consequently CHP operators prefer to operate in times of high electricity prices when they can make the highest economic yields from the fuels they are burning (Marcus-Møller, 2007).

2.3.3 CHP producers not paid for standby

In Denmark one of the government incentives to promote wind power expansion has been a convention that has ensured that wind power takes priority over CHP electricity production (given that heat demands are met). This means that in Denmark, CHP is typically required to "stand-by" or shut down first, before wind turbines. Due to feed-in tariffs in Denmark, which guarantee a premium on wind power electricity, wind power can still potentially generate revenue even at a zero market price for electricity. This advantage is not afforded to CHP producers who must reduce production or shut down when the wind blows, and re-start when wind dies down (Lafferty & Ruud, 2008). Such a system requires back-up capacity to be maintained, and CHP plants are thus required to be in constant "stand-by" mode prepared to ramp up or down very rapidly, although they receive no compensation to maintain this state of readiness. The deteriorating business case for CHP operators as prioritized RES increases is compounded by the fact that many large CHP operators sign long term contracts for both fuel and heat and electricity output, in addition to having major capital investments for infrastructure that are lying dormant (Eurolectric, 2011).

2.3.4 Summary part 1:

- Denmark's electricity production currently has a high percentage of intermittent renewables (25%) and this is set to grow to as much as 40% by 2020
- Current sources of balancing supply – Swedish and Norwegian hydropower – may not continue as those countries develop their own wind resources, and as climate change affects the predictability of wet and dry years
- Building more transmission capability to other, larger markets can reduce periods when excess supply can not be exported, but construction of High Power transmission lines is expensive and slow due to resistance from public and environmental concerns
- Intermittent wind energy from Denmark already causes Nord Pool electricity market prices to fluctuate with weather conditions, and this appears likely to increase as all Nord Pool members increase wind other intermittent RES
- A likely outcome is increased fluctuations in electricity price, and periods of low prices when wind is blowing
- Unpredictable prices affects the investment climate for new infrastructure
- With the priority for wind generated electricity, CHP are forced to ramp up or down, but not compensated for this "back up" security

2.4 Part 2: Solution - Better use of Electricity for a Domestic Purpose

2.4.1 Options for domestic use:

The issues described above may be partially addressed by the greater use of wind-generated electricity for a domestic rather than export market. This approach is beneficial from a future planning perspective, as a hedge against the inability to balance or increase transmission, and also from an economic perspective, that is, to avoid having to offload electricity cheaply on Nord Pool.

There are several options for making greater use of this electricity domestically such as: 1) smart grids 2) electric vehicles, 3) electricity storage.

1. Smart grids are a collection of technologies that intelligently use electricity, such as appliances that monitor electricity prices and turn themselves on or off accordingly. Such intelligent use of electricity could help limit challenges of excess supply (SmartGrids ETP, 2011).

2. Electric vehicles run on electricity, usually stored in batteries. Larges numbers of electric car batteries, plugged into a grid should theoretically be able to provide capacity for 'storing' an excess capacity (European Environment Agency, 2011). Unfortunately, like smart grids, electric vehicles are still years away from widespread use (Brown, Pyke, & Steenhof, 2010); (American Society of Mechanical Engineers, 2011); (Wilson, 2010).

3. Electricity storage refers to storing electricity in some medium until it is needed or is more economically favourable to sell it. There are many technologies available and in use around the world to achieve this. Some include pumped hydro, (which uses a small amount of electricity to pump water to the top of a hydropower reservoir), large batteries, compressed air storage, hydrogen fuel cells, and large flywheels. Electricity storage technologies vary greatly in their scale, cost, and discharge rate and market readiness. In the Nordic electricity network, pumped hydro is the only electricity storage used, and then only in very limited capacity (Vartiainen et al, 2011). A brief description of the main electricity storage technologies can be found in Appendix D.

A fourth option and the focus of this paper, is making heat with heat pumps (a market-ready solution using technologies that are widely available in Sweden and Denmark) and then storing that heat, using Thermal Energy Storage, TES.

2.4.2 Use electricity for domestic heat production

In cold climates with a demand for heat, one option is to use wind generated electricity to produce heat, either at the district heating level or individual house level rather than exporting it at low market prices. Producing heat from electricity is a well-known technology and electrically heated water can be fed directly into district heating networks (A. Brix-Thomson, Personal Communication, 10 May 2011).

Immersion boilers: One method is to use immersion boilers, which operate on the same principal as large kettle. This has been proposed in several academic and government circles in Denmark since the early 2000s (Munster & Lund, 2003); (Larke & Lund, 2008). A trial government program for using large electric immersion boilers at several CHP several district heating plants began in 2008, called the "Elpatronov" program (Diget, 2010). While immersion boilers systems are well understood and relatively simple to install, they are not an "exegetically favourable"[2] option for producing heat when compared to alternative method of heat production, in this case using heat pumps.

Heat Pumps: Heat pumps work by 'pumping' (or more accurately condensing dispersed heat) a low temperature source of heat to a higher temperature. This source of heat can be from ambient air, water, soil, or underground rock and earth. This is achieved via a refrigerant to another media (usually air or water). Electricity is used to power the condenser and heat exchanger. While there are many types of heat pumps, the basic concept is similar to a

---

[2] Exergy is a thermodynamics concept that defines the maximum potential of an energy input to create a useful work output. It is different than efficiency, which can be thought of as how well one thing can be turned into something else (Dincer & Rosen, 2011). To illustrate, immersion boilers are very "efficient" at turning electricity into heat. They operate on a one-to-one ratio, where one unit of electricity is converted into one unit of heat. Immersion boilers are not "exegetically efficient" in that the same unit of electricity, using a heat pump, could be converted to between 3 and 5 units of electricity (Vad Mathiesen & Lund, 2004).

refrigerator, run in reverse. Heat pumps can be scaled for individual home use or district heating. For a more detailed description of heat pumps, see Appendix D.

The value of a heat pump is that, depending on the system applied, it is possible to get between 150-500% as much heat out the same unit of electricity (DESIRE, 2007). From a renewable energy perspective, every unit of heat produced with renewable electricity, equals vastly more "renewable" heat if it is displacing heat otherwise coming from burning fossil fuels.

In studies at Aalborg University, which simulated different options for the use of wind generated electricity for heating, heat pump systems were the most favourable for: increasing the flexibility of the Danish energy system, reducing excess electricity production and conserving CHP fuel (Mathiesen & Lund, 2009); (Munster & Lund, 2003); (Vad Mathiesen & Lund, 2004).

2.4.3 Heat Pumps for energy system flexibility

Using heat pumps may provide the energy system with the flexibility to allow generators to decide to when to export electricity and when to use it domestically. It also allows system operators to chose the most economical times to use CHP plants to produce heat and when to use heat pumps, thus reducing heat-bound electricity and having to export excess electricity for low prices on Nord Pool. Using electricity for heat pumps for district heating generates many more times as much heat as with direct resistance boilers.

Unfortunately, for all "heat-from-electricity-technologies" heat is not required all year round. From April to September, especially in the Öresund region, the heat demand is quite low. In addition, in both Sweden and Denmark, heat demand in summer is often already met by waste incineration (J.Brandt-Sørenson, Personal Communication, 21 June 2011).

In this scenario, seasonal Thermal Energy Storage can offer a solution by storing heat generated by electric heat pumps from the time it is generated to the time it is required (Munster & Lund, 2003).

2.4.4 Thermal Energy Storage to store heat from RES electricity:

Seasonal Thermal Energy storage refers to the long term storage of energy to heat or to cool. In this paper, unless stated otherwise, TES refers to the storage of heat. There are a wide variety of technologies available for the seasonal storage of heat (or cool). These include storing underground, either in rock or aquifers, storing in large pits in the ground, in molten salts, among others. Like electricity storage technologies, TES vary greatly in availability size, capacity, cost, and market readiness. A description of the main TES technologies available can be found in Appendix D.

2.4.5 Summary Part 2:

- Greater use of electricity domestically can reduce the export of excess electricity at low prices and decrease market volatility
- Some options for better domestic electricity use include Smart Grids, Battery Electric Vehicles, and Electricity storage, but few are market ready
- Converting electricity to heat is a market ready option
- Heat pumps are an effective way to use electricity for heating and increase system flexibility
- Use TES to store heat during times of low heat demand

3 Comparing Energy Systems & Energy Storage in Sweden and Demark

This section gives an overview of the current technologies most commonly used in Sweden in Denmark to produce and store heat and electricity. This chapter is divided into two parts: first, understanding the energy system in each country, and second, determining the technologies for energy storage that are unique to one country or the other.

3.1 Energy System Sweden

3.1.1 Country Overview:

Electricity and heat are generated separately in Sweden, although this is changing as CHP is increasingly introduced. Electricity generation is dominated by hydropower and nuclear power. Although Sweden has some remaining electricity-only thermal power plants (powered by biofuels, natural gas and coal), these are increasingly being phased out in favour of CHP connected with district heating. Within CHP plants, biofuels and municipal waste are consumed, with some fossil fuels (gas and coal) used in reserve. Wind generated electricity makes up a small but increasing amount of total generation. Solar photovoltaic electricity is insignificant at this time. The only electricity storage technology used is Pumped Hydro Energy Storage, although this is limited.

Heat for district heating is primarily from heat-only boilers and large heat pumps. Boilers are primarily fuelled by biofuels although fossil fuels and waste heat from industry are used. Solar thermal district heating is very limited.

For individual homes and buildings that do not use district heat, primary sources of heat are heat pumps or direct electrical heating. Heat pumps include air-to-water and ground source heating. Bio-fuelled heating occurs and is often in the form of wood pellets. Some buildings use natural gas or heating oil but are not common.

3.1.2 Pure Electricity production Sweden:

Nuclear: Nuclear power accounts for approximately 45% of electricity production in Sweden. Sweden currently has 10 reactors in operation located throughout the southern half of the country (International Atomic Energy Agency, 2009).

Hydropower: Hydropower typically also accounts for approximately 45% of electricity supply, although this can vary greatly depending on precipitation levels (Swedish Energy Agency, 2010). Sweden has over 2,000 hydropower plants currently in operation, primarily in the northern, mountainous part of the country (Svenskvattenkraft, 2011).

Wind: Wind accounts for approximately 2% of the electricity produced in Sweden (European Wind Energy Association, 2011). Sweden has a total installed capacity of 2,052 MW, which ranks it 14th in the world. In the past decade Sweden has significantly increased wind power particularly offshore wind, where it has some of the most installed capacity in Europe (World Wind Energy Association, 2011).

Solar Photovoltaic (PV): Solar PV provides a negligible (less than 0.1%) of the electricity supply in Sweden (Swedish Energy Agency, 2010).

3.1.3 Pure Heat production (District heating):

District heating supplies approximately 50% of the heating demand in Sweden (Ericsson, 2009).

Boilers: Most modern Swedish district heating boilers are capable of combusting a variety of fuels. Biofuels are the most common fuel source, which can include waste wood chips, pellets, pulverized sawdust, or biogas. Fossil fuels such natural gas and heating oil continue to provide some input for district heating boilers though these are often used only at peak demand times (Swedish Bioenergy Association, 2011).

Large Heat Pumps: Large heat pumps account for approximately 5% of Sweden's district heating supply (Swedish Energy Agency, 2010). These are mainly around Stockholm where the heat input is usually seawater (T. Wall, Personal Communication, 28 June 2011). An exception is Lunds Energi, a district heating company in Lund, which uses shallow geothermal heat from a underground aquifer coupled with a large heat pumps to provide base-load district heating (M.Gierow, Personal Communication, 18 May 2011).

Waste Heat: Waste heat from collected from industry and fed into the heating network accounts for an additional 5% of district heating supply (Swedish Energy Agency, 2010). An example of an industrial source of heat is the Nordic Sugar factory in Lund, which supplies the district heating company with waste heat during the sugar beet season (Lunds Energi, 2010).

Solar Thermal: In the 2010 energy report the Swedish Energy Agency does not list solar thermal as a significant district heating input. However the technology does exist - two examples are the 10,000m2 solar facility in Kungalv and the 5,000m2 facility in Falkenberg, which generate hot water for their local district heating companies (Swedish Energy Agency, 2010).

3.1.4 Pure Heat Production (Individual House/ Building):

Furnace / Stoves: Buildings or detached houses primarily in rural areas may generate heat by burning either fossil or biofuels. The main fossil fuels are heating oil and a small percentage of natural gas. Biofuels used for individual heating is mainly firewood or wood pellets (Swedish Bioenergy Association, 2011).

Electric heating: Sweden uses electricity for domestic heating more than any country in Europe. Electricity use can be divided into direct resistance heating and heat pumps.

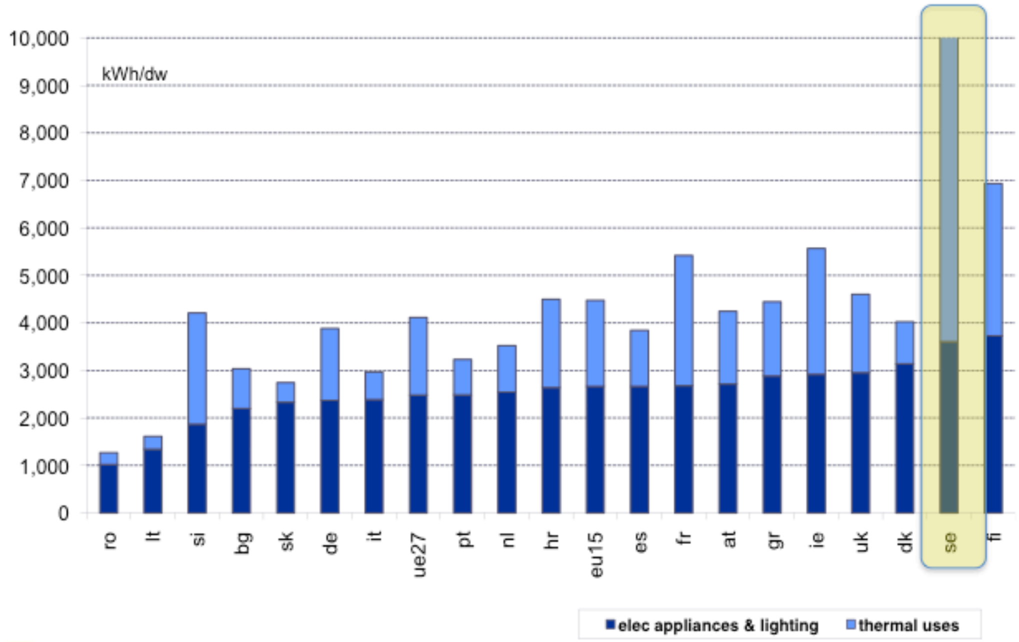


Figure 3-1 'Domestic Electricity use in Selected European Countries Caption'

Source: (Enerdata, 2008)

Resistance Heating: Resistance heating uses electricity to directly produce heat in the same principal as an electric burner on a stove. Resistance radiators have a Coefficient of Performance of 1, meaning that they produce one unit of heat from one unit of electricity (NRCAN, 2004).

Small Heat Pumps: Sweden is one of the world's leading countries in heat pump installation, with about 230,000 installed and increasing by 25,000 annually. Approximately 40% of detached houses use heat pump systems (Lund, Freeston, & et al., 2010). The most common heat pump systems in Sweden are ground-source systems, which extract heat from the earth, and exhaust-to-air systems. Ground source heat pump systems typically have a coefficient of performance between 3 and 5, meaning one unit of electricity produces 3 to 5 units of heat. While efficient, heat pumps often only supply 75-90% of heating needs, and are thus often installed with another form of heat supply for use during the coldest parts of the year (Karlsson et al., 2003). A more detailed description of heat pumps and ground-source heating systems can be found in Appendix D.

3.1.5 Combined Heat and Power production

CHP production in Sweden commonly uses biofuels such as wood waste, peat black liquor and biogas and occasionally fossil fuels (oil, coal, or natural gas). In total, there are 160 CHP plants operating in Sweden (Swedish Bioenergy Association, 2011). CHP from waste incineration is another important source for CHP generation in Sweden. Currently about, 30 waste incineration plants are in operation in the country, including some of the worlds largest and most efficient (Avfall Sverig, 2011).

3.2 Energy System Denmark

3.2.1 Country Overview:

Unlike Sweden, electricity and heat generation in Denmark is overwhelmingly combined as CHP. Today, only wind turbines produce a significant amount of pure electricity. However, many CHP plants can switch between producing both heat and electricity or strictly electricity depending on market prices. No electricity storage technologies are currently used.

Heat generation from CHP plants use a variety of fuels – primarily coal or natural gas, but increasingly biofuels such as straw and pellets are burned. Waste incineration also plays a substantial role in Danish CHP. CHP plants were initially large centralized units, but increasingly smaller and de-centralized plants are preferred, although several large CHP plants remain in urban areas. The heat from CHP plants is used in district heating, the most common source of heating. Solar thermal district-heating plants exist and are usually built in conjunction with CHP. Two geothermal heat plants provide heat, in conjunction with heat pumps, to district heating networks.

Individual house heating occurs only in designated areas where natural gas is the main fuel choice, with some remaining heating oil systems. Two significant characteristics about the Danish system are the small share of heat produced from electricity and the almost non-existence of heat pumps.

Large TES systems are found at the district heating level as large accumulator tanks in conjunction with CHP and large heat pits in conjunction with solar thermal district heating. Borehole or aquifer TES systems are essentially non-existent.

3.2.2 Pure Electricity Production Denmark:

Wind: Wind makes up approximately 21% of Danish electricity generation. It has the 6th largest installed capacity in Europe at 3,734 MW, but the highest per person (World Wind Energy Association, 2011). The Danish government plans to increase the percentage of wind energy, especially offshore, as part of the 30% renewable energy goal by 2020 and the "fossil fuel free" goal of 2050 (Government of Denmark, 2011).

3.2.3 Pure Heat production (District Heating):

Geothermal: Geothermal heat production uses hot water that exists in aquifers in porous rock deep (>300m) underground. Aquifers at this depth are heated from the earth core. Water from these aquifers can be pumped to the surface and used in district heating, if hot enough, or upgraded with heat pumps. In Denmark, established aquifers suitable for deep geothermal heat production occur between 800m and 3,000m (Danish Energy Agency (2), 2009). Denmark has two geothermal heating plants, the first was built in 1984 in Thistad and the second in Copenhagen in 2005. Both use large heat pumps to upgrade hot water to district heating temperature.

Solar thermal: Solar Thermal district heating is an established technology in Denmark. Solar arrays produce hot water rather than electricity, which is used in district heating networks. Solar thermal is most often used in conjunction with another heat source – such as waste heat from industry or a small CHP boiler to ensure supply (Arcon Solar, 2011).

Non-CHP Boilers: A small percentage of district heating is provided by heat-only boilers. These primarily burning fossil fuels and are generally only used rarely during peak demand.

Denmark is working to convert remaining heat-only boilers to CHP (Danish Energy Agency, 2011). In addition, many CHP plants (operating on a variety of fuels) can operate in condensation mode, which means they can produce only heat (and not electricity), effectively acting as a heat-only boiler.

3.2.4 Individual Heating:

Furnace / Stoves: Individual heating fuel supply is provided mainly by fossil fuels such as heating oil and natural gas. A small number of consumers have furnaces burning wood. (Danish Energy Agency, 2011).

Electric heating: Electricity provides a very small amount of heat production at the individual level. Where it exists, it is mainly provided by direct electric radiators. Heat pumps are not common in Denmark, where only 0.4% of heating in the country is provided by heat pumps (Danish Energy Agency, 2011). Of these, most are recently installed and use horizontal ground source heat pumps. Vertical borehole systems or aquifer systems coupled with heat pump are virtually non-existent in the country (Varmpumpordningen, 2011).

3.2.5 Combined Heat and Power production Denmark:

CHP is highly developed in Denmark. There are over 430 CHP plants – several large centralized plants in urban areas and many small distributed plants serving rural areas (Danish Energy Agency, 2010). District heating primarily fired by CHP supplies over 60% of the population with heat and electricity (EnergyMap Denmark, 2011). Danish CHP plants use a variety of fuels, though natural gas and coal are the main sources. Denmark has recently pioneered the use of agricultural waste as a biofuel and this along with wood chips and biogas have now become a fuel choice at the larger, centralized CHP plants (Voytenko & Peck, 2011). In order to eliminate fossil fuels (coal and natural gas) completely from the energy system, the government expects biofuels to become the primary CHP fuel source (Government of Denmark, 2011).

Waste incineration is another major source of fuel for CHP. There are 18 waste incineration CHP plants operating in Denmark. By law, certain types of waste must be incinerated, consequently these plants take priority in the summer when heat demand is low and other CHP plants are forced to shut down (Marcus-Møller, 2007).

Table 3-1 'Summary Comparison Sweden and Denmark Current Domestic Energy Systems'

Sweden	Denmark
Technologies for producing purely electricity: • Nuclear • Hydropower • Wind • Non-CHP Thermal power (Biofuel + Fossil fuels - primarily reserve	**Technologies for producing purely electricity:** • Wind
Technologies for producing purely heat: District Heat: • Boilers (Biofuel, fossil fuel, electric) • Large Heat pumps	**Technologies for producing purely heat:** District Heating: • Geothermal • Solar thermal • Some remaining heat-only boilers

Individual heating: (home/building) • Heat pumps (various) • Resistance electric heaters • Fossil fuel burners (Natural gas, small amount oil) • Wood	**Individual heating: (home/building)** • Fossil fuel burners (Natural gas, oil,) • Solar thermal
Technologies for Combined Heat and Electricity: • Combined heat and power providing district heating (Primarily biofuels, natural gas oil, coal, oil + waste incineration	**Technologies for Combined Heat and Electricity** • Combined heat and power providing district heating (Coal, oil, natural gas, biofuels + waste incineration

Source: 'Author'

3.3 Energy Storage Technologies Sweden:

3.3.1 Electricity Storage:

Pumped Hydro: Sweden has a small number of pumped hydro storage facilities in conjunction with hydroelectric dams (E.Vartiainen, 28 June 11, 2011). A description of pumped hydro storage is found in Appendix D.

3.3.2 Thermal Energy Storage:

In Sweden, Thermal Energy Storage consists primarily of Tank TES for short term storage, and Aquifer and Borehole TES for long term storage.

3.3.3 Tank Thermal Energy Storage (TTES):

In Sweden, TTES consist of large hot water accumulator tanks used to provide short term storage of hot water for district heating. Short term is usually regarded as 6-10 hours of total demand. In Sweden, district heating companies use TTES to cover short-term peak demand. This allows more for efficient sizing of district heating plants, as smaller plants are able to run at full capacity, rather than oversizing just to cover a short period (P.Öhrström, Personal Communication, 18 May 2011). TTES are included in most district heating plants in Sweden. Tanks are usually made of stainless steel and act on the same principal as a large vacuum bottle. TTES is an inexpensive, well-understood technology that can maintain high temperatures and does not require re-heating before it can be used in district heating. The disadvantage is limited capacity and limitation to short term storage.

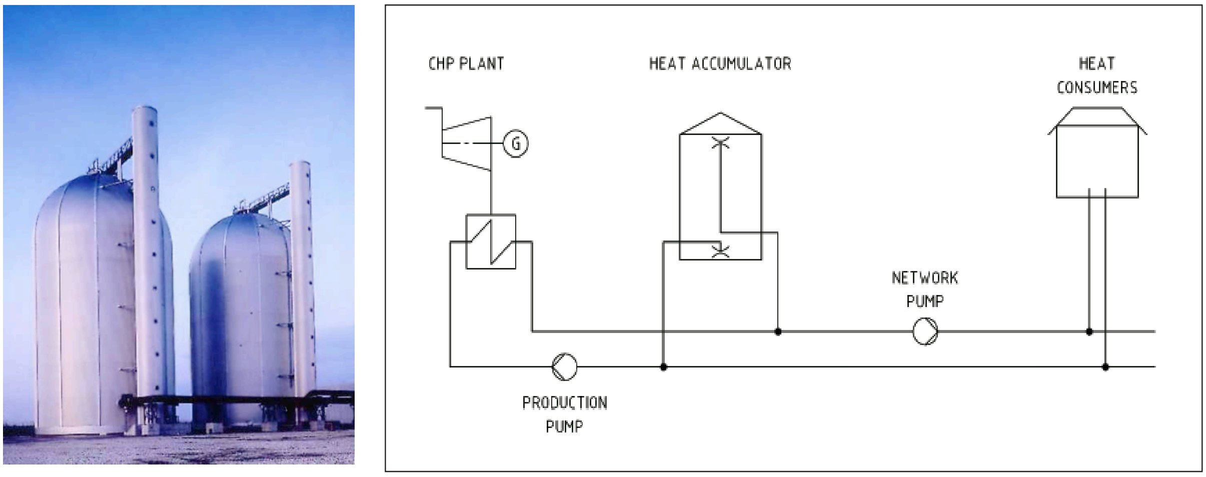
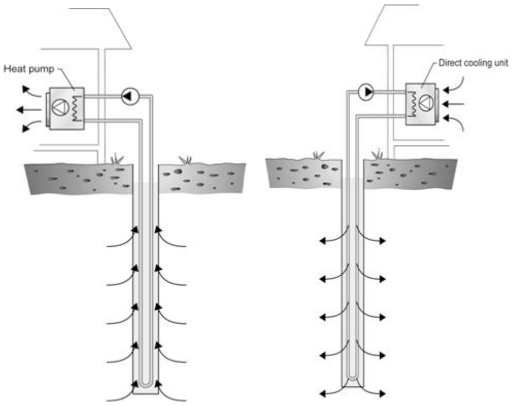


Figure 3-2 'Tank Thermal Energy Storage & Common system design TTES'

Source 3-2: (Danish Energy Agency (2), 2010); (Petersen & Aagaard, 2004)

3.3.4 Borehole Thermal Energy Storage (BTES)

BTES is a technology for storing thermal energy in underground geological formations. Hot or cold water is circulated in pipes set into boreholes between 50m and 200m deep. According to thermodynamic principals, heat follows a temperature gradient, flowing from high to low temperature. Below a depth of about 15m, the temperature at a given depth is not affected by climactic temperatures and stays relatively constant year round; (J.Barth, Personal Communication, 19 August 2011). Consequently if hot water is circulated through the borehole pipes, heat transfers from the water and to the surrounding earth and rock through direct heat transfer. The same principal applies to extracting heat, that is, circulating cool water through the borehole pipes, allows heat to be transferred back to the water, which is brought to the surface and usually upgraded with a heat pump. The warmed or cooled earth and rock surrounding the borehole can maintain the modified temperature for months at time, allowing the earth itself to be used for 'seasonal' thermal energy storage.



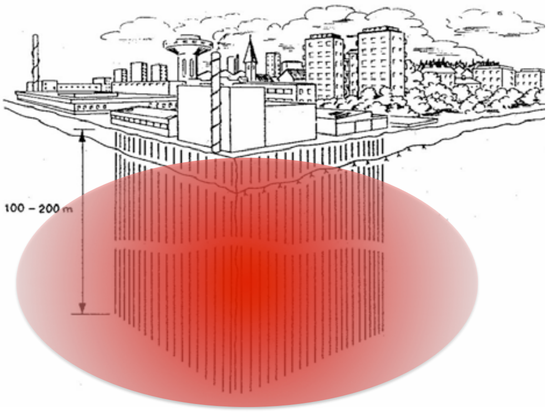


Figure 3-3 'Single family BTES & 'Large Scale use of BTES system'

Source: (Nordell, Grein, & Kharseh, 2007) ; (GEOTRAINET, 2011)

BTES has been primarily used for demand-side management– that is, managing heating and cooling 'demand' at the home or building level to rather than at district heating 'supply' level. Akademiska Hus, a property management company based in Lund, Sweden, installed one of the country's largest BTES systems supplying heating and cooling to several its buildings at Lund University (H. Petersson, Personal Communication, 1 July 2011).

BTES can also act as a supply-side management option at the district heating level. The city of Boxholm, Sweden is in the process of developing such a system. The district heating company receives a large amount of waste industrial heat throughout the year. During the summer when heat demand is low it plans to store the heat in a large BTES system. In the winter, when heat demand is high, it will extract the heat, upgrades it to district heating temperature with a heat pump and use it for district heating (J.Barth, Personal Communicatn, 19 August 2011).

Costs to install BTES systems vary depending on the size and geological conditions. The largest investment is in drilling the boreholes (Hellström, 2008). Cost for drilling increase with depth and number of holes, and the availability of drilling companies. In Sweden there are many companies that offer installation and compete on price. Depending on the temperatures required, BTES almost always requires investing in a heat pump. Operating costs depend primarily on the price of electricity to run the system (Fröhlingsdorf, 2011). Despite high upfront costs, a relatively fast payback time and long lifespan (20+ years) and low maintenance costs can make the system economical. Averaged costs in general are competitive or better than district heating (Stignor, Lindahl, Alsbjer, Nordman, Rolfsman, & Axell, 2009).

Efficiency of a BTES system depends on the size. Thermal losses, which can be as high as 40% for small systems, decrease with the number of boreholes. For systems of over 100,000m3 of heated underground earth, annual losses can be as low as 10-15% (Nordell, Grein, & Kharseh, 2007). They can have a coefficient of performance between 4-7 (Dincer & Rosen, 2011).

BTES can be used in virtually all geological conditions (GEOTRAINET, 2011); (P. Tenberg, Personal Communication, 4 July 2011). Each year in Sweden, BTES systems supply 20% of heat demand, the most wide-spread use of BTES systems in Europe (Nordell, Grein, & Kharseh, 2007). The main disadvantage is the high upfront costs of installation.

3.3.5 Aquifer Thermal Energy Storage (ATES)

Like BTES, ATES is a method for storing thermal energy underground. Unlike BTES, ATES makes direct use of groundwater contained in porous rock formations rather than transferring heat indirectly via boreholes.

Groundwater naturally flows through porous geological matrices of rock and earth. Like the surrounding rock formations, at depths lower than approximately 15m, groundwater remains at a constant temperature year round, unaffected by surface temperatures (J.Barth, Personal Communication, 19 August 2011). This property can be exploited as a seasonal store for heat. To charge the aquifer with heat, an extraction well called a 'cold' well is drilled to the water layer and the groundwater pumped to the surface. There, a heat exchanger transfers heat (either from the building during the summer or some other source) to the groundwater, which is then re-injected into a 'warm' well some distance away. The warmed groundwater flows though the geological matrix, warming the rock and earth it as it moves. The modified temperature remains relatively constant until the heat is required. To extract the heat the process is reversed. Warm water is pumped up from the warm well, the heat is extracted, and the cooled water re-injected down the cool well (ECES, 2007); (Nordell, Grein, & Kharseh, 2007).

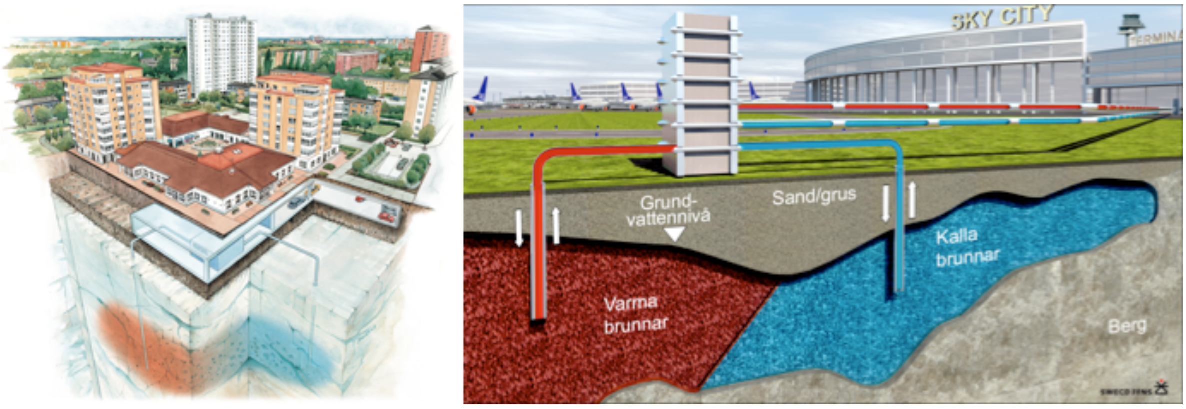


Figure 3-4 'ATES system for building complex & ATES at Arlanda airport'

Source: (Sweco, 2008)

Like BTES systems, in Sweden ATES systems are generally used at the building level as a demand-side management option. They are more common in large buildings than detached houses. ATES is well suited to manage building cooling as well as heating. For heating, whether the system needs to be used in conjunction with a heat pump depends on the temperature demanded. In many cases, a heat pump is used (Sweco, 2008).

The technology can also be used at the district heating level. Lunds Energi, the district heating company in Lund, has used an aquifer system to provide base-load heat for the district heating system sine 1984. While not currently used for seasonal storage, it is planned for the near future. (M.Gierow, Personal Communication, 18 May 2011). The storage capacity of the aquifer will allow Lunds Energi to accept and store excess waste industrial heat from European Spallation Source, a high-energy physics research facility to be built in Lund by 2018 (T.Parker, Personal Communication, 23 May 2011).

Aquifer systems are more complicated to build than borehole systems because a detailed understanding of the aquifer – its size, depth, flow rates and other criteria must be tested and designed for. In addition, ATES is an open system that interacts directly with ground water, and regulations are typically much more stringent than for boreholes. This is especially the case where the aquifer may interact with public drinking water. In Sweden, acquiring the proper government permits to install an ATES system can take between 4 months to a year and the system reequires constant monitoring (J.Barth, Personal Communication, 19 August 2011).

However, once in place, ATES systems can be more cost effective than BTES systems. Aquifer systems are more efficient than boreholes systems in four ways:

1. Due to the increased surface area, groundwater is much better at transferring heat to surrounding rock formations than a borehole.
2. Fewer holes need to be drilled, greatly reducing installation costs.
3. Aquifer TES systems generally allow higher temperatures and a lower thermal losses over time (P.Tenberg, Personal Communication, 4 July 2011.
4. Aquifer TES systems can achieve a Coefficient of Performance much higher than BTES systems, ranging between 8-20 (J.Barth, Personal Comunication, 19 August 2011)

The disadvantages are that the system:

- Cannot be used where an aquifer does not exist
- Is governed by a more complicated permitting system to use groundwater
- Often requires more maintenance

3.4 Energy Storage Technologies Denmark:

3.4.1 Electricity Storage:

Denmark has no commercial electricity storage systems in place. Instead, it uses the electricity grid interconnection to sell its excess wind electricity on the Nord Pool market to Sweden and Norway, which can hold back their hydropower. Thus Denmark 'stores' electricity as un-released hydropower (CESPOS, 2009).

3.4.2 Thermal Energy Storage:

In Denmark Thermal Energy technologies include Tank TES for Short term storage and Pit TES for long term storage.

3.4.3 Tank Thermal Energy Storage (TTES):

TTES is used extensively in Denmark. According to the Danish Board of District Heating, virtually all smaller-distributed CHP district heating plants and most of the larger, centralized CHP plants have TTES systems installed. Like Sweden, the tanks are designed to provide short-term storage for several hours worth of heat demand. Unlike Sweden, the tanks were initially designed to provide CHP operators the flexibility to maximize economic gains from government-determined heat prices (since removed) throughout the day, rather than to provide for peak demand load (Petersen & Aagaard, 2004). The main advantages of TTES is they are a well-understood technology and relatively inexpensive to construct. The disadvantage of TTES is that it is insufficient in size to be used for a seasonal store.

3.4.4 Pit Thermal Energy Storage (PTES)

PTES is a method of storing thermal energy seasonally in a large water-filled pit. The pits are usually dug into the ground, lined with an impermeable plastic barrier, filled it with water covered by an insulating roof. PTES resembles a large covered swimming pool.

PTES acts like an extra large accumulator tank. The water is charged with a heat exchanger from a heat source that warms the water. Properly insulated, the elevated temperature is capable of being maintained from season to season. This works on the principal that increasing the volume proportionally deceases the surface area and thus reduces heat losses (Sillman, Baylin, & Sanford, 1980). To extract the heat, the water from the pit is run through a heat exchanger. If higher temperatures are required, the heat can then be upgraded with a heat pump (Sørensen, Holm, & Jensen, 2008).

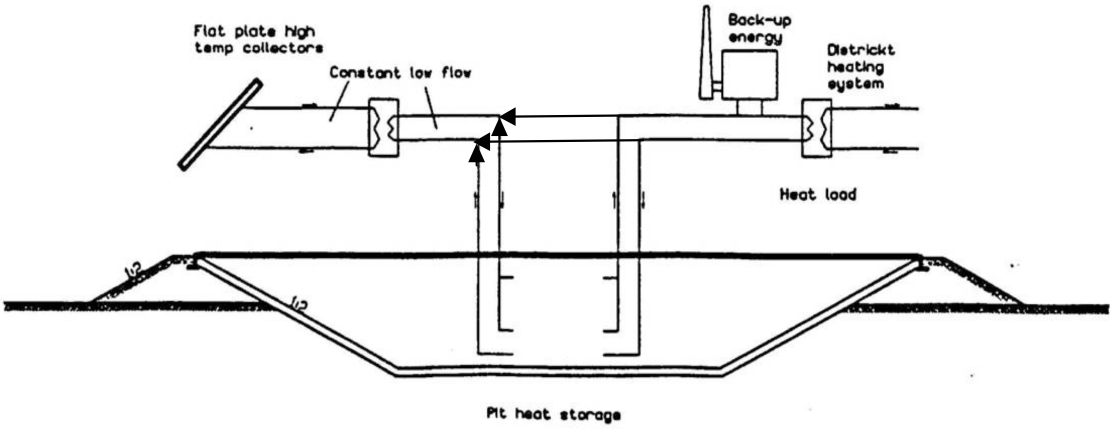


Figure 3-5 'Schematic of PTES system'

Source: (Ellehauge & Pedersen, 2007)

PTES is used as a long-term, seasonal storage technology. In Denmark, PTES is most commonly used in conjunction with solar thermal heating as a method of addressing the seasonal mismatch between maximal solar thermal production (summer) and heat demand (winter). Solar thermal plants use the PTES to store heat in the summer, and the thermal energy is extracted by the heat pump and used in the district-heating network in the winter. One of the largest examples of this is the Marstal Fjernvarme (Marstal District heating company) on the island of Ærø, which has a 10,000m3 PTES store. See figure 3-9 (Beuse, 2010).

Figure 3-6 'Marstal PTES construction & Proposed North Harbour dry-dock PTES site'

Source: (Ellehauge & Pedersen, 2007); (Københavns Energi, 2011)

However, PTES does not need to be a seasonal storage technology nor does it need to be used with solar thermal. Kobenhavens Energi, a district heating company in Copenhagen recently completed a feasibility study for converting an un-used dry dock to 300,000m3 PTES storage in the proposed North Harbour redevelopment (see figure 3-9). This would act as a large accumulator for the large centralized CHP plants in the area (Marcus-Møller, Personal Communication, 17 June 2011).

PTES systems can be very cost effective and simple to build. The one exception is the construction of the insulating lid, which can be substantial depending on the size of the pit

(Ellehauge & Pedersen, 2007). There is no special legislation or permit required to build a PTES system, further reducing costs.

PTES systems are located throughout Denmark in conjunction with solar district heating systems. They are not geographically bound and can be deployed in any area with enough room. Other advantages of PTES are the simple, well-understood technology and the ease of construction with readily available materials. The main disadvantage is the space requirement, making PTES unsuitable for most urban settings.

Table 3-2 'Summery of Energy Storage Technologies Sweden and Denmark'

Technologies for Storage: Sweden	Technologies for Storage: Denmark
Electricity: • Limited pumped hydro	**Electricity**: • No domestic electricity storage – interconnected electricity grid allows Sweden and Norway to 'store' un-released hydropower
Thermal: • Tanks (TTES) • Borehole (BTES) • Aquifer (ATES)	**Thermal**: • Tanks (TTES) • Pits (PTES)

Source: 'Author'

3.5 Summary Comparison of TES technologies used in Sweden and Denmark:

Table 3-3 Style 'Summary Table of TES Technologies Used in Sweden and Denmark'

Aquifer TES	Borehole TES	Tank TES	Pit TES
Description: • Usually at least two wells (minimum) reaching underground aquifer • Direct heat transfer to groundwater • Mostly used for seasonal storage • Large scale – can be used at building complex or district heating level	**Description**: • Heat transferred to or from fluid in borehole tube to ground via temperature difference • Usually multiple boreholes • Closed loop, no direct interaction with ground water • Can be small or large scale • Usually used at building level	**Description**: • Heat transferred directly to and from large stainless steel tanks • Not used as seasonal storage • Used to balance short term demand fluctuations (Swe) • Used to provide flexibility to CHP district heat producers (DK)	**Description**: • Heat transferred to and from plastic lined dug-out pit • Often used in conjunction with solar thermal

Used in: Sweden	**Used in**: Sweden	**Used in**: Sweden and Denmark	**Used in**: Denmark
Used for: Seasonal Storage mainly at building level, potential for DH	**Used for:** Seasonal Storage mainly at building level, potential for DH	**Used for**: Short-term Storage at DH level	**Used for**: Seasonal Storage at DH level
Advantages: • High heat capacity • Economical • Often higher heat temperatures	**Advantages**: • Can be used in almost all locations • Less regulatory requirements than ATES	**Advantages**: • Can be used quickly • Simple construction • Unsophisticated technology • Inexpensive	**Advantages**: • No regulatory requirements • Cost efficiencies with scale • Inexpensive
Disadvantages: • Wells need constant maintenance • Suitable locations scarce • Stricter permitting and environmental regulations • Monitoring and maintenance • Requires electricity for pump, heat exchanger, and heat pump	**Disadvantages:** • Limited heat store capacity per/borehole need more for large scale applications • Drilling expensive • Requires electricity for circulation pump and heat pump • Requires technology and specialized expertise	**Disadvantages:** • Small capacity • Not suited to balance seasonal fluctuations	**Disadvantages:** • Takes up large space • Not suitable for urban suburban areas

Source: 'Author'

4 Chapter 4 – Comparison of Path Dependency in Swedish and Danish Energy Systems

4.1 Introduction

Chapter 3 identified differences in the energy systems found in Sweden and Denmark in terms of how each country generates and stores heat and electricity. In Sweden, technologies for seasonal TES are primarily underground – ATES and BTES. They are used as demand side management tools to manage heat and cooling demand at the building level, although there are a few systems using ATES and BTES at the district heating level as storage options. In Denmark seasonal TES technologies are much less common and PTES is essentially used only to store solar thermal energy for district heating; a supply side management option.

Describing these differences does not explain why they exist. The factors that determined each country's specific energy system will likely have a strong influence on the successful transfer of any new TES technology. An understanding of why things developed the way they did is thus required before any recommendations for technology transfer are possible.

4.2 Introduction to Path Dependency Theory

Path dependency theory developed as a concept for explaining how decisions taken can influence future choices (Sydow et al., 2005). It introduces the idea of 're-enforcing mechanisms' - small actions that collectively can make initial decisions increasingly difficult to divert from, and in the absence of 'exogenous shocks' (external events which alter the situation and make radical change possible), can lead to 'lock in' – a situation where pathways are almost impossible to change.

Path dependency runs counter to the basic assumption in economics that the market will always chose the most efficient solution to a problem. Paul David, one of the early proponents of path dependency, used it to explain why certain technologies came to dominate despite a less-than-optimal design. David cited the example of QWERTY keyboards for typewriters, which despite being slower for typists than other keyboard arrangements came to be the dominant design. As more people purchased QWERTY keyboards and learned to use them (reinforcing mechanism), the costs to switch to a different design grew until the QWERTY design became 'locked in' (David, 1985). Similar uses have be used to explain why VHS succeeded over BETA, why train tracks gauges are 1.438 meters apart, or why light-water nuclear reactors became more popular than others (Puffert, 2010). Another early developer of the theory, W. Brian Arthur used path dependency concepts of positive feedbacks (reinforcing mechanisms) and lock-in to explain historical influence on the economy (Arthur, 1989). In subsequent years path dependency has been used to explain a range of phenomena, from the formation of language (Hathaway, 2001) to the location of cites (Page S. , 1999).

More recently, path dependency has been applied to energy systems. Kivimaa, Lovio and Mickwitz of the Finnish Environment Institute and Aalto University use path dependency to explain why biofuels have been slow in achieving prominence in Finland (Kivimaa et al., 2010); (Heiskanen et al., 2011). Lafferty and Ruud use path dependency to discuss difficulties renewable energy technologies face when entering new markets (2008).

4.3 Path Dependency and the Development of the Swedish and Danish Energy System:

While there is considerable debate over the exact terminology used to describe the components of path dependency, there is some level of agreement on four components (Garud et al., 2010); (Sydow et al., 2005); (Page S. E., 2006):

1) **Initial situation**; sometimes referred to as 'resource endowments', the historical starting point that determines at least some of future outcomes for the phenomenon being analysed
2) **Reinforcing mechanisms**; sometimes referred to as increasing returns or reinforcing loops - events that create positive feedbacks and increasingly make divergence from a certain pathway more difficult
3) **Lock-In**; the final state where the reinforcing loops result in a situation "stuck" in a certain pathway
4) **Exogenous shock**; A 'game-changing' disruption imposed from outside the system, which can cause a drastic change in path direction not usually possible from inside

These definitions are applied here to investigate the historical "paths" of the Swedish and Danish energy systems and to describe the most significant events through the evolution of each. The goal of this section is to provide some insight into why each system developed the way it did, and the development of accompanying TES technologies. It is not meant to be an exhaustive list of every influential event or policy measure.

In this paper 'initial conditions' refers to the natural resources each country had and the type of economy and energy system each country had developed from 1900 to the late 1960s. Two 'exogenous shocks' were selected - the 1973 oil crisis and the early 1990s carbon constraints. Both were highly disruptive events and each country responded in distinct ways. 'Reinforcing mechanisms' refers to the actions taken that strengthened those responses to arrive at the 'locked-in' system for energy production and storage that each county currently uses.[3]

4.4 Path Dependency – Sweden

4.4.1 Initial situation 1900-1970:

Sweden is a large, heavily forested country with a mountainous northern region and many large rivers. Early in the century Sweden built hydropower dams on many of the country's main rivers and transmitted this electricity by high power transmission lines to all major cities. By the 1930s, Sweden had an abundant supply of inexpensive electricity which was a key driver in Sweden's industrial development, allowing the growth of heavy manufacturing industries such as steelmaking, pulp and paper production, chemicals manufacture and machinery (Lafferty & Ruud, 2008).

As exploitation of hydropower resources began to reach capacity in the 1960s, the case for using CHP to supplement hydropower electricity generation and provide heat for district heating arose. Heating in Sweden had traditionally been at the home or building level and supplied by wood burning stoves or oil or coal furnaces. Early CHP and heat-only district heating boilers burned mainly imported fossil fuels such as coal and oil. Although CHP

---

[3] Note: not all 'Lock-in's are equal. The lock-in resulting from 100 years of using coal, for example, is not the same as the lock-in for using PTES. In these cases lock-in refers more to a way of thinking rather than the strict definition from theory and does not mean 'impossible to change' – just difficult.

development allowed for some combined generation, the majority of heat and electricity in Sweden continued to be generated separately (Marcus-Møller, 2007). Sweden has no domestic fossil fuel resources, and by the early 1970s was reliant on foreign imports to supply fuel for its heating needs.

4.4.2 Exogenous Shock 1: Oil Crisis

The effect of the OPEC-induced oil crisis in 1973 on the Swedish economy was pronounced. Although relatively little electricity generation depended on oil, the heating, transportation and industrial sectors were strongly affected by the sharp increases in fuel prices. The government responded with a variety of policy measures to reduce the country's oil dependence.

Response: Diversify energy supply away from oil

Development of nuclear power: The Swedish government had begun the development of nuclear power in the 1950s through the agency Atomenergi AB (International Atomic Energy Agency, 2009). At that time nuclear power was seen as the "future" technology for developed economies, and the possession of domestic nuclear industry a symbol of a country's technological sophistication (Yim, 2010). There was initially little organized public resistance to nuclear power, and the first commercial scale reactors came online in the early 1970s. The oil crisis prompted a rapid increase in new construction and development expanded at the rate of one new reactor per year until 1985. Nuclear electricity quickly became the dominant source of electricity in the country, eclipsing hydropower (World Nuclear Association, 2011).

Development of alternate fuels for district heating: High oil prices made CHP and heat-only boilers running on oil exceedingly expensive to operate. In response, research began into using biofuels. Wood-waste biofuels had long been used in the forestry industry. The use of biofuels facilitated the continued expansion of district heating (Swedish Bioenergy Association, 2011). Waste incineration also began to be used as a CHP fuel sources as (Marcus-Møller, 2007).

Government Research and Development into RES: The Swedish government supported university research into renewable energy sources such as wind, solar, heat-pumps and advanced biofuels such as bio-gasification, black liquor and pellets (Swedish Bioenergy Association, 2011).

Development of heat pumps for building and district heating needs: In the late 1970s the Government held a competition throughout the country to come up with new heating solutions. One successful technology was shallow geothermal heating systems using horizontal ground loops and vertical boreholes coupled with heat pump systems (J. Barth, Personal Communication, 18 Aug 2011)(See Appendix D). At the district heating level, large heat pumps using seawater as a heat source began to be installed in conjunction with district heating in Stockholm (C.Bergland, Personal Communication, 27 June 2011).

Development of first season seasonal TES technologies: As a spin-off development of borehole geothermal heating systems, pioneering research into using similar principals to store heat underground using BTES and ATES technology began at Lund University including the first large scale demonstration projects and computer modelling of such systems (J.Cleasson, Personal Communication, 23 June 2011).

4.4.3 Reinforcing mechanisms:

Increased electricity use: Rapid nuclear expansion resulted in an oversupply of electricity in the 1980s. Cheap and abundant electricity allowed the continued development of electricity intensive industries, which in turn required more electricity. Electricity consumption increased an average of 5% per year from 1970 to 1990, and Sweden became one of the highest per capita users of electricity in the world (Swedish Energy Agency, 2010).

Continuation of nuclear electricity supply: public ambivalence to nuclear power also allowed its expansion and continued electricity over-supply. Businesses were strongly in favour of nuclear power (Kåberger, 2002), while wider public opinion was divided. However, nuclear was seen a cleaner option than the expansion of hydropower or coal power. Although public sentiment became more critical over time, especially after the Chernobyl disaster in 1986, the absence of a unified anti-nuclear movement permitted nuclear power to continue (Lafferty & Ruud, 2008).

Low success of wind and solar PV: Wind and solar electricity generation were slow to become established in Sweden for three reasons: 1) with an abundance of electricity from hydro and nuclear power, electricity supply was not a high concern; 2) early Swedish government policy backed only large MW sized turbines, at a time when there was no market for this size; 3) wind power producers were less organized than in Denmark, and suffered from the public perception that wind would never be able to supply a significant part of Sweden's electricity (Bergek, Jacobsson, & Sandén, 2008). As a consequence, as late as 1992 Sweden only had 39 wind turbines installed in the country (Bergek & Jacobsson, 2002).

Reinforcing mechanisms for biofuels: Demand for biofuels, which were seen as a domestic, clean resource, increased as CHP and district heating boilers were converted to biofuels. Demand helped drive research into advanced biofuels delivered by processes such as gasification (Bergek, 2002).

Reinforcing mechanisms for electric heating: A result of cheap electricity also allowed many technologies that had previously run on fossil fuels to be economically shifted to electricity. This included using direct electric heat as well as heat pumps as a widespread replacement for fossil fuel heat both at the individual level and district heating level. As the use of electricity for heating become more widespread, it reinforced demand.

Drilling experience and public acceptance of geothermal heating and BTES and ATS viable: Both borehole geothermal heating and BTES and ATES storage requires drilling, testing and installation. Expansion of this technology was facilitated by carry-over drilling expertise from the substantial domestic mining and geotechnical industries. There were many existing companies with the equipment and expertise to complete the boreholes. Public acceptance of ground source heating and heat pumps became a reinforcing loop for the technology as the more people "knew someone who had one." (J.Cleasson, Persoanal Communication, 23 June 2011)

4.4.4 Exogenous shock: Carbon constraint of the 1990s

By the late 1980s and early 1990s events such as the 1987 Bruntland commission report on sustainable development and the 1992 Rio Earth summit marked the consolidation of public and governmental awareness of the new problem of climate change. This created a new constraint on the energy system: a requirement to reduce C02 emissions.

Response: Reduce carbon emissions from the energy system:

Government incentives for Renewable Energy Sources of electricity: Sweden developed a green certificate system where providers of RES electricity to the grid are required to be "certified" by a third party. Afterwards, they are issued renewable energy certificates that can be sold or traded. All electricity providers in the country are required to prove that a portion of the electricity they provide comes either from certified renewable sources they themselves own, or from certificates from other providers they have purchased (Swedish Energy Agency, 2010).

Tax on CO2: In 1990 the Swedish government introduced the world's first tax on carbon dioxide emissions, applied to all fuels that emit carbon dioxide except biofuels (Swedish Energy Agency, 2010).

Ratification of the Kyoto protocol and EU Integration: The Kyoto protocol obliged Sweden to cut its C02 emissions, and joining the European Union meant accepting the emissions trading scheme (EU ETS). The EU ETS allowed large emitters to buy and sell emissions credits on the open market (European Comission, 2011).

Use of TTES to manage short term district heating peak load: Swedish district heating companines devloped TTES technology as a method of more efficiently sizing boilers, some of which still used fossil fuels. TTES allowed the companies to build smaller boilers to meet 90% of the days demand, and store hot water for peak demand times (M.Gierow, Personal Communication, 18 May 2011).

4.4.5 Carbon Reduction Reinforcing Mechanisms:

CO2 tax reinforces use of biofuels and electricity for and heating: District heating and CHP plants that burn biofuels are not subject to C02 tax, which further increased demand for these fuels and reinforced investment in new technologies such as bio gasification. Because Swedish electricity (primarily hydro and nuclear power) is basically C02 free, a C02 tax creates an incentive to use electricity for heat – both with large heat pumps at the district heating level, or small heat pumps at the building level.

Government investment in heat pumps: Partly for the reasons described above, in the mid 1990s the Swedish National Board for Technical Development bought a large number of ground source heat pumps as part of a government procurement program. This helped reinforce the public acceptance for ground source heat pumps. Sales after the procurement increased 400% (Karlsson et al., 2003).

Market rather than mandate for heating: Unlike Denmark, where government mandates dictated what heating technologies were to be used, Swedish Government regulations did not favour a particular heating technology. This market system allowed heat pumps to compete for market share with district heating and other heating technologies (M.Gierow, Personal Comnication, 18 May 2011). Competition freed customers to choose combinations of technologies to meet their needs. An example is Akademiska Hus in Lund, which uses a combination of BTES and district heating for more control over its heating and cooling needs (H.Petersson, Personal Communication, 1 July 2011).

4.4.6 Summary and Lock-in: Energy System

1) **Continued use of nuclear power and hydropower for electricity:** Sweden has developed an electricity-intensive economy. Nuclear and hydropower together supply 90% of the county's electricity C02 free and will remain the only way to supply such demands domestically without a massive shift to alternatives such as biofuel and wind generated electricity. Although public opinion is still divided, in a carbon constrained economy Sweden is 'locked in' to nuclear and hydropower electricity for at least the near term.

2) **Biofuels for CHP and district heating**: Sweden has a long history of using biofuels. Large investments into research and development and government incentives have helped Sweden achieve world leadership in biofuels technology, particularly bio-gasification. Sweden also possesses abundant domestic forest resources to ensure continued supply and export (Johnson & Jacobsson, 2001). Carbon constraints have added a further incentive for using biofuels for CHP.

3) **The use of electricity for heating**: As electricity in Sweden initially came from domestically produced hydro and nuclear power rather than combusting imported fossil fuels, electricity for heating was regarded as a method of reducing oil dependence. Later when carbon emissions became recognized and taxed, heating from Swedish electricity benefited from generating negligible carbon emissions. Acceptance of using electricity for heating also allowed the development of highly efficient heat pump technology – both large scale for district heating applications and small scale at the building level.

4.4.7 Summary and Lock in: Thermal Energy Storage Systems:

1) **Using Tank TES as method of short term storage**: TTES has become a widely used technology for short term storage at the district heating level.

2) **Using Borehole TES and Aquifer TES over other seasonal storage technologies:** Abundant electricity, a historical competence in drilling from the mining and geotechnical sector and long experience using heat pumps allowed the development of borehole shallow geothermal heating systems in Sweden. Government investment, an open market for heating technologies and a high level of public acceptance for using electricity for heating allowed geothermal use of heat to become widespread. Research and development into using the same technologies not only for heating, but also for seasonal storage of heat helped pioneer the uses of BTES and ATES. Early demonstration projects proved the viability of the technology, and past experience with shallow geothermal heating helped create widespread public acceptance of BTES and ATES storage systems. Large solar thermal district heating projects in Sweden did not find acceptance as they did in other countries such as Denmark. Consequently, Pit TES systems, often used in conjunction with solar district heating also did not become widespread. Sweden is currently locked into equating seasonal TES with the underground technologies BTES and ATES as demand-side management options at the building level, rather than supply side options at the district heating level.

4.5 Path Dependency Denmark:

4.5.1 Initial situation 1900-1970:

In contrast to Sweden, Denmark is a small country of islands, without any mountains or major rivers. Denmark has no domestic hydropower and prior to 1980 did not have any fossil fuel resources. A predominantly agricultural country with little heavy industry, Denmark supplied its early electricity demands with thermal power stations burning imported coal and oil. Denmark was an early pioneer of both district heating and CHP. The first system was installed in 1903 and used a variety of fuels including waste, making it also one of the earliest waste-to-energy plants. By the 1930s district heating was well established in most Danish cities, but heating and electricity generation remained predominantly separate, and produced almost exclusively with coal and oil (DBDH, 2011). Following WW II, low world prices for oil shifted electricity and heat production to oil from coal. As a result, by the end of the 1960s Denmark had a well developed district heating sector but was almost completely reliant on imported oil and coal to meet both its heating and electricity needs (Ibsen & Poulsen, 2007). No facilities for thermal energy storage of any type existed at that time.

4.5.2 Exogenous Shock 1: Oil Crisis

The oil crisis of 1973 exposed the risk of oil dependence, virtually halting the economy when imported oilprices spiked. The Danish government immediately responded with a number of policy measures that dramatically altered the way the country generated and used energy.

Response: To diversify energy supply away from oil

Decision NOT to develop nuclear power: As a developed country with no domestic resources, Denmark would seem to have been good candidate for a nuclear program. Instead a well-organized and highly vocal anti-nuclear movement turned public opinion strongly against the idea, and nuclear power development was rejected (Lafferty & Ruud, 2008).

Development of domestic oil and gas: With the option to pursue nuclear energy unavailable, the government moved to rapidly develop off-shore fossil fuel resources in the North Sea. The state-owned Danish Oil and Natural Gas Company, (DONG) was quickly established and given exclusive rights to Denmark's oil and gas reserves in the North Sea (Ibsen & Poulsen, 2007).

Switch to CHP: Another response was the government enforced consolidation throughout the country of thermal plants (separately generating heat and electricity) and conversion to combined heat and power. Development of CHP quickly expanded (see figure 4-1). The government also instituted price controls for CHP produced heat, thereby setting the price companies were allowed to charge for heat (Marcus-Møller, 2007).

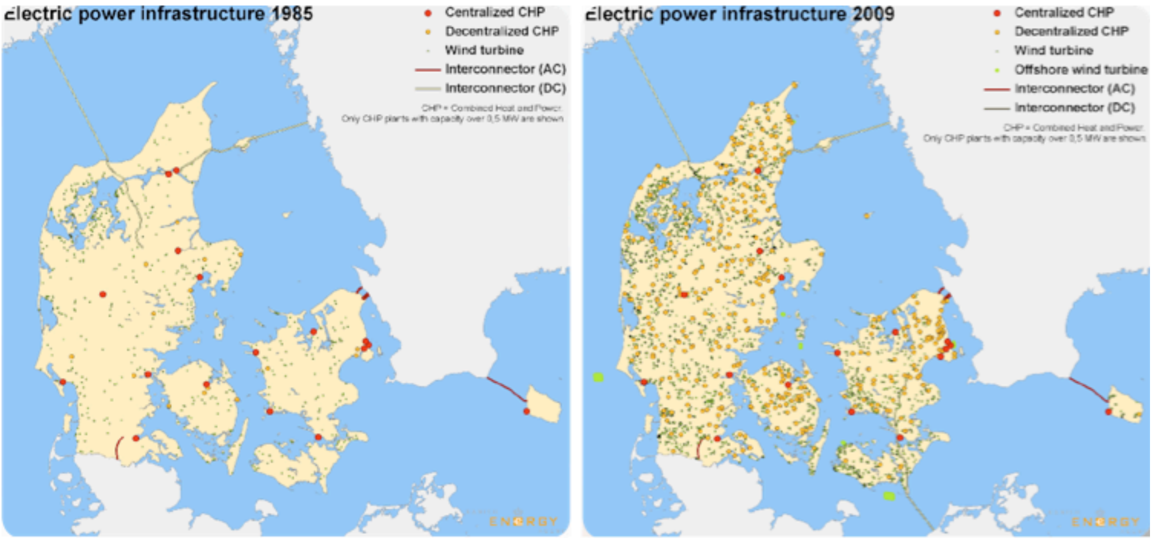


Figure 4-1 'CHP Deployment 1985 and 2009'

Source: (Danish Energy Agency (2), 2010)

Developing alternative energy sources: The Danish government set up the Energy Research Program in 1976 and the Development Program for Renewable Energy in 1980 as mechanisms to fund research and development for renewable energy projects (Danish Energy

Agency (2), 2011). Wind generated electricity was an early focus of Danish research and development. In the late 1970s The Danish government set up a wind power facility at Risø - Danish Technical University (DTU) in Røskilde, for testing new experimental designs (Bergek & Jacobsson, 2002).

Early development of seasonal TES storage: DTU also pioneered research in solar thermal technologies. In this period the first seasonal PTES storages were developed and tested for incorporation with solar distract heating systems (Kielsgaard & Nordgaard, 1981). Early PTES systems were based on the design of "slurry pits" already used in the agriculture industry for waste separation (Heller, 2000).

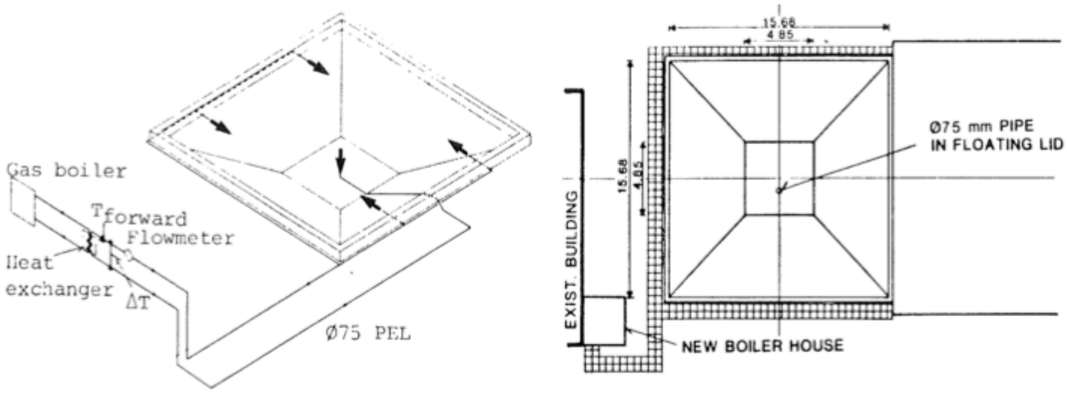


Figure 4-2 'Early PTES designs at DTU'

Source: (Kielsgaard & Nordgaard, 1981)

4.5.3 Oil shock Response Reinforcing Mechanisms:

Wind research centre becomes world renowned: By the mid 1980's the RISØ research and development centre became the pre-eminent wind power testing centre attracting many engineers and designers from Europe and around the world (Bergek & Jacobsson, 2002).

Wind power producers organized: In the mid 1970s wind power producers formed associations such as The Danish Wind Turbine Owners' Association and the Wind Committee of the Academy of Technical Sciences. These groups created and distributed information about recent developments in wind technology reinforcing the understanding and acceptance of wind as a viable energy technology to both industry and the public (Lafferty & Ruud, 2008).

Government incentives push wind development: Despite resistance by Danish utility companies, in the late 1970s the government made it a requirement for utilities to purchase wind electricity. The guarantee of electricity sales helped reinforce expansion of new wind capacity. Wind power expanded rapidly (Danish Energy Agency, 2009).

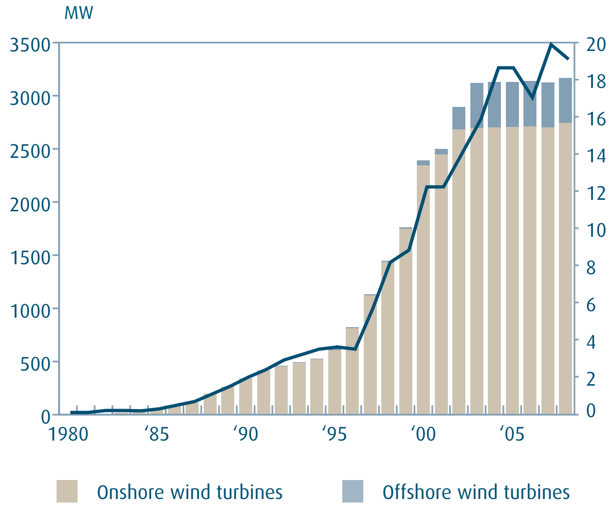


Figure 4-3 'Development of Danish Wind Electricity as Percentage of Supply

Source: (Danish Energy Agency (3), 2010)

Government mandates for DH and CHP: In 1979 the Danish government unveiled the "Heat Supply Law for Denmark," dividing the country into regions that would be supplied with domestically produced natural gas, and those that would be supplied with CHP produced district heating (Ibsen & Poulsen, 2007). Furthermore, the government created an "obligation to connect law" which required citizens to connect to district heating or natural gas if it was available, and outlawed the use of electric heating for new building construction. This acted as a reinforcing loop – creating a strong domestic demand for the new Danish gas, and also for the continued expansion of district heating (Danish Energy Agency (2), 2011).

TES Storage technologies become established: As a response to the mandated heat prices, the first district heating companies installed TTES to take advantage of the differing government prices for heat at different times. The recognition of this advantage quickly spread throughout the country and TTES was widely installed. For seasonal storage, first commercial solar thermal district heating projects were established using PTES developed at Danish Technical University. These early projects demonstrated feasibility and cost effectiveness of the PTES technology and Denmark quickly became a leader in solar thermal district heating using PTES (Johnson & Jacobsson, 2001); (Arcon Solar, 2011).

Government discouragement of electric heating: Incentives and mandates for switching to district heating and natural gas heating rather than direct heat radiators convinced the public that using electricity for heating regardless of the technology used was wasteful. (A. Larsen, Personal Communicatuon, 21 July 2011).

4.5.4 Exogenous shock 2: Carbon constraint of the 1990s

Like in Sweden, by the late 1980s the Danish public had became increasingly aware of the country's carbon footprint. Government policies since the oil crisis of the 1970s had helped the economy wean itself from imported oil, however Danish CHP was still highly dependent on carbon-producing fossils fuels such as coal, oil and natural gas.

Response: Reduce carbon emissions from the energy system

Government incentives for RES: In 1991 the Danish government implemented a feed-in tariff scheme to promote renewable electricity, which grants a price premium for electricity from renewable sources such as wind and solar PV. As a further incentive to shift to wind, the government created a rule that wind powered electricity would receive priority in the grid over CHP (Lafferty & Ruud, 2008).

Tax incentives and research into biofuels: The government created a tax on fossil fuels to drive the shift from coal and natural gas to biofuels in CHP plants. Unlike Sweden the development of biofuels had not been a major focus of research compared to wind. This changed in the mid 1990s when research into using straw and other agricultural waste as a fuel stock in CHP began in earnest (Voytenko & Peck, 2011).

Development of deep geothermal heating: Research into non-carbon sources of heat production also included the development of a small geothermal heat plant providing district heat in conjunction with a heat pump (Danish Energy Agency (2), 2009).

4.5.5 Carbon Reduction Reinforcing Mechanisms:

Wind energy leadership: By the mid 1990's Denmark had one of the world's highest percentages of wind energy. As the percentage of wind electricity in the energy mix increased, so did the country's prestige of being an example of progressive renewable energy policy. This resulted in reputational benefits for the Danish government and energy companies with wind energy in their portfolio. In fact, having wind power became an essential aspect of the "social license to operate" for Danish energy companies as well as an important part of corporate branding and marketing (Lafferty & Ruud, 2008).

Wind industry influence: As well as bringing reputational benefits, building wind turbines became a major economic generator for the country. By 2006, the Danish Wind turbine industry generated around 4 billion euros in exports and 34% of the world market. Turbine companies became one of the country's largest employers, giving the industry strong influence in Danish politics (CESPOS, 2009).

European Union integration: EU integration, the Kyoto Protocol, and joining the EU ETS, a market for C02 emissions trading among large industrial emitters were not as strong a factor in shaping Danish policy because the country already had higher targets for renewable energy (Lafferty & Ruud, 2008). However, these world energy events were a strong reinforcement that the Danish renewable energy policies were worthwhile.

Law discouraging heat pumps: In 2005 the government passed law L1417 which taxes electric heating systems on amount of heat produced. This penalizes the use of heat pumps, which produce between 3 and 5 times as much heat for the same unit of electricity as a direct resistance heater (A. Larsen, Personal Communication, 21 July 2011)

Using TTES at district heating level: With the Fossil Fuel tax, which made coal and natural gas fuelled CHP more expensive, CHP operators who had not already installed TTES systems had increasing incentive to do so. TTES systems allowed operators to store hot water to be used for district heating rather than burning fuel (Munster & Lund, 2003).

Using PTES over other types of seasonal storage: A study in 1995 of single borehole BTES to store solar thermal heat found the technology to be uncompetitive with PTES. (Heller, 2000). As new solar thermal district heating systems were built, PTES became the only technology considered for seasonal storage. Danish solar thermal district heating expanded to include the largest plant in Europe. Danish businesses were able to leverage expertise in solar thermal into a fledgling export industry, further reinforcing the technology (Arcon Solar, 2011).

4.5.6 Summary and Lock in: Energy System

1) **Continued use of fossil fuels**: Denmark has invested heavily in natural gas and coal infrastructure. This includes embedded supply chains and distribution networks that are not easily changed. As a state owned enterprise, the sale of natural gas contributes to government revenue. Consequently Denmark is "locked" into using natural gas.

2) **CHP as the dominant technology for providing heating and electricity:** A century of government mandates and incentives have resulted in substantial experience and world leading technology. Furthermore, recent investment in infrastructure, and few alternatives for domestic electricity generation indicates that Denmark is "locked" in to CHP.

3) **Biofuels and wind over other renewable investment**: Biofuels, particularly those using domestic agricultural waste, represent a CO2 neutral source of heat and electricity and can used with existing CHP infrastructure. The Danish wind industry is one of the largest employers in the country and a huge export industry. Demark is "locked" not only to using wind generated electricity but also to expand both wind and into agricultural biofuels as energy sources (Lafferty & Ruud, 2008).

4) **Public aversion to using electricity for heat**: Despite the government recently relaxing anti-electric heating regulation, the Danish public is averse to using electricity for heating or heat pumps, despite their high efficiency. Denmark is "locked" into a low use of electricity for heating and a weak public understanding of heat pump technology (A.Brix-Thomsen, Personal Communication, 10 May 2011); (A.Larsen, Personal Communication, 17 July 2011).

4.5.7 Summary and Lock in: Thermal Energy Storage systems

1) **Using TTES at district heating level**: TTES systems were installed as an economic measure both to take advantage of government mandated prices for heat and to economize on taxed fossil fuels. TTES are a long-used and well-understood technology used for supply-side management (Petersen & Aagaard, 2004).

2) **Using PTES over other seasonal storage technologies**. PTES evolved from a well-used design from Denmark's agricultural history. PTES systems were developed domestically at DTU in the late 1970s specifically as a seasonal storage method for solar thermal heating. Early tests into using borehole storage appeared to indicate that the technology was not economically competitive with PTES for solar thermal storage. Other seasonal TES methods such as BTES and ATES also typically require heat pumps and thus electricity for heating, a subject of little experience or enthusiasm in Denmark. In Denmark, seasonal storage has been almost exclusively used for solar thermal district heating. Consequently, this is how the public generally comprehends that technology is to be used. However, the North Harbour storage proposal is showing this technology can be used in the same way as a large accumulator tank. Denmark is thus 'Locked' into using PTES over the use other TES technologies and using it as a supply-side management tool.

4.5.8 Summary comparison of Path Dependant development of Swedish and Danish energy and TES systems

Table 4-1 Style 'Summary of Path Dependant Development of Swedish and Danish energy and TES systems'

Sweden	Denmark
Initial Situation: 1900-1970 • Large capacity for hydropower • Industrial economy, high electricity use • Heating and electricity provided separately – hydro + oil boilers • No domestic fossil fuel supply – dependent on imports (primarily for heat) • Preliminary nuclear industry research • District heating almost non-existent • Abundant forestry waste (for future biofuels)	**Initial Situation: 1900-1970** • Almost no capacity for hydropower • Agricultural economy, low electricity use • Heating and electricity provide separately: Coal and oil thermal electric plants + heat boilers • No domestic fossil fuel supply, dependent on imports • District heating well established • No forestry waste
Exogenous shock 1: Oil Crisis 1970s **Response:** Diversify energy supply away from oil • Rapid development of nuclear power • Development of alternative fuels for DH • Government / University R+D into wind, solar and biofuels • Development of heat pumps • R+D into BTES and ATES thermal energy storages **Reinforcing Mechanisms:** • Increased electricity use • Continued expansion of nuclear power • Low success of wind and solar PV • Reinforcement of biofuels • Reinforcement of electricity for heating • Drilling experience facilitates ATES and BTES	**Exogenous shock 1: Oil Crisis 1970s** **Response:** Diversity energy supply away from oil • Decision NOT to develop nuclear power • Rapid development of domestic oil and gas • Expansion of CHP and conversion of heat or electricity-only generation to CHP • R+D developments in Wind power, solar, geothermal • R+D into PTES thermal energy storages **Reinforcing Mechanisms:** • RISØ Wind testing Centre becomes renowned • Wind producers highly organized • Government incentives push wind development • Government mandates CHP-DH and natural gas usage, obligation to connect • First commercial Solar Thermal DH

Exogenous shock 2: Carbon constraint 1990s **Response:** Diversify from fossil fuels • Government incentives for RES: Green Certificates • C02 price on carbon • Ratify Kyoto, EU ETS • Use of TTES to increase DH boiler efficiency **Reinforcing Mechanisms:** • CO2 tax reinforces biofuels • Government investments in heat pumps • Market rather than mandate for heating technologies	systems using PTES storage demonstrate feasibility • Government discouragement of electricity for heating **Exogenous shock 2: Carbon constraint 1990s** **Response:** Diversify from fossil fuels • Government incentives for RES: Feed-in tariff • Tax incentives for biofuels • R+D into deep geothermal **Reinforcing Mechanisms:** • Government / National pride in wind power • Wind power industry highly influential • EU integration – carbon prices • Law L1417 tax on amount of heat produced discourages heat pumps • TES at DH level • PTES over other sources of heating
Lock in: Energy System • Nuclear power and hydropower • Biofuels for CHP • Electricity for heating **Lock in: Thermal Energy Storage Systems:** • TTES short term storage at DH for peak-load reasons • BTES and AQTES	**Lock in: Energy System** • Continued use of fossil fuels • CHP for heating and electricity • Wind and biofuels • Public aversion to using electricity for heating **Lock in: Thermal Energy Storage Systems:** • TTES short term storage at DH for economic reasons • PTES for solar thermal DH

Source: 'Author'

4.5.9 Selected Summary Timeline Sweden:

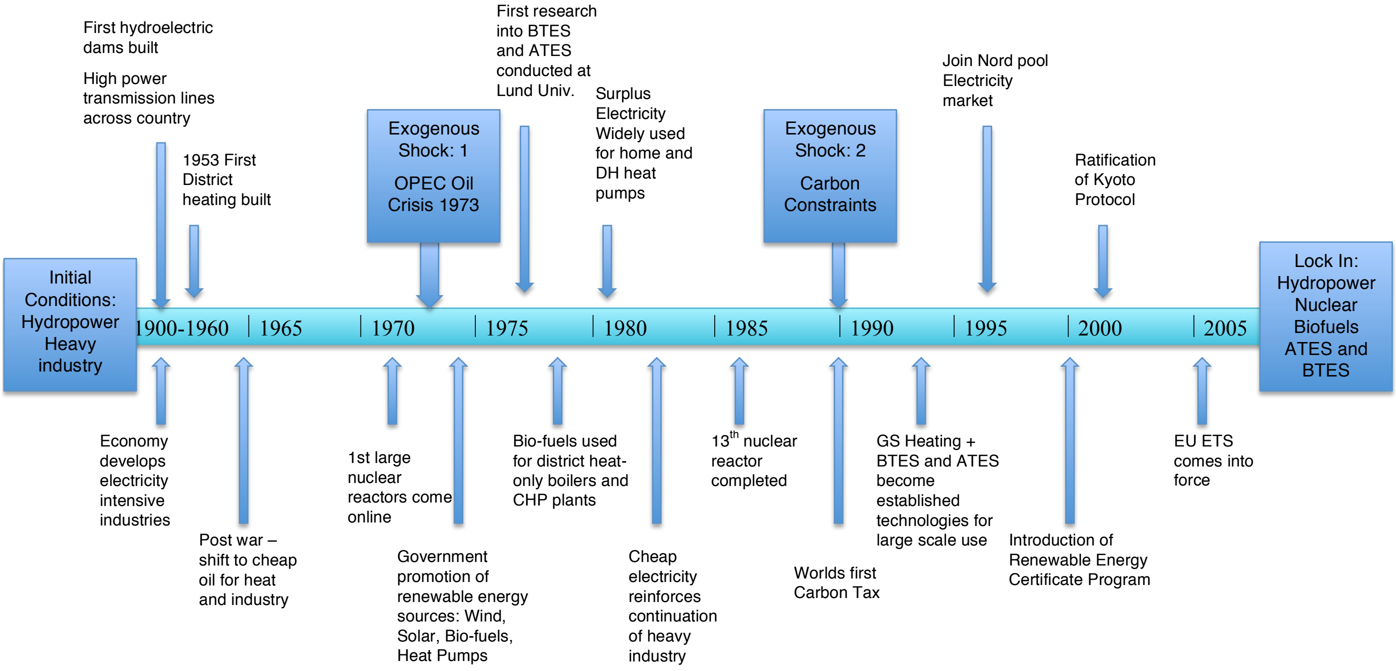


Figure 4-4 'Selected Path Dependency Timeline Sweden'

Source: 'Author'

4.5.10 Selected Summary Timeline Denmark:

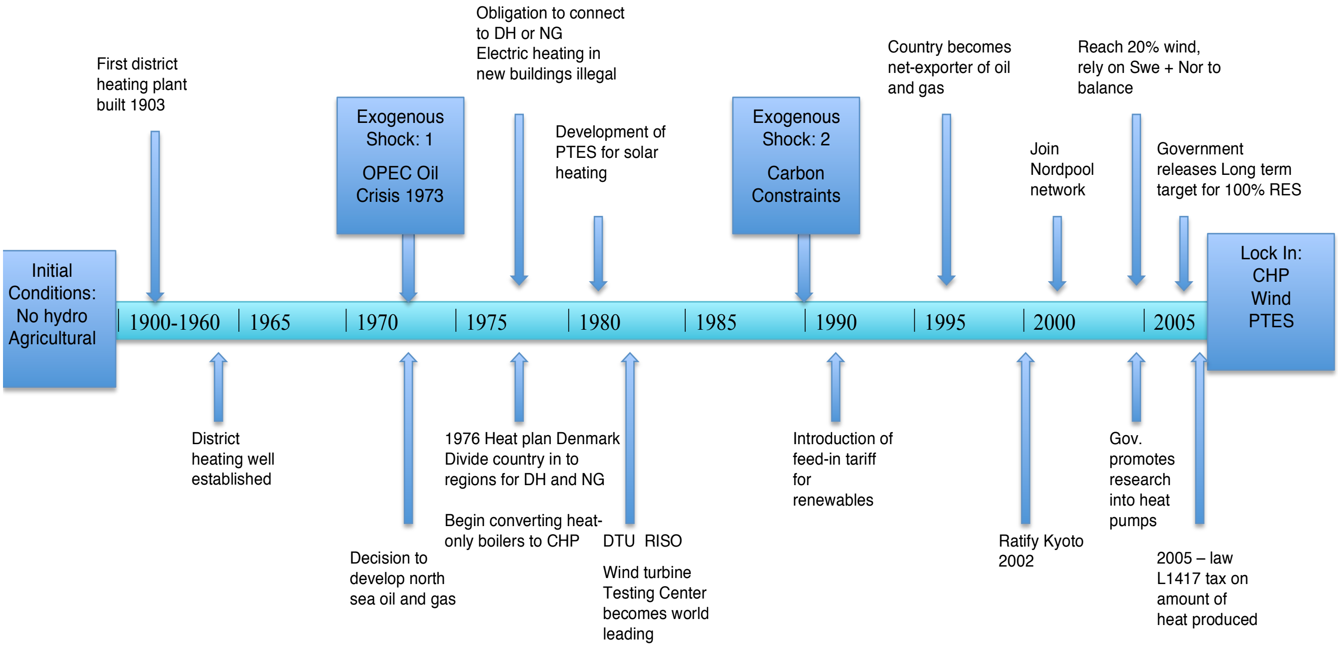


Figure 4-5 'Selected Path Dependency Timeline Denmark'

Source: 'Author'

5 Chapter 5: Technology Transfer

5.1 Introduction:

As discussed in the previous chapter, Sweden and Denmark developed different energy systems based on their respective primary energy generation paths. These differences have in many cases proven complementary; it has been feasible for high amounts of intermittent wind electricity from Denmark to be balanced by Swedish (and Norwegian) hydropower. However, as discussed in Chapter 2, All Nord Pool members plan to incorporate increasing rates of intermittent RES in their energy systems thus this complementarity will likely be reduced.

In a future with integrated systems that include increasing proportion of intermittent RES, thermal energy storage via the use of large scale heat pumps is expected to play a much larger role in the efficient domestic use of electricity. In this scenario ALL types of thermal energy storage may be necessary in each country, especially those that allow seasonal storage. Sweden and Denmark have expertise in different technologies for TES it appears that significant potential for Technology Transfer exists between the two countries.

5.2 Technology Transfer Theory:

Technology transfer has its roots in management theory. The concept of how new ideas, methods, and practices develop and disseminate in the business world was the subject of much of Joseph Schumpeter's early 'social evolution' theory (Schumpeter, 1934). How technology interacts with society, and the importance of different actors such as government and businesses in the development of a technology is the subject of a large body of work (Winner, 1978); (Pacey, 1983). The study of how new technologies disrupt the status quo and how technologies 'favourable' to society evolve is the subject of Technical Innovation Theory developed by Anna Bergek and Steffan Jacobson (2001; 2002; 2003; 2008). More recently the United Nations Framework Convention on Climate Change has used the concept of technology transfer to assist the dissemination of climate friendly technologies from the developed world to the developing world, although the concept applies equally well to transfer between two developed countries (UN, 2008).

Technology transfer, according to the widely cited definition used by the Intergovernmental Panel on Climate Change, refers to, "a broad set of processes covering the flows of know-how, experience and equipment… amongst different stakeholders such as governments, private sector entities, financial institutions, non-governmental organizations and research/education institutions...across and within countries" (IPCC, WMO, UNEP, 2000, p. 3). This is echoed by the International Energy Agency: "Technology transfer is not simply about the supply and shipment of hardware... It is about the complex process of sharing knowledge and adapting technology to meet local conditions" (IEA, 2001, p. 7)

Clearly, the successful transfer of technology involves far more than installing the physical components in a new location. The International Institute for Advanced Systems Analysis, a Vienna based policy institute developed a way of categorizing the components of Technology Transfer described by the IPCC and IEA useful for this discussion. They are Hardware, Software, and Orgware (IIASA, 2006).

Components of Technology Transfer:

- **Hardware**: The manufactured objects
- **Software**: The knowledge required to manufacture and use the hardware

- **Orgware**: The rules, policies and institutional settings for the generation of technological knowledge and use of the technologies

By these definitions, technology transfer refers to not only moving the physical equipment and supplying "tech support" but must also address laws, actors and public customs and attitudes (Brazilian et al., 2008). In relation to the cross-transfer of Swedish and Danish TES technology, the first two components of technology transfer hardware and software are relatively straightforward and are discussed in Part 1. The transfer of Orgware is more complex and is discussed in part 2.

5.3 Technology Transfer Part 1: Hardware and Software:

5.3.1 Hardware:

Transfer of the physical components of ATES, BTES and PTES technology between Sweden and Denmark is straightforward. Unlike transferring such components to a distant developing nation, in most cases the components already exist in both countries. In addition, each has the engineering capacity to produce complex technologies. However, in the initial phase due to restrictions on transfer of intellectual property and other business interests, the short-term outcome may be that each country buys the technology components from the other.

Sweden → Denmark:

For Sweden to Denmark transfer, the basic hardware components both for ATES and BTES systems are relatively simple - plastic tubing, a circulating liquid, and a heat pump, all of which are available in Denmark. However, installing the hardware requires more specialized equipment. As discussed in Chapter 4, Sweden developed borehole geothermal heating and therefore BTES and ATES systems thanks in part to its mining history, which includes centres of excellence in drilling, equipment design and manufacture as well as numerous drilling companies (Atlas Copco, 2011). In contrast, drilling contactors with rigs, and equipment suitable for BTES or ATES installation are not common in Denmark (J.Barth, Personal Communication, 19 Aug. 2011). Consequently in the short term at least Denmark would likely need to import some of the drilling equipment and expertise from outside the country.

Denmark → Sweden:

The basic components Danish PTES system- digging equipment, an impermeable lining, cover material components as well as heat pumps are also all available in Sweden. Transferring the hardware components of this technology would not be expected to be an issue.

5.3.2 Software:

The transfer of the technical know-how between Sweden and Denmark is simplified by the physical proximity of the countries and by similar language and social norms. This has the potential to save some transaction costs.

Sweden → Denmark:

The components of Swedish BTES and ATES technology, while not complicated, do require expertise to design and install properly. Technical issues such as the heat-transferability and permeability of the underground rock formations and aquifer flow rates require specialized testing equipment and specially designed computer modelling software. One example of how this knowledge is shared in Sweden is the GeoTrainet program, a shallow geothermal training course for system designers and installers. There is potential for something similar in Denmark (2011).

Denmark→Sweden:
Installing PTES systems also requires substantial knowledge. Design specifications regarding size, cover and insulation materials have been documented but the main technical knowledge exists within several engineering firms. There is no "GeoTrainet" equivalent for PTES systems. Knowledge transfer would therefore presumably require more direct teaching and coordination between prospective installers in Sweden and the companies that built and designed the systems in Denmark. In the short term, it may be necessary to contract with existing companies in the other country.

Summary Technology Transfer Part 1: Hardware & Software

Table 5-1 Style 'Summary Technology Transfer Part 1: Hardware and Software'

Swedish BTES +ATES → Denmark	Danish PTES → Sweden
Hardware: • Physical components – tubing, pipes • Drilling equipment • Large heat pump technology	Hardware: • Water barrier and insulation layers • Cover technology materials • Heat pump technology
Software: • System design tools / experience • Computer modelling software • Geological testing knowledge • Installation knowledge • Drilling knowledge	Software: • System design tools/ experience • Cost estimates, design configurations • Use with Solar thermal and without

Source: 'Author'

5.4 Technology Transfer Part 2: Orgware

According to the IIASA definition, Orgware refers to the **rules** and '**institutional settings**' that would need to be addressed in order for successful transfer of a new technology to take place.

5.4.1 Rules (Laws):

Sweden → Denmark:
There are several Danish laws that would apply to installing ATES or BTES technology and would need to be addressed in order to facilitate transfer of BTES and ATES technology.

1. Law L1417, passed in 2005 by the Danish Parliament placed a tax on electric-produced heat based on the amount of heat produced, rather than the amount of electricity used to produce the heat. This creates a disincentive for using heat pumps

for district heat use or storage (Togeby et al., 2009); (A. Larsen, Personal Communication, 21 July 2011).

2. The 'Obligation to Connect' law requires consumers in certain areas of Denmark to connect to district heating or gas heating. In many urban areas in Denmark, there is no alternative. Consequently, many Danish heat consumers have no experience with other sources of heating. As discussed in Chapter 4, In Sweden, without such government constraints, individual customers installing shallow geothermal systems was key in allowing the technology to become widespread, and contributed to the development of BTES and ATES (J. Barth, Personal Communication, 19 August 2011).
3. In Denmark, accessing any source of geothermal heating, shallow or deep, requires a permit from the Danish Energy Agency (Danish Energy Agency (2), 2009).
4. Denmark also has strict regulations on the use of groundwater as a heat source. (Bayer, Blum, & Haehnlein, 2010).

Denmark → Sweden:
Swedish law allows for the market use of heating technologies subject to zoning bylaws and applicable building code. There do not appear to be any laws that would directly conflict with the use of above-ground PTES.

5.4.2 Institutional settings:

Besides explicit rules and laws guiding a new technology in a new setting, there are also are the implicit social rules and norms that must be addressed for a new technology to be accepted. In order for a new technology to achieve social acceptance, it must be considered familiar, trustworthy and safe by the relevant institutions (government, lenders, regulators, incumbent actors) and the general public (Bergek, Jacobsson, & Sandén, 2008). Legitimacy is a prerequisite for any new technology to succeed and is achieved when it reaches the stage it is considered by these institutions as the "way we do these things" (Scott, 2001, p. 57).

Management theory for corporations supports this concept of legitimacy. DiMaggio and Powell describe how businesses adopt new business practices not simply because they may be more efficient, but because they are considered legitimate by relevant stakeholders (DiMaggio & Powell, 1983). Aldrich and Foil (1994) expand the concept of legitimacy using the terms 'cognitive legitimacy' and 'socio-political legitimacy' to describe challenges and solutions that entrepreneurs may encounter when entering new markets. Peck et al (2009) in their paper on promoting legitimacy of the biofuels industry, roughly equate the terms cognitive legitimacy to 'acceptance' and socio-political legitimacy to 'understanding.' In their definition, 'acceptance' refers to the degree that industry, the government, and the public accept a new technology. 'Understanding,' on the other hand, refers to how much knowledge these actors have of the new technology and their perception of its utility (Peck et al, 2009). Without acceptance and understanding, governments and risk-averse businesses and their customers will resist new technologies (DiMaggio & Powell, 1983); (Aldrich & Fiol, 1994). Clearly, legitimacy must be addressed if technology transfer of a 'new' TES is to be successful.

5.4.3 Legitimacy issues with TES:

Personal interviews conducted over the course of this research indicate that legitimacy is key to the transfer Swedish TES technology to Denmark and vice versa. For underground TES technologies in Denmark in particular, a lack of legitimacy would be a strong barrier to their implementation. Explanations of the use of BTES and ATES elicited responses showing a major lack of understanding, trust and knowledge. For example, when discussing the use of ATES and BTES systems in Denmark, typical responses included:

- "Really? You can store heat underground? Doesn't it disappear?"
- "Danes are not used to used to the idea of using electricity for heat"
- "We have been taught by the government for 30 years that you DO NOT USE ELECRICITY FOR HEAT"
- "We think of heat as a waste product from making electricity"
- "Seasonal storage? For how long? You would need a tank the size of a house for each house"
- "We don't understand the technology over here"
- "We tried that but it doesn't work in Denmark"
- "We aren't aware of the capabilities"
- "Underground is risky – its hard to predict what is down there, better to do it above ground – where you can see and understand what's going on"

Excerpts taken from available literature support these comments from interviews:

- "Lack of knowledge of the technology [BTES and ATES] is considered a key barrier to further development (IF Tech, 2005)
- "For unknown reasons, borehole heating systems have not developed in Denmark" - The Danish heat pump association (Varmpumpordningen, 2011)
- "Getting heat from the ground may seem like hocus-pocus" – Danish Heat pump association (Varmpumpordningen, 2011)

Clearly, achieving legitimacy is necessary for TES technology exchange between Denmark and Sweden. The next section discusses methods for how that may be achieved:

5.5 Addressing Legitimacy:

Aldrich and Foil offer several potential strategies for entrepreneurs addressing legitimacy, four of which could be relevant to building legitimacy for TES technologies. These include:

5.5.1: Developing "collective action" for TES
5.5.2: Standardization of the TES concept
5.5.3: Building a professional crop of TES professionals; and
5.5.4: Pursuing synergy with incumbent industries.

5.5.1 Collective action

According to Aldrich and Foil, knowledge and understanding requires a sense of the 'stability' of the new technology through such actions such as: organizing trade counsels, forming industry associations, conducting trade shows, and publishing marketing and promotional materials (Aldrich & Fiol, 1994). The goals are to communicate technical information to external stakeholders and to create the public perception of professionalism and reliability. These can help build trust and slowly enhance the reputation of the technology (Peck, Berndes, & Hektor, 2011).

Sweden → Denmark:
As described in Chapter 4, The Danish wind industry followed just such a strategy in the late 1970s. At that time, wind energy producers created several trade journals to disseminate information about the industry, one result of which was to build trust among sceptical consumers (Lafferty & Ruud, 2008). Similar options appear to be open for promoters of BTES and ATES systems looking to showcase the technology to sceptical individuals with no previous knowledge of its use.

Denmark → Sweden:
In a similar manner, proponents looking to establish Danish PTES technology in Sweden could ensure that literature on PTES technology is distributed and perhaps presented as one of several available and competitive technologies for storage.

5.5.2 Standardization of the Thermal Energy Storage concept

Aldrich and Foil found that the lack of a "standard design" of a technology makes it more difficult for stakeholders to understand and thus introduces doubt, for example by making a technology appear immature (Aldrich & Fiol, 1994). They recommend that actors providing the technology come to an, 'implicit agreement' as to what the technology means. Similarly Peck et al. found the lack of a standard understanding for what "biofuels" means was a barrier to wider acceptance in that industry. In that paper, the authors recommended coming to common standards at least to recognize the social and environmental benefits (and drawbacks) of biofuels (Peck et al., 2010). This same advice would apply to TES, where interviews indicted considerable lack of understanding about even the concept of TES.

Sweden → Denmark:
Though generally standardized in design, ATES and BTES systems vary in their level of complexity. Variables in BTES include number of heat exchange pipes in each borehole, their configuration, the depth boreholes are drilled to, the number of holes, the heat storage capacity of the underground rock formations, even what the boreholes are backfilled with, all of which affect the performance of the system (GEOTRAINET, 2011). Reasons for this diversity include evolving design parameters and technical adjustments to suit local conditions (J.Barth, Personal Communication, 19 Aug. 2011). In addition, because it is mostly under ground, an ATES or BTES system can be difficult to visualize. Unlike a windmill or a solar panel, ATES or BTES can seem rather abstract to someone unfamiliar with the technology (Williams, 2011). Thus, there appear to be opportunities for proponents of these systems to develop simple, standardized communications materials to help convey the basic aspects of the technology.

Denmark → Sweden:
Establishing PTES systems in Sweden may be easier as PTES technology is above ground, more easily visualized, and the concept more understandable. However, there are no standards for size, design, shape or structural materials. Thus, similar to ATES and BTES in Sweden, proponents of PTES systems may find opportunities to describe a common design in their promotion materials.

5.5.3 Building a professional 'corps'

Aldrich and Foil describe the need to professionalize a new technology or practice through education (1994). One of the ways to do this is to establish links with universities, technical and trade schools and provide training materials. These links not only can provide information for future designers, installers and regulators, but "professionalization" demonstrates to government and the public the legitimacy of the technology (Peck, Berndes, & Hektor, 2011).

Sweden → Denmark

The BTES and ATES methods are taught throughout Sweden at universities and technical schools such as Lunds Techniska Hogskolan and Chalmers Techniska Hogskolan (J.Cleasson, Personal Communication, 23 June 2011). For those looking to promote ATES and BTES in Denmark, there appears to be potential to establish similar course curricula at Danish universities such as Danish Technical University, or Aalborg University where programs for renewable integration and PTES for solar thermal district heating are already in place.

Denmark → Sweden

In a similar way, there appears to be opportunities for universities in Sweden currently providing ATES and BTES training to expand their curriculum to include PTES technology. Expansion of this concept could include the use of TES technologies as supply-side measures at the district heating level where it is primarily used and understood in Denmark. The goal could be to make PTES one of several, established options for TES, especially as a technology for areas not suitable for ATES or BTES.

5.5.4 Synergistic relationships with incumbent industries

Incumbent industries hold key positions of power and have strong influence on government and public opinion (Bergek, Jacobsson, & Sandén, 2008). The successes or failure of a new technology can depend on how well it can integrate with existing industry players. A synergistic relationship where the newcomer is seen as beneficial to incumbent actors can greatly improve its chances of becoming established (Aldrich & Fiol, 1994).

Sweden → Denmark

As discussed in Chapter 4, BTES and ATES technologies are primarily used as demand-side management measures that allow building owners some autonomy to manage their own heating and cooling needs without district heating. However, Boxholm and Lund Municipalities aim to show that BTES and ATES can be successfully used at the district heating level as supply-side management tool as well. How well BTES and ATES technologies are accepted by incumbent Danish district heating companies depends partially on whether the technology is used as a demand-side measure, (thus a competing technology for district heating), or as a supply-side measure to be used by the district heating companies themselves.

As a demand side measure, BTES and ATES are likely to face strong resistance by district heating companies in Denmark who fear a threat to their customer base. As a supply-side measure, the incumbent district heating companies themselves would enjoy the benefits of BTES and ATES. As described in chapter 2, these technologies would allow them the flexibility to produce heat from combustion of expensive fuels only when necessary, and otherwise use less expensive electricity and stored heat to produce district heat for customers. **Consequently it appears to the greatest potential for synergy with incumbent actors in Denmark lies with promoting ATES and BTES as a supply-side technology used by district heating companies.**

Denmark → Sweden

In Sweden, seasonal heat storage is mainly considered a demand-side management option, but has potential to be used at district heating level. PTES has long been used at the district heating level in Denmark (in conjunction with solar thermal plants). Therefore there appears to be opportunity to demonstrate to Swedish district heating companies and CHP producers that TES systems such as PTES can be an economical supply-side option (along with BTES and ATES) for them as well.

Table 5-2 'Summary Part 2 Orgware affecting the transfer of energy technologies'

Swedish BTES +ATES → Denmark	Danish PTES → Sweden
Rules /Laws • Heat pump law • Obligation to connect • Geothermal concessions – Dong • Water table restrictions	Rules /Laws • Zoning restrictions
Institutional / Legitimacy: • Collective action • Standardization of BTES /ATES concept • Building professional corps • Interaction with incumbent actors	Institutional / Legitimacy: • Collective action • Standardization of PTES concept • Building a professional corps • Interaction with incumbent actors

Source: 'Author;

6 Discussion

6.1 Private vs. Public allocation of installation costs

The costs of the installation of any TES technology must be addressed before technology transfer can occur. One way to assign the responsibility to fund this work is to determine who benefits and where the storage is to be applied. An important consideration is deciding where the transferred technology is to be used, either for supply or demand side management. ATES or BTES systems from Sweden have been proven at the building level for demand-side management, but there is less experience at the district heating level for supply-side management (although possible, e.g. Boxholm and Lund). Likewise while PTES systems in Denmark have been proven at the demand-side district heating level, their capacity to be used at the building level (perhaps in a smaller scale) has not been explored. Consequently, there is appears to be opportunity for technology transfer of TES not only between countries, but within each country as well:

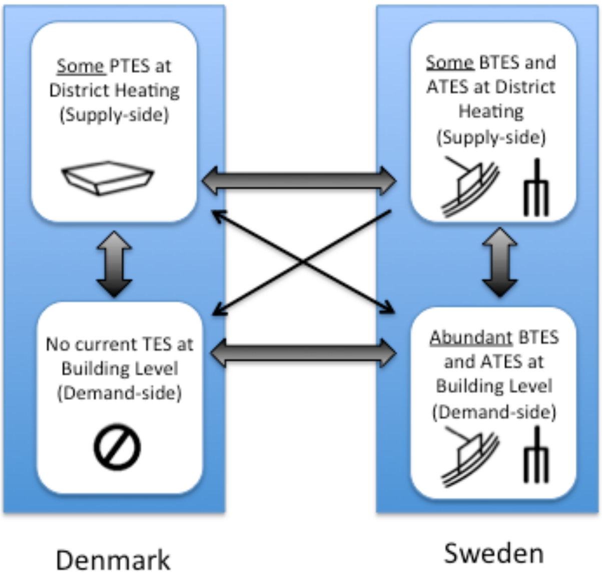


Figure 6-1 'Diagram of country-to-country and intra-country technology transfer potential'

Source: 'Author'

Whether funding the installation of TES is the responsibility of private business or government depends in part on the level and location where it is to be used, whether direct financial benefit accrues, and whether public goods are supplied. At the building level, as TES is mainly used in Sweden, storage allows the building owner to reduce his heating and cooling costs, and can reduce the exposure to increasing price trends for district heating. In this case, if the benefit were enough to both the cost of installation and operation, logically the costs for installation should fall to private building owners rather than the government.

For storages applied at the supply-side district heating level, as TES is mainly used in Denmark, funding responsibility is more complicated. On the surface, it appears that the benefit lies with the district heating company or CHP operator. As described in Chapter 2, TES allows operators the flexibility to determine when to burn expensive fuels to generate heat (and electricity) and ramp up and down expensive power plants OR when to use stored heat and low electricity prices to meet heat demand. There appears to be an economic case for CHP and district heating operators to install individual seasonal storages without government assistance.

However, as the example of the proposed North Harbour PTES has shown, when the storage is to be shared by multiple users the situation is less clear. Dong and Vattenfall, the CHP operators, as well as Kobenhavens Energi, a district heating company, would share the North Harbour storage. Allocating the costs of construction and the benefits from the operation between each user is highly complex (C.Marcus-Møller, Personal Communication, June 17, 2011). A further consideration is whether heat storage at the supply-side represents a public good. Provision of public goods is generally, though not neccesarily, the role of government rather than private enterpirse. This distinction has important implicatons for government policy makers. There are two indications that TES at the supply-side level represents a public good:

The first is that is that every hour of heat that is produced by RES electricity and heat pumps (either directly or from a TES), could represent one less hour produced from CHP or heat-only boilers that burn oil or coal (less important for biofuels). Thus fewer emissions and less C02 is released, clearly a benefit to society.

The second is that greater domestic use of electricity for heat generation reduces the variability of electricity spot prices. As discussed in Chapter 2, high amounts of RES in the electricity market currently results in volatile electricity prices, and future projections show this volatility is likely to increase. Variability prices make it difficult for business and government to make long term cost projections, and can inhibit new infrastructure development. Therefore, measures that reduce this uncertainty, e.g. by using electricity to produce heat, could also be a benefit to society.

Thus, if the benefits of using TES are strong enough for district heating companies to install and fund the system alone then it appears they should shoulder the cost. However, if the economic case for private installation of TES is not strong, or, if the heat storage is to be shared with multiple actors, or if there is obvious public benefit, then government may chose to assist the TES installation by financial contribution or by policy, such as mandating that TES be used.

7 Conclusions

7.1 Central problem addressed:

As described in Chapter 1, Öresund is emerging as an increasingly integrated region: socially, technically and economically. As a consequence of technical integration, energy management choices in one country can affect the electricity supply and market prices faced by another. The region already has a high percentage of intermittent RES due to Danish wind power. As the percentage of intermittent electricity generation rises, integrating systems so that electricity can be managed to the greatest level of 'social good' – as well as economic benefit, will require a variety of new technologies and methods– and sharing of existing ones.

TES is one method for better integrating intermittent RES. Energi Öresund identified that the TES technology and how it could assist RES integration is not well understood by all group members. Energi Öresund has made addressing this cognitive gap one of their key priorities.

This thesis provides insight into the integration of intermittent renewable electricity into electricity grids with particular attention to TES. It addresses the knowledge gap about TES identified by Energi Öresund, by describing the individual technologies used in Sweden and Denmark in the historical context, by describing methods for TES technology transfer and by discussing social impediments to adopting TES.

7.2 Main findings from the research:

The main findings from the research indicated that there is a strong case for using TES, that Sweden and Denmark have very different energy systems and TES technologies and that there is opportunity for technology transfer between the two countries.

7.2.1 Finding 1: Clear case for using TES

As discussed in Chapter 2, both Sweden and Denmark share a grid connection and buy and sell electricity on the Nord Pool electricity spot market. Today, high amounts of wind generation from Denmark at times can exceed domestic demand. Excess electricity is exported on Nord Pool, increasing the supply and causing market price fluctuations. This is compounded by heat-bound CHP generation during cold months, which adds more electricity and further volatility. Common weather patterns across Nord Pool states mean that in the future, as all members add their projected amounts of intermittent renewable energy sources; market prices will become increasingly responsive to weather conditions and increasingly volatile.

Unpredictable prices have a negative effect on the investment climate for new infrastructure and place additional pressure on the operators of traditional sources (CHP) to adjust power generation rapidly to meet demand. Traditionally Swedish and Norwegian hydropower was capable of balancing intermittent electricity supply from Denmark. However, as Sweden and Norway (and other Nord Pool members) increase their electricity generation from wind and solar and climate change affects the predictability of wet and dry years, buffering and storage from traditional sources like hydropower may not be adequate to dampen the volatility of electricity supply. Expansion of transmission capacity to other markets such as Germany may ameliorate the situation somewhat, but domestic solutions are needed.

Using some of the electricity to power highly efficient heat pumps for CHP / district heating at times when it would otherwise be exported could help stabilize volatile prices and reduce demand for heat generated from combusting fuels. Other options include smart grids, battery electric vehicles, or electricity storage.

Heat demand is not constant throughout the year. Thermal energy storage helps address this variability in demand by storing heat from when it is produced throughout the year to when it is needed in the cold months. While there are several technically sound TES methods, understanding the historical context and public acceptance of these techniques is critical before they can be implemented.

7.2.2 Finding 2: Sweden and Denmark use and developed very different technologies for generating and storing heat and electricity

In Sweden, electricity and heat are most often generated separately. Electricity generation mainly comes from hydro and nuclear power, while boilers, large heat pumps, and CHP provide district heating. Individual building heating include small heat pumps, direct electric heating and bio/fossil fuel furnaces. Borehole TES and Aquifer TES technologies are mainly used by building owners to manage heating and cooling demand and reduce dependence on relatively expensive and externally controlled district heating. A limited number of alternative examples, soon to be installed, such as the BTES storage system in Boxholm and the ATES in Lund show that the technology can be applied at the supply-side (district heating) level as well.

In contrast, in Denmark electricity and heat are primarily produced together via CHP. Wind provides some pure electricity production. Heating is done mostly at the district heating level, with some individual bio/fossil fuel furnaces. Pit TES has been primarily used as a supply side management option for solar thermal district heating systems, although an un-used Copenhagen dry-dock may be converted to large Pit TES system for CHP district heating. There has been little use of TES for building-level demand-side management in Denmark.

7.2.3 Finding 3: Path Dependant evolution of each countries energy system had a strong impact on both generation and storage technologies developed

Sweden in the 1980s was characterized by an abundant supply of electricity from hydropower and nuclear power. Inexpensive electricity provided conditions conducive to the first direct electrical (resistance) heating and then to the development of heat pump technology for both building and district heating level. Sweden's extensive mining and geotechnical capacity aided the installation of shallow geothermal heat pumps. TES technologies such as BTES and ATES built on this experience and used similar techniques to store heat. Although mostly used at the building level, ATES and BTES can also be used at the district heating level. In Sweden using electricity for heating has long had widespread public acceptance – in the past using direct electricity heating, more recently applying a range of heat pump technologies.

In Denmark, without hydro or nuclear power, CHP electricity from burning fossil fuels has historically been expensive. Government requirement for heat consumers to hook up to district heating or natural gas heating where they are available reduced individual heating technology development. Renewable energy investment helped establish wind power and solar thermal district heating, and PTES developed as a method of storing solar heat from summer to winter. Government discouragement of using electricity for heating contributed to a very low use of heat pumps and poor public understanding and acceptance of this use of electricity despite the high efficiency.

7.2.4 Finding 4: The research found a number of areas where technology transfer is possible and mutually beneficial

Applications of technologies from either jurisdiction to the other will require transfer of hardware, software (skills, knowledge) and orgware (e.g. regulations, incentives, 'standard practice', etc.) Chapter 3 described the differences in TES technology used in Sweden and Denmark that represent significant potential for technology transfer. Chapter 5 described how technology transfer could occur. The hardware and software components are relatively straightforward to transfer and are technically suitable for application in either country. However, research indicates that both the explicit and implicit social rules and customs (orgware) can constrain applications and would need significant attention if technology transfer is to effectively take place.

7.3 Conclusions:

This research found that there is a strong case for mutual beneficial use TES in both Sweden and Denmark and that transferring the technology itself is not the main challenge. Engineers on either country have the capacity to design and build such systems. However, the research clearly indicates that the fundamental issue is **societal acceptance of using electricity to produce heat in the first place**. This is particularly applicable to Denmark.

TES is a method that facilitates the use of electricity for heating– often by the application of high yield electrical heat pumps. In Sweden, where widespread use of electricity for heating via heat pumps at various levels occurs already, public acceptance of such measures already exists. In Denmark however, multiple personal interviews confirmed that Government policies started in the 1970s to discourage the use of electricity for heat (as both an energy conservation measure and a promotion of efficient CHP) have had a significant, long lasting effect on the Danish perception of that use for electricity. **This despite the fact that the paradigm for using electricity for heating has fundamentally changed with the advent of increasing amounts of renewable wind electricity and the emergence of high yield heat pump technologies.**

Somewhat perversely, Denmark is also the country where using excess wind electricity for heat would be the **most applicable** as it has by far the highest wind generated supply and is dealing with the problems of excess electricity today. Converting some of this capacity to heat and storing it in Denmark makes sense, yet it is Sweden that has far greater acceptance of using electricity for heat (via heat pumps) and widespread distribution of technologies to make use of it. **Thus this work suggests the Danish aversion to using 'electricity for heat' must be addressed first, before any discussion about TES installation can prove meaningful.**

There is clear indication that greater interaction between Sweden and Denmark can help address this issue and there are roles for government, industry and Energi Öresund. Some of the best examples of each country's TES technologies were developed and exist in the region. The key attribute Sweden brings to the relationship is exactly what Denmark needs – a public comfortable with and experienced using electricity for heating (via heat pumps), and technologies and methods to achieve this. Assuming that the potential cost and benefits have been fully explored, the following section includes some brief recommendations.

7.4 Recommendation:

7.4.1 What Governments can do:

For example:

- Create awareness programs for businesses, industrial actors and the public to change the way using ‘electricity for heating’ is perceived – recent technological advances show it can in fact be advantageous if it is used with wind electricity and heat pumps
- Promote heat-pumps as an effective method of using electricity for heating currently available
- Examine legislative or regulatory barriers to heat pump applications **or** legislation that restricts the use of heat pumps
- In Denmark, consider relaxation of some “obligation to connect” restrictions for buildings
- Encourage Öresund universities to continue research into efficient electric heating methods and perhaps combinations of technologies that includes district heating
- Create economic modeling of balancing systems including TES
- Continue to discourage fossil fuel use for heating by increasing the cost (i.e. tax)

7.4.2 What businesses can do:

For example:

- Industry actors and energy service companies dealing with heat pump technologies (and or ground source heating technologies) could improve the acceptance and understanding of these technologies, particularly in Denmark. Such work would need to address both political understanding and public acceptance of the method of supplying electricity and acceptance of the current technology. Some examples of actions in this regard include: promoting the technology though promotional materials, including links on the Danish Energy Agency and Danish Heat Pump Associations websites, creating trade associations, and participating at annual renewable energy /heating /CHP conferences and trade shows
- In the case of ATES or BTES in Denmark, use standardized, simplified images to demonstrate the basic concepts of the technology and adjust the technical language to suit the audience
- Keep industrial and individual customers and the public informed of changes and reasons though mail outs, TV ads and webpage updates
- Conduct open house at new or upgraded energy facilities
- Offer facility tours to local schools on either side of bridge
- Collaborate with Öresund universities on research needs and applications

7.4.3 What Energi Öresund can do:

For example:

- As they operate in the region where some of the best examples of Swedish and Danish TES technologies exist, facilitate study tours and exchanges between Swedish and Danish businesses and municipalities
- Coordinate exchange and competitions between Öresund universities
- Ensure local and national governments are well informed on the latest developments in heat pump and other electric heating technology on either side of the sound
- Ensure local and national governments have up-to-date technical information and are

aware of laws and other restrictions that might inhibit using electricity for heating

- Continue to coordinate academic research and masters thesis projects on the topic, offer co-ops for engineering, economic and business students
- Lobby for grants to continue research into other, potentially more cost effective TES technologies
- Keep public on both sides of the Sound informed
- Bring economists on board or on staff to evaluate relative costs and provide fiscal information to industry and Government

7.5 Suggestions for future research:

7.5.1 Delineate of cost / benefit sharing of TES installation:

This paper has not attempted to define the responsibly for the costs of TES installation. Nor has it attempted to calculate the costs to install and operate a TES system at the different user levels – or the financials benefit of using TES. However, clearly both need to be addressed before technology transfer can take place. Such research would help solidify the economic case for TES installation.

7.5.2 Look beyond Scandinavia for TES comparison:

This paper has focused primarily on technologies currently used in Sweden and Denmark as a potential for information and business opportunity sharing within the Öresund Group. However, as the research has indicated, Sweden and Denmark have very different energy systems and markedly different attitudes towards using electrical heating. Future research could examine if Denmark shares more energy commonality and more suitable technology transfer with countries such as Germany or the Netherlands, than with Sweden.

7.5.3 Consider Distributed of Heat Generation and Storage:

This paper has focus primarily on the case of using of TES as a supply-side management technique. However, TES as a demand side management technique may hold advantages as well, especially in a future 'smart heat' system. In this situation, customers may be able to make heat when the electricity price drops, and store it themselves. Furthermore, future smart heat systems could allow micro heat generation and selling into the heat "grid" of district heating, the same way as micro generation of electricity. In such a scenarios, TES could be used at both supply and demand side.

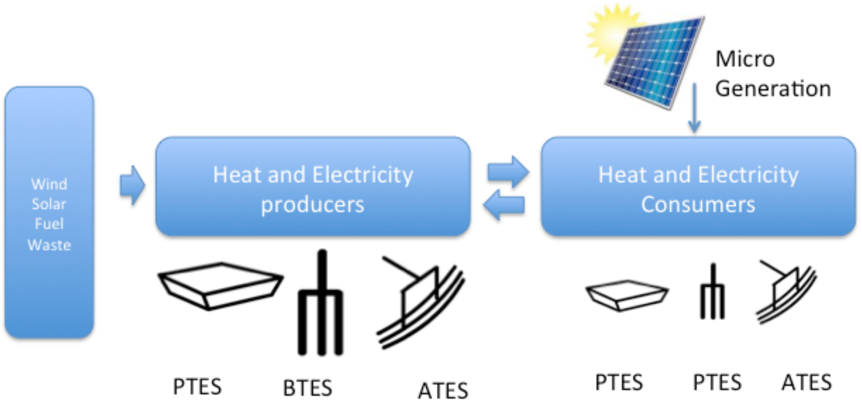


Figure 7-1 'Potential future supply and demand side TES'

Source: 'Author'

7.6 Final remarks:

This work has presented a method for comparing energy systems and outlined some considerations for technology transfer that are equally valid for other countries. As more countries deal with the issue of intermittent renewable energy integration, new solutions are likely to arise. Both Sweden and Denmark happen to be in "first-movers" position regarding renewable energy. Many countries can learn from the Danish and Swedish experiences, challenges and successes.

Bibliography

Aldrich, H. E., & Fiol, M. C. (1994). Fools Rush In? The Institutional Context of Industry Creation. *Academy of Management Review , 19* (4), 645-670.

American Society of Mechanical Engineers. (2011). Market Based Allocation of Power in the Smart Grid. *American Contol Conference.* San Fransisco.

Arcon Solar. (2011). *District Heating Plants.* Retrieved 08 11, 2011 from Arcon Solar: Refrence Projects: http://www.arcon.dk/referencer%20v2/Varmevaerker.aspx

Arthur, B. (1989, 11 26). Positive Feedbacks in the Economy. *Scientific American* , 92-99.

Atlas Copco. (2011). *About us.* Retrieved 08 31, 2011 from http://www.atlascopco.se/sesv/

Avfall Sverig. (2011). *Towards a greener future with Swedish waste-to-energy: The worlds best example.* Avfall Sverig (Swedish Waste Management). Malmo: Avfall Sverig.

Barth, J. (2011, 08 19). Founder, GeoTech. (M. Harris, Interviewer) Lund, Sweden.

Bayer, P., Blum, P., & Haehnlein, S. (2010). International legal status of the use of shallow geothermal energy. *Renewable and Sustainable Energy Reviews , 14*, pp. 2611-2625.

Bergek, A. (2002). *Shaping and Exploiting Technological Opportunities: The Case of Renewable E nergy Technology in Sweden.* Chalmers University of Technology, Department of Industrial Dynamics. Göteborg, Sweden: Chalmers University of Technology Press.

Bergek, A., & Jacobsson, S. (2002). The emergance of a growth industry: a comparative analysis of the German, Dutch and Swedish wind turbine industries. In J. S. Metclafe, & U. Cantner (Eds.), *Change, Transformation and Development.* Berlin, Germany: Physica Verlag.

Bergek, A., Jacobsson, S., & Sandén, B. (2008). Legitimation and development of positive externalities: Two key processes in the formation phase of technological innovation systems. *Technology Analysis & Strategic Management , 20* (5), 575-592.

Bergland, C. (2011, 06 27). Project Manager. (M. Harris, Interviewer). Stockholm, Sweden

Beuse, E. (2010). A True Fairy Tale on Solar Heating. (L. Gullev, Ed.) *Hot Cool: International Magazine for District Heating and Cooling* (3).

Brandt-Sørenson, J. (2011, 05 21). Project Developer, VEKS. (M. Harris, Interviewer). Copenhagen, Denmark

Brazilian et al. (2008). *Considering technology within the UN climate change negotiations.* Energy Research Centre of the Netherlands, Petten.

Brix-Thomsen, A. (2011, 05 10). Executive Climate Officer, Copenhagen Municpality. (M. Harris, Interviewer) Copenhagen, Denmark.

Brown, S., Pyke, D., & Steenhof, P. (2010). Electric vehicles: The role and importance of standards in an emerging market. *Energy Policy , 38*, 3797–3806.

CESPOS. (2009). *Wind Energy: The Case of Denmark*. Center for Politiske Studier. Copenhagen: Center for Politiske Studier.

Cleasson, J. (2011). Professor of Thermodynamics - Lund University & Chalmers University. (M. Harris, Interviewer) Lund, Sweden.

Danish Energy Agency (2). (2010). *Danish Energy Policy 1970-2010.* The Danish Energy Agency, Copenhagen.

Danish Energy Agency (2). (2009). *Denmark's Oil and Gas Production and Subsoil Use.* Danish Energy Agency, Copenhagen.

Danish Energy Agency (2). (2011). *Public Heat Planning 1970's and 1980's.* Retrieved 08 13, 2011 from Danish Energy Agency: Heat Supply: http://www.ens.dk/en-US/supply/Heat/Goals_and_means/planning/Sider/Forside.aspx

Danish Energy Agency (3). (2010). *Wind Turbines in Denmark*. The Danish Energy Agency, Copenhagen.

Danish Energy Agency. (2011). *Basic Facts on Heat Supply in Denmark*. Retrieved 08 12, 2011 from http://www.ens.dk/en-US/supply/Heat/Basic_facts/Sider/Forside.aspx

Danish Energy Agency. (2010). *Technology Data for Energy Plants.* Energinet.dk. Copenhagen: Danish Energy Agency.

Danish Energy Agency. (2009). *The History of Danish Support for Wind Power.* Copenhagen: The Danish Energy Agency.

David, P. A. (1985). Clio and the Economics of QWERTY. *The American Economic Review , 75* (2), pp. 332-337.

DBDH. (2011). *Danish Board of District Heating.* Retrieved 08 13, 2011 from Danish District Heating History: http://www.dbdh.dk/artikel.asp?id=464&mid=24

DESIRE. (2007). *Long-term perspectives for balancing fluctuating renewable energy sources.* DESIRE: Desemination Stratedy on Electricity Balancing Large Scale Integration of Renewable Energy, University of Kassel, Department of Efficient Energy Conversion . Kassel: University of Kassel .

Diget, P. (2010). System Integration Between Wind and District Heating. (L. Gullev, Ed.) *Hot:Cool The International Magazine of District Heating and Cooling* .

DiMaggio, P. J., & Powell, W. W. (1983, April). The Iron Cage Revisited: Institutional Isomorphism and Collective Rationality in Organizational Fields. *American Sociological Review* , 147-160.

Dincer, I., & Rosen, M. A. (2011). *THERMAL ENERGY STORAGE: SYSTEMS AND APPLICATIONS* (2nd ed.). Chichester, West Sussex, United Kingdom: John Wiley & Sons, Ltd.

ECES. (2007, 03 12). *Energy Storage: Storage Techniques*. Retrieved 09 27, 2011 from International Energy Agency - Energy Conservation through Energy Storage: International Energy Agency

Ellehauge, K., & Pedersen, T. E. (2007). *Solar heat storages in district heating networks.* Energinet.dk. Århus/Lyngby: Ellehauge & Kildemoes; COWI A/S.

Enerdata. (2008). *European Energy & CO2 Data.* Retrieved 08 12, 2011 from Enerdata: Global Energy Intellegence: http://www.enerdata.net/enerdatauk/knowledge/subscriptions/database/energy-market-data-and-co2-emissions-data.php?zone=europe

EnergyMap Denmark. (2011). *Technology Areas: Combined Heat and Power (CHP) Plants.* Retrieved 08 12, 2011 from EnergyMap Denmark: http://energymap.dk/Technology-Areas/Efficient-Energy-Production/Combined-Heat-and-Power-%28CHP%29-Plants

Enslow, R. (2010). *China, Norway and Offshore Wind Development* . World Wildlife Federation Norway and Azure International, Oslo.

Ericsson, K. (2009). *Introduction and development of the Swedish district heating systems. Critical factors and lessons learned.* Lund, Sweden: Lunds Univeristy / European Commission.

Eurolectric. (2011). *RES Integration and Market Design: are Capacity Remuneration Mechanisms needed to ensure generation adequacy?* . Eurolectric. Brussels: Union of the Electricity Industry - Eurolectric.

European Comission. (2011). *European Comission Climate Action.* Retrieved 09 07, 2011 from Emissions Trading System: http://ec.europa.eu/clima/policies/ets/index_en.htm

European Environment Agency. (2011). *The electric car — a green transport revolution in the making?* Retrieved 08 20, 2011 from The European Environment Agency: http://www.eea.europa.eu/articles/the-electric-car-2014-a-green-transport-revolution-in-the-making

European Wind Energy Association. (2011). *Pure Power Wind energy targets for 2020 and 2030* . European Wind Energy Association. Brussels: European Wind Energy Association.

EWEA. (2005). *Large Scale Integration of Wind Energy in the European Power Supply: analysis, issues and recommendations.* European Wind Energy Agency, Brussels.

Fröhlingsdorf, M. (2011, 04 18). NIMBY Protests Threaten Germany's Energy Revolution. *Der Speigel International* .

Garud et al. (2010). Path Dependence or Path Creation? *Journal of Management Studies* , *47* (4).

GEOTRAINET. (2011). *GeoTrainet Training Manual for Designers of Shallow Geothermal Systems.* (M. McCorry, & G. Jones, Eds.) Brussels, Belgium: GEOTRAINET.

Gierow, M. (2011, 05 18). Project Manager Lunds Energi. (M. Harris, Interviewer) Lund, Sweden.

Government of Denmark. (2011). *Energy Stragegy 2050: From Coal, Oil and Gas to Green Energy.* Government of Denmark, Copenhagen.

Harboe, C. (2011, 06 15). Project Manager, Energi Oresund. (M. Harris, Interviewer) Copenhagen, Denamark.

Hathaway, O. (2001). Path Dependence in the Law: The Course and Pattern of Legal Change in a Common Law System. *86* (2).

Heiskanen et al. (2011, 2 08). Path creation for sustainable consumption: Promoting alternative heating systems in Finland. *Journal of Cleaner Production* .

Helfat, C. (1994). Evolutionary trajectories in petroleum firm R&D. *Management Science , 40*, 1720-1247.

Heller, A. (2000). 15 Years of Experiance in Central Solar Heating in Denmark. *Solar Energy , 69* (6), 437-447.

Hellström, G. (2008). *Energlager i Mark – Olika systemlösningar (Energy Strorgae in Ground - Various Solutions).* Luleå University of Technology. Luleå: Luleå University of Technology Press.

Ibsen, C., & Poulsen, L. (2007). Path dependence and independent utility regulation: The case of Danish energy and telecommunications regulation. *Scandinavian Economic History Review , 55* (1), 41-63.

IEA. (2001). *Technology Without Boarders.* Paris: International Energy Agency.

IF Tech. (2005). *Underground Thermal Energy Strorage for Efficiant Heating and Cooling of Buildings.* IF TECH.

IIASA. (2006, 06 13). *What is Technology ?* Retrieved 08 05, 2011 from International Institute for Applied Systems Analysis (IIASA): http://www.iiasa.ac.at/Research/TNT/WEB/Page10120/page10120.html

International Atomic Energy Agency. (2009). *Country Report: Sweden.* International Atomic Energy Agency, Publications. United Nations International Atomic Energy Agency.

INTERREG IV. (2011, 08 04). *About the programme: Helping Regions share solutions.* Retrieved 08 04, 2011 from http://www.interreg4c.eu/

IPCC, WMO, UNEP. (2000). *Methodological and Technological Issues in Technology Transfer* . Intergovernmental Panel on Climate Change, World Maritime Organization, United Nations Envrionment Programme. IPCC Press.

Johnson, A., & Jacobsson, S. (2001). Inducement and Blocking Mechanisms in the Development of a New Industry: the case of renewable energy technology in Sweden. In R. Coombs, K. Green, A. Richards, & V. Walsh, *Technology and the Market: Demand, Users and Innovation.* Cheltenham, Glos., UK: Edward Elgar Publishing.

Johnson, A., & Jacobsson, S. (2001). Inducement and Blocking Mechanisms in the Development of a New Industry: The Case of Renewable Energy Technology in Sweden. In R. Coombs, & et al (Eds.), *Technology and the Market: demand, users and innovation* (p. 307). Cheltenham, Glos, UK: Chalmers University of Technology Press.

Københavns Energi. (2011). *Heat Storage in North Harbour (Varmelager i Nordhavn).* Copenhagen: Corporate presentation.

Kåberger, T. (2002). Swedish nuclear power and economic rationalities. *Energy and Environment , 13* (2), 193-4.

Karlsson et al. (2003). *Heat Pump Systems in Sweden: Country Report for the International Energy Agency.* Swedish National Testing and Research Institute & Chalmers University. International Energy Agency.

Kielsgaard, H., & Nordgaard, H. (1981). *Stratified Operation of a 500m3 Test Pit.* Danish Technical Univerisity, Thermal Insulation Laboratory. Lyngby, Denmark: Danish Technical University Press.

Kivimaa et al. (2010). P*ath dependence and path creation in energy systems: competing theories and the influence of system interlinkages.* Aalto University School of Economics & Finnish Environment Institute .

Lafferty, W. M., & Ruud, A. (2008). *Promoting Sustainable Electricity in Europe Challenging the Path Dependence of Dominant Energy Systems.* Cheltenham, Glos, UK: Edward Elgar Publishing Limited.

Larke, M. B., & Lund, H. (2008). The effectiveness of storage and relocation options in renewable energy systems. *Renewable Energy , 33*, 1499-1507.

Larsen, A. (2011, 07 21). Energy Analyst : Ea Energy Analytics. (M. Harris, Interviewer) Copenhagen, Denmark.

Lund, J. W., Freeston, D. H., & et al. (2010). Direct Utilization of Geothermal Energy 2010 Worldwide Review. *Proceedings World Geothermal Congress 2010.* Bali, Indonesia: World Geothermal Congress.

Lund, J., Sanner, B., & et al. (2004, March). Geothermal (Ground- Source) Heat Pumps: A World Overview. *Geo-Heat Center Quarterly Bulletin* .

Lunds Energi. (2010). *Annual Report 2010.* Lunds Energi , Lund.

Marcus-Møller, C. (2007). *CHP in a liberalised power market.* Danmarks Tekniske Universitet, Institut for Mekanik, Energi og Konstruktion. Copenhagen: DTU Press.

Marcus-Møller, C. (2011, 06 17). Project Leader. (M. Harris, Interviewer) Copenhagen, Denmark.

Mathiesen, B. V., & Lund, H. (2009). Comparative analyses of seven technologies to facilitate the integration of fluctuating renewable energy sources. *IET Renewable Power Generation , 3* (2), 190-204.

Munster, E., & Lund, H. (2003). Management of surplus electricity-production from a fluctuating renewable-energy source. *Applied Energy , 76*, 65-74.

Nord Pool Spot. (2011, 08 04). *Nord Pool: About Us.* Retrieved 08 04, 2011 from http://www.nordpoolspot.com/about/

Nordell, B., Grein, M., & Kharseh, M. (2007). Large-scale Utilisation of Renewable Energy Requires Energy Storage. *International Confrence forRenewable Energies and Sustainable Development.* Lulea: Department of Architecture and Infrastructure Luleå University of Technology .

North, D. (1990). *Institutions, Institutional Change and Economic Performance.* Cambridge: Cambridge University Press.

NRCAN. (2004). *Heating and Cooling With a Heat Pump* . Natural Reasources Canada, Energy Efficiancy. Ottawa: Government of Canada.

Nylander, A. (2011, 07 04). Energy Strategist. (M. Harris, Interviewer) Lund, Sweden.

Öhrström, P. (2011, 05 18). Distrit Heating Consultant. (M. Harris, Interviewer) Lund, Sweden.

Oresunds Regionen. (2011). *About.* Retrieved 08 04, 2011 from Oresunds regionen web portal: http://www.oresundsregionen.org/

Pöyry. (2011). *The challenges of intermittency in North West European power markets.* PÖYRY Management Consulting.

Pacey, A. (1983). *The culture of technology.* Cambridge, MA: MIT Press.

Page, S. E. (2006). Path Dependence. *Quarterly Journal of Political Science* (1), 87-115.

Page, S. (1999). On the Emergence of Cities. *Journal of Urban Economics , 45*, pp. 184-208.

Parker, T. (2011, 03 23). European Spallation Source Energy Manager. (M. Harris, Interviewer) Phone interview conducted in Lund with Interviewee stationed in Tennesse, US, Skane, Sweden.

Peck et al. (2009). Examining understanding, acceptance, and support for the biorefinery concept among EU policy-makers. *Biofuels, Bioproducts and Biorefineries , 3*, 361-383.

Peck, P., Berndes, G., & Hektor, B. (2011). *Mobelizing Global Supply Chains - Keys to Unlocking the Potential of Bionergy.* International Institute for Industrail Environmental Economics at Lund University for Swedish Energy Agency. Lund: Swedish Energy Agency.

Perez, C. (1983). Structural change and assimilation of new technologies in the economic and social systems . *Futures , 15* (4), 357-375.

Petersen, M., & Aagaard, J. (2004). Heat Accumulators. *Hot Cool: Danish Board of Distict Heating.*

Petersson, H. (2011, 07 1). Enegineer - Akademika Hus. (M. Harris, Interviewer) Lund, Sweden.

Puffert, D. (2010, 02 1). *Path Dependence.* Retrieved 09 28, 2011 from EH.Net - Economic History Association Encyclopedia: http://eh.net/encyclopedia/article/puffert.path.dependence

Sørensen, P., Holm, L., & Jensen, N. (2008). *Water Storages, Solar thermal and Heat pumps in District Heating.* EuroSun 2008 Confrence paper, PlanEnergi Consulting, Skørping, Denmark.

Scania. (2006). *Histrory of Scanian Wars*. Retrieved 09 04, 2011 from Scania : Skaneland. A region in europe: http://www.scania.org/facts/pages/wars.htm

Schumpeter, J. (1934). *The Theroy of Economic Devlopment: An inquiry into Profits, Capital, Credit, Intrest and the Business Cycle* ((1949 ed.) ed.). Cambridge, MA: Harvard University Press.

Scott, W. R. (2001). *Institutions and Organizations* (2nd Edition ed.). Thousand Oaks, CA: Sage Publications, Inc.

Sillman, F., Baylin, R., & Sanford, M. (1980). *ANNUAL-CYCLE THERMAL ENERGY STORAGE FOR A COMMUNITY SOLAR SYSTEM: DETAILS OF A SENSITIVITY ANALYSIS*. Solar Energy Research Institute. U.S. Department of Energy.

SmartGrids ETP. (2011). *Smart Grids European Technology Platform*. Retrieved 08 20, 2011 from The European Technology Platform for Electricity Networks of the Future: http://www.smartgrids.eu/

Stignor, C., Lindahl, M., Alsbjer, M., Nordman, R., Rolfsman, L., & Axell, M. (2009). *Next generation heat pump systems in residential and commercial premises (Nästa generations värmepumpssystem i bostäder och lokaler))*. SP Sveriges Tekniska Forskningsinstitut, Borås, Sweden.

Svenskvattenkraft. (2011). *Hydropower in Sweden*. Retrieved 09 12, 2011 from Svenskvattenkraft (The Swedish Hydropower Association): http://www.svenskvattenkraft.se/default.asp?L=EN

Sweco. (2008). *Sweco designing world's largest thermal energy storage facility*. Retrieved 08 26, 2011 from SWECO News 2008: http://www.swecogroup.com/en/Sweco-group/Press/News/2008/Category-1/Sweco-designing-worlds-largest-thermal-energy-storage-facility/

Swedish Bioenergy Association. (2011, 07 05). *SVEBIO - The Swedish Bioenergy Association*. Retrieved 07 05, 2011 from Bio energy facts: http://www.svebio.se/english/bioenergy-facts

Swedish Energy Agency. (2010). *Energy in Sweden 2010*. Swedish Energy Agency. Eskilstuna: Statens Energimyndighet.

Sydow et al. (2005). Organizational Paths: Path Dependency and Beyond. *21st EGOS Colloquium*. Berlin.

Tenberg, P. (2011, 07 05). Geophysical Engineer, Vattenfall . (M. Harris, Interviewer) Malmö, Sweden.

The Economist. (2011, June 16). Tilting at windmills Teething troubles in the clean-energy sector. *The Economist Magazine* .

Togeby et al., M. (2009). *Better Integration of Wind (Translated from Danish: Bedre integration af vind)*. Ea Energianalys and Risø DTU for Energistyrelsen Denmark and Skatteministeriet Denmark. Copenhagen: Ea Energianalys and Risø DTU.

Trendens Öresund. (2011, 1 1). Retrieved 7 4, 2011 from Trendens Öresund: http://www.tendensoresund.org/en/key-map

UN. (2008). *Climate Change: Technology Development and Technology Transfer.* United Nations Department of Economic and Social Affairs.

Vad Mathiesen, B., & Lund, H. (2004). *Fuel-efficiency of hydrogen and heat storage technologies for integration of fluctuating renewable energy sources.* Retrieved 05 13, 2011 from Aarlborg University: vbn.aau.dk/en/publications/fuelefficiency-of-hydrogen-and-heat-storage-technologies-for-integration-of-fluctuating-renewable-energy-sources

Varmpumpordningen. (2011). *Om Varmepumper.* Retrieved 08 19, 2011 from Varmpumpordningen: http://www.vp-ordning.dk/info.asp

Vartiainen et al. (2011). *Energy storage technologies and business opportunities* . Corporate Presentation, Fortum AB, Stockholm.

Vartiainen, E. (2011, 06 28). Research and Devlopment Manager Fortum. (M. Harris, Interviewer) Stockholm via video conference from Espoo, Finland, Sweden.

Voytenko, Y., & Peck, P. (2011). Organisational Frameworks for Straw-Based Energy Systems in Sweden and Denmark. *Biomass and Bioenergy* .

Wall, T. (2011, 06 28). Research and Devlopment Manager, Fortum. (M. Harris, Interviewer) Stockholm, Sweden.

Wassenber, F. (2009). *Transmission system expansion in Germany: Underground cable or overhead lines?* Retrieved 08 18, 2011 from WIRE: Dusseldorf: http://www.wire.de/cipp/md_wiretube/custom/pub/content,oid,7766/lang,2/ticket,g_u_e_s_t/~/Transmission_system_expansion_in_Germany_Underground_cable_or_overhead_lines.html

Williams, C. (2011, 06). *What the Geothermal Heat Pump Industry Can Learn From the Solar Pros.* Retrieved 09 20, 2011 from Renewable Energy World: http://www.renewableenergyworld.com/rea/blog/post/2011/06/what-the-geothermal-heat-pump-industry-can-learn-from-the-solar-pros

Wilson, J. F. (2010, May). Reconsidering Resource Adequacy: Capacity planning for the smart grid. Part 2. *Public Utilities Fortnightly* .

Winner, L. (1978). *Autonomous technology: technics-out-of-control as a theme in political thought.* Cambridge, MA: Massetusets Institute of Technology.

World Nuclear Association. (2011). *Nuclear Power in Sweden.* Retrieved 08 14, 2011 from World Nuclear Associaton: http://www.world-nuclear.org/info.inf42.html

World Wind Energy Association. (2011, April). *World Wind Energy Report 2010* .

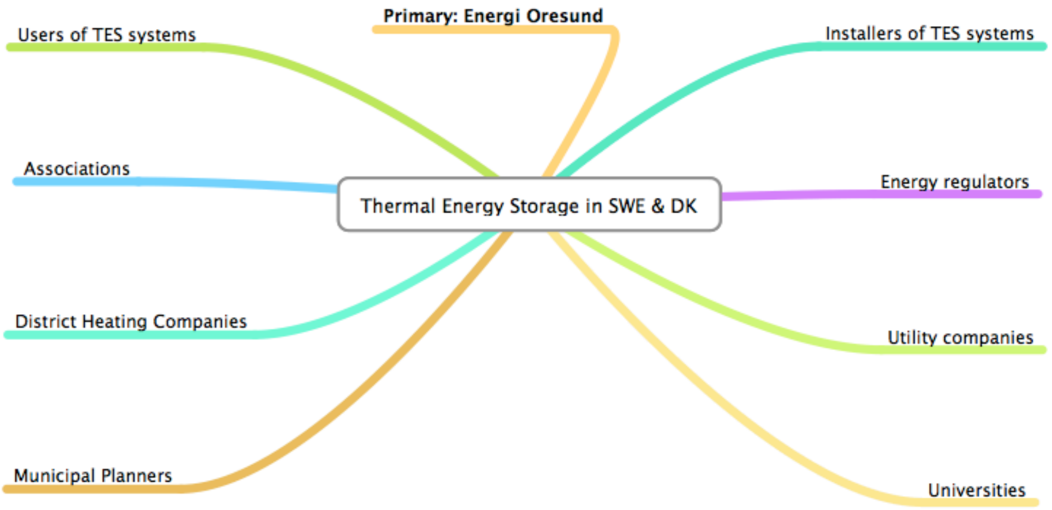
Yim, M.-S. (2010). *Nuclear Non-Proliferation and the Future Expansion of Nuclear Power.* North Carolina State University , Department of Nuclear Engineering , Chapel Hill.

Appendix A: Energi Öresund Group Members

Country: Denmark	Organization Type:
City of Copenhagen	Municipal government
Alberton Varmeværk	CHP and District heating producer
Amagerforbrænding	Waste incineration
Ballerup municipality	Municipal government
Kobenhavens Energi	CHP and district heating producer
Vestegnens Cogeneration Company	CHP producer
Copenhagen Cleantech Cluster	Business development group
Aalborg University	Academic institution

Country: Sweden	Organization Type:
City of Malmo	Municipal government
Skåne Energy Agency	State government energy agency
Kristianstad Municipality	Municipal government
Lund Municipality	Municipal government
Lunds Energi	District heating company producer
International Institute for Industrial Environmental Economics	Academic institution
Lund University	Academic institution
Skåne Sustainable Business Hub	Business development group

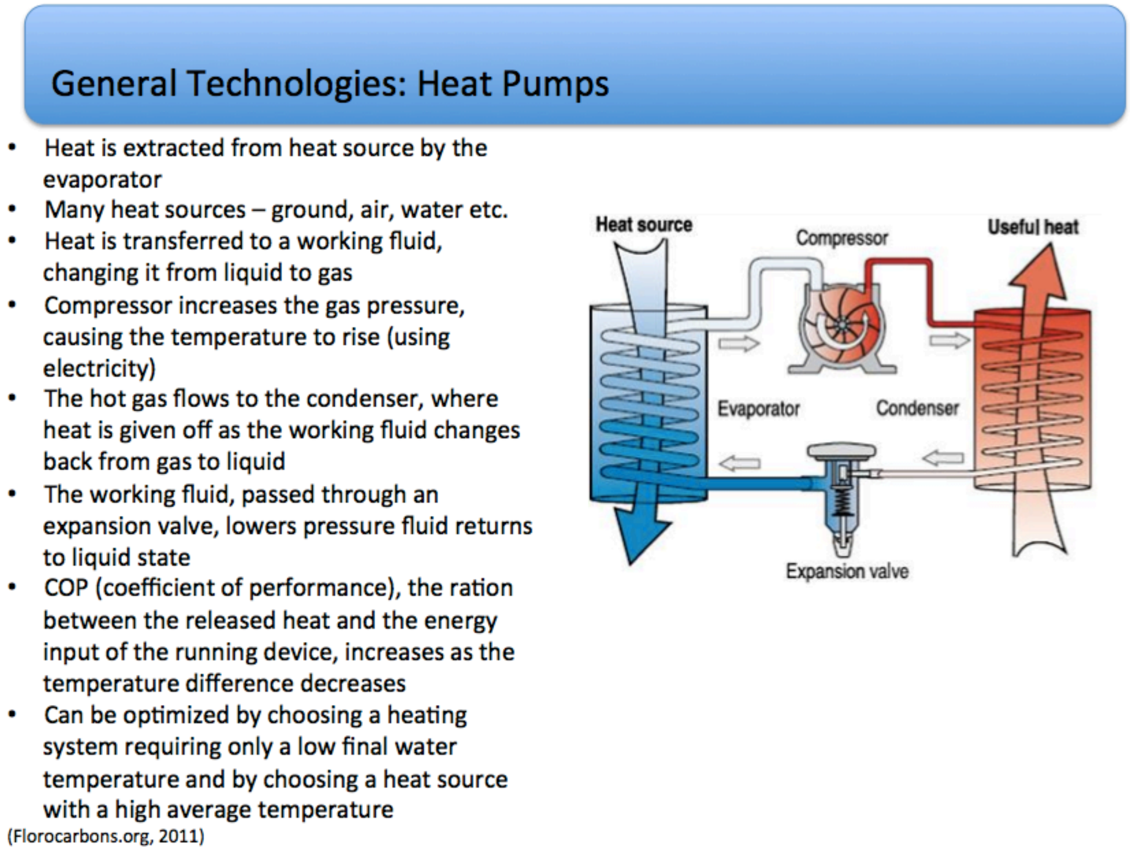
Appendix B: Abbreviated Stakeholder Map



Appendix C: Stakeholder Interviews:

First Name	Last Name	Title	Compay/ Organization	Date Met:
Casper	Harboe	Project Manager	Energi Øresund	10-May-11
Anders	Brix-Thomsen	Executive Climate Officer	City of Copenhagen	10-May-11
Matin	Gierow	Project Leader, Heat Production	Lunds Energi	18-May-11
Peter	Öhrström	Energy Consultant	BizKat	18-May-11
Linda	Birkedal	Environmental Strategist	Lund Municipality	20-May-11
Thomas	Parker	Energy Manager	European Spalation Source	23-May-11
Bernd	Möller	Associate Professor, Dipl.-Ing., Ph.D	Aalborg University	01-Jun-11
Catarina	Marcus-Møller	Project Leader	Københavns Energi A/S	17-Jun-11
Jennifer	Lenhart	Project Coordinator	Malmo Municipality (Previous)	21-Jun-11
Jens	Brandt Sørensen	Project Devlopment	Veks	21-Jun-11
Johan	Claesson	Professor	Lund University	23-Jun-11
Marie	Fossum	VP Business Development and R&D	Fortum AB	27-Jun-11
Bengt	Johansson	Business Development	Fortum Distribution	27-Jun-11
Christer	Bergerland	R & D	Fortum Distribution	27-Jun-11
Osmo	Huhtala	R&D Manager Nordic	Fortum Corporation	28-Jun-11
Thomas	Wall	R&D Manager Sweden	Fortum AB	28-Jun-11
Eero	Vartiainen	R&D Manager Finland	Fortum Corporation	28-Jun-11
Hans	Petersson	Driftingenjor	Akademiska Hus	01-Jul-11
Anders	Nylander	Achitect and Energy Expert	Skane Energy Agency	04-Jul-11
Per-Johan	Wik	Project Manager	Skane Energy Agency	04-Jul-11
Per	Tengborg	Geotechnical Engineer	Vattenfall	04-Jul-11
Kalle	Lundstrom	Energy Strategy	Vattenfall	04-Jul-11
Anders	Larson	Energy Analyist	Ea Energy Anylitics	21-Jul-11
Johan	Barth	Geologist, Founder GeoTech	GeoTech	19-Aug-11

Appendix D: Technology Reader



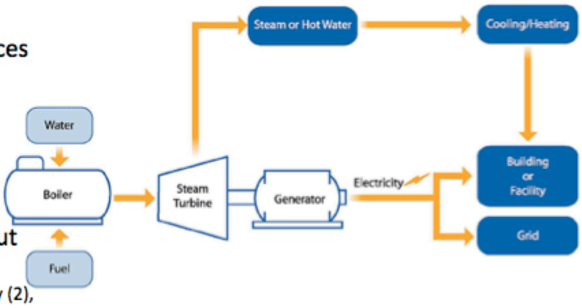
General Technologies: Heat Pumps

- Heat is extracted from heat source by the evaporator
- Many heat sources – ground, air, water etc.
- Heat is transferred to a working fluid, changing it from liquid to gas
- Compressor increases the gas pressure, causing the temperature to rise (using electricity)
- The hot gas flows to the condenser, where heat is given off as the working fluid changes back from gas to liquid
- The working fluid, passed through an expansion valve, lowers pressure fluid returns to liquid state
- COP (coefficient of performance), the ration between the released heat and the energy input of the running device, increases as the temperature difference decreases
- Can be optimized by choosing a heating system requiring only a low final water temperature and by choosing a heat source with a high average temperature

(Florocarbons.org, 2011)

General Technologies: Combined Heat and Power

- The simultaneous production of electricity and heat
- Recovers the heat normally lost in electricity generation for use in cooling, heating, and dehumidification
- Heat is used directly for district heating
- Compared with separate generation of electricity and heat, CHP systems can operate at more than 80 percent (overall) efficiency
- Most effective when heat demand is nearby
- Can be designed to run on a variety of fuel sources
- Backpressure plants produce fixed ratio of heat and electricity from fuel
- Condensations plants can can vary production between producing strictly heat or strictly electricity
- Higher single efficacy if produce one or other, but lower overall efficiency

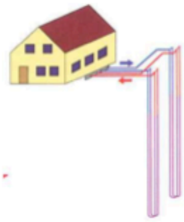


(US Department of Energy, 2011); (EPA, 2011) (Danish Energy Agency (2), 2010)

General Technologies: Shallow geothermal heating

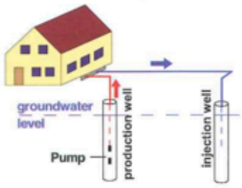
Horizontal loop shallow geothermal heating

- Ground loop is installed approximately 1m depth
- Requires large amount of space
- Heat source is solar heat from the sun
- Not used for storage



Borehole shallow geothermal heating

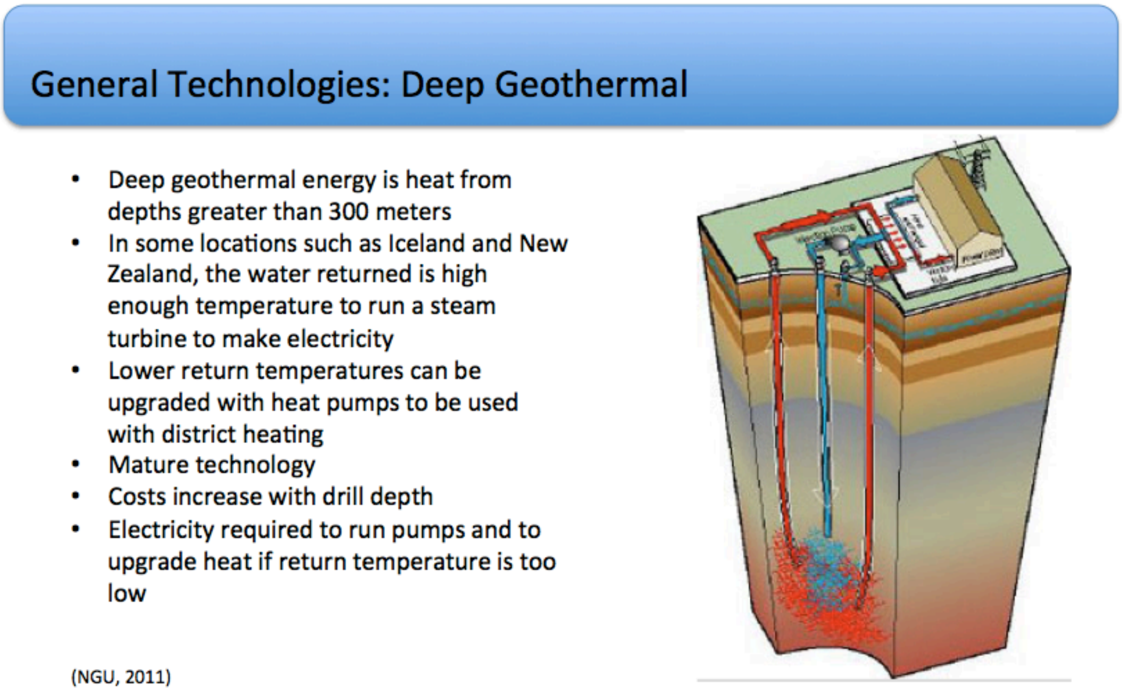
- Vertical boreholes are drilled in earth/rock 50-200m
- Heat source is mix of solar from surface (at shallow depths) and heat from the earth core (as depth increases)
- Require space
- Can be used for storage



Aquifer shallow geothermal heating

- Wells drilled to groundwater source, 50-300
- Deeper the aquifer, higher the temperature
- Heat source for warmed groundwater mix of solar and heat from the earth core

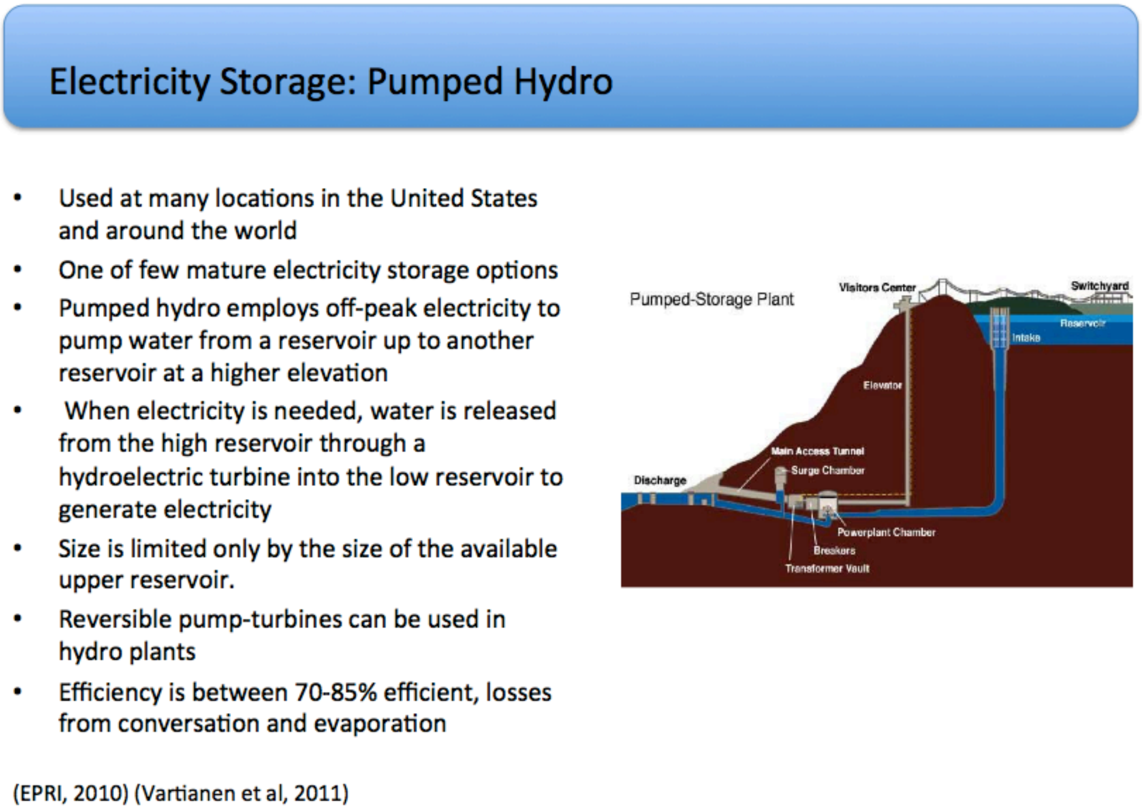
(Geotrainet, 2010)



General Technologies: Deep Geothermal

- Deep geothermal energy is heat from depths greater than 300 meters
- In some locations such as Iceland and New Zealand, the water returned is high enough temperature to run a steam turbine to make electricity
- Lower return temperatures can be upgraded with heat pumps to be used with district heating
- Mature technology
- Costs increase with drill depth
- Electricity required to run pumps and to upgrade heat if return temperature is too low

(NGU, 2011)



Electricity Storage: Pumped Hydro

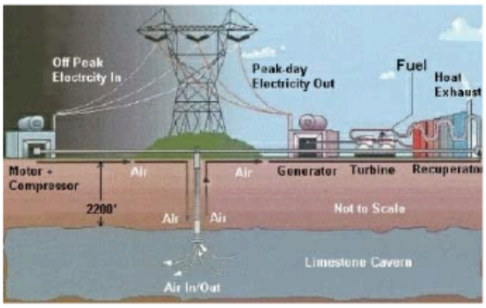
- Used at many locations in the United States and around the world
- One of few mature electricity storage options
- Pumped hydro employs off-peak electricity to pump water from a reservoir up to another reservoir at a higher elevation
- When electricity is needed, water is released from the high reservoir through a hydroelectric turbine into the low reservoir to generate electricity
- Size is limited only by the size of the available upper reservoir.
- Reversible pump-turbines can be used in hydro plants
- Efficiency is between 70-85% efficient, losses from conversation and evaporation

(EPRI, 2010) (Vartianen et al, 2011)

Electricity Storage: Compressed Air

- Compressed Air Electricity Storage (CAES) uses off-peak electricity to compress air and store in underground reservoir
- Reservoir can include underground salt or limestone caverns, abandoned mines, depleted natural gas fields or aboveground pipes or storage tanks
- When electricity needed, the compressed air is heated, and expanded air can drives conventional turbine-generator or piston to produce electricity, or as combustion air for gas turbine
- Storage efficiency can be as high as high as 70-80%, losses coming from electricity to compress and re-heat air
- Considered a mature technology, mainly used in Germany and the US

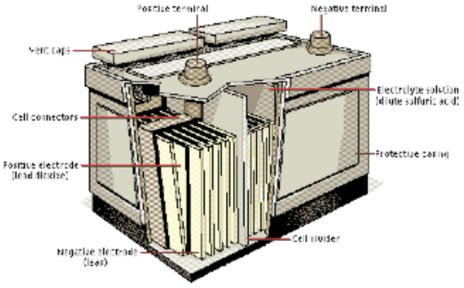
(Vartiainen et al, 2011) (EPRI, 2010)



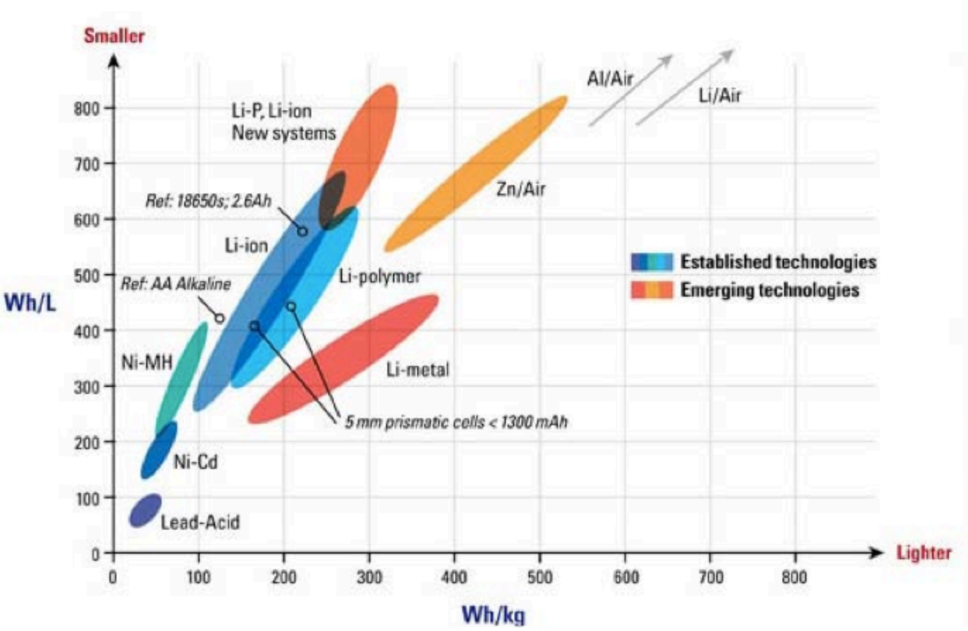
Electricity Storage: Batteries

- Multiple battery technologies currently under research
- Some include: Flow batteries, Lithuim ion, Nikel Cadmium, Metal Hydryde, Soduim Sulfer, Lead Acid, Vanadium Redox, and Zn/Br Redox
- Many advantages and disadvantages with each – cost, size, #of charges/discharges, speed of charge and discharge, capacity for storage
- Primarily used in the US as grid peak load management, increasingly with wind turbines
- Expected that new battery technology being developed for electric cars will allow far greater density of electricity storage, allowing smaller and more portable designs

(AES, 2011)



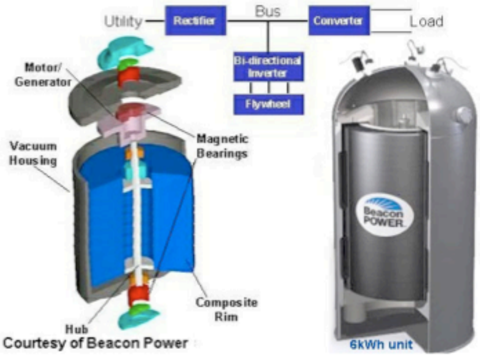
Electricity Storage: Batteries continued



Vartiainen et al, 2011

Electricity storage: Flywheels

- Used for shorter energy duration systems, up to 1 hour
- Primarily used for grid support applications
- Store kinetic energy in a spinning rotor
- Charge by drawing electricity from the grid to increas rotational speed, and discharge by generating electric rotation slows
- They have a very fast response time and may be used short
- High efficiencies of about 93%
- Power densities 5 to 10 times that of batteries
- Can be scaled up by adding more flywheel system mo
- Advanced systems to store large quantities of energy least 4 or 5 years from utility demonstration.
- Few commercial players (e.g. Beacon Power) (Vartiainen et al, 2011); (EPRI, 210)

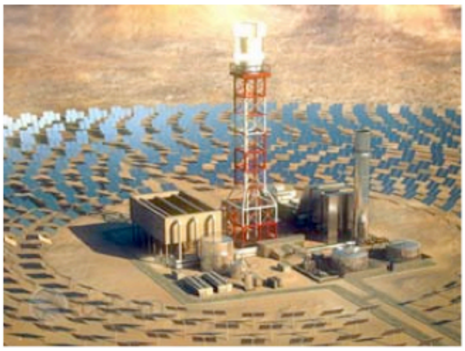


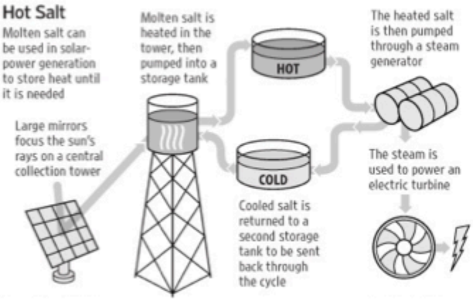
Courtesy of Beacon Power

Thermal Energy Storage: Molten Salts and Oils

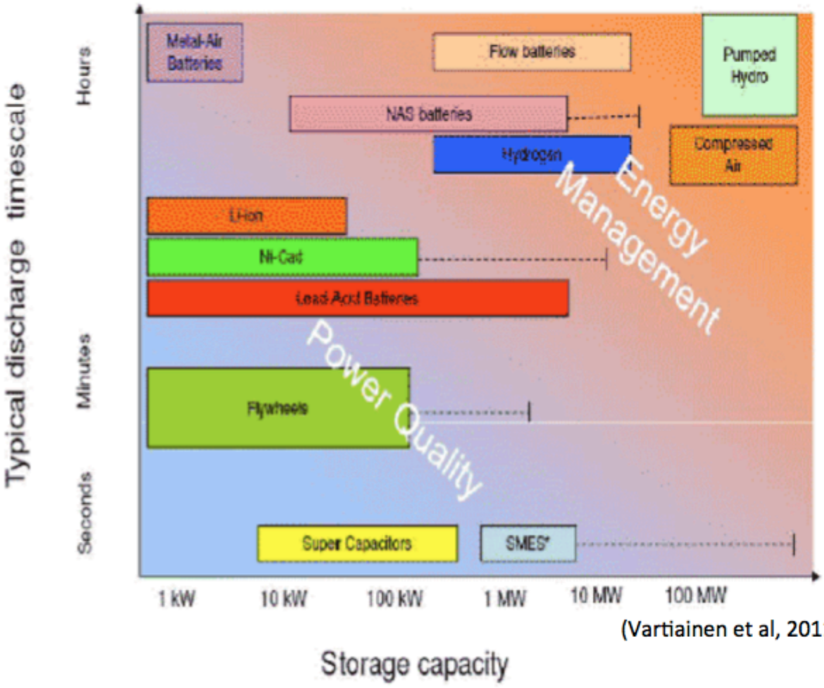
- Molten salts (mixture of sodium and potassium nitrate), Oils such as paraffin work on same principal
- Stored in two tanks; one hot, the other cold. Salts or oils on the way to the hot tank for storage are heated through a heat exchanger
- To recover of thermal energy salts or oils pass back through exchanger transferring the heat
- Temperatures can high enough to drive steam turbine and make electricity, or make hot water for district heating
- Can be used for load balancing for utilities, as well as concreting solar fields
- Special materials are required to avoid salt corrosion
- Salt has a higher freezing point than other heat transfer fluids, which means that pipes must be kept warm to keep the salt molten.
- Mainly used in Spain, Portugal, and the US
- Salts can operate at higher temperatures than oils, thus higher efficiency and power output

(Vartiainen et al, 2011); (Brightsourceenergy, 2011); (Treehugger, 2008)





Storage Technology Comparison



(Vartiainen et al, 2011)

Sources:

AES. (2011). *Energy Storage*. Retrieved 09 08, 2011, from http://www.aesenergystorage.com/news/ny-times-can-batteries-replace-power-generators.html

Brightsourceenergy. (2011). *Molten Salts*. Retrieved 09 08, 2011, from http://www.brightsourceenergy.com/

Danish Energy Agency (2). (2010). *Danish Energy Policy 1970-2010.* The Danish Energy Agency, Copenhagen.

EPA. (2011). *Combined Heat and Power*. Retrieved 09 02, 2011, from http://www.epa.gov/chp/basic/: http://www.epa.gov/chp/basic/

EPRI. (2010). *Electricity Energy Storage Technology Options A White Paper Primer on Applications, Costs, and Benefits* . Electric Power Research Institute. EPRI.

Florocarbons.org. (2011). *How do heat pumps work?* Retrieved 09 02, 2011, from Florocarbons.org:http://www.fluorocarbons.org/en/applications/heat_pumps/how_do_heat_pumps_work_.html

GEOTRAINET. (2011). *GeoTrainet Training Manual for Designers of Shallow Geothermal Systems.* (M. McCorry, & G. Jones, Eds.) Brussels, Belgium: GEOTRAINET.

NGU. (2011). *Geothermal heating*. Retrieved 09 01, 2011, from Geological Survey of Norway: http://www.ngu.no/en-gb/hm/Resources/Ground-source-energy/Geothermal-energy/

Treehugger. (2008, 06 30). *Molten Salts*. Retrieved 09 08, 2011, from http://www.treehugger.com/files/2008/06/molten-salt-storage-solar.php

US Department of Energy. (2011). *Energy Efficiancy and Renewable Energy*. Retrieved 09 02, 2011, from US Department of Energy:

http://www1.eere.energy.gov/industry/distributedenergy/technologies.html
Vartiainen et al. (2011). *Energy storage technologies and business opportunities* . Corporate Presentation, Fortum AB, Stockholm.