Power-to-Heat as a flexibility resource to facilitate introduction of intermittent renewable energy sources

– a case study of how to optimize the power distribution system using the district heating system

John da Costa Stranne & Christoffer Josefsson

Examensarbete 2016
Miljö- och Energisystem
Institutionen för Teknik och samhälle
Lunds Tekniska Högskola

LUNDS UNIVERSITET
Lunds Tekniska Högskola

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Examensarbete

Juni 2016

Organisation, The document can be obtained through	Type of document
LUND UNIVERSITY Department of Technology and Society Environmental and Energy Systems Studies Box 118 SE - 221 00 Lund, Sweden Telephone: int+46 46-222 00 00 Telefax: int+46 46-222 86 44	Master thesis Date of issue June 2016 Authors John C. Stranne Christoffer Josefsson

Title and subtitle

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Number of pages	Language	ISRN
109	English	ISRN LUTFD2/TFEM-- 16/5113--SE + (1-109)

Preface

This thesis was written in collaboration with E.ON Sweden and the Department of Environmental and Energy Systems at Lund University, Faculty of Engineering. The thesis has been supervised by John Backe and Hans G. Johansson at E.ON and Karin Ericsson at Lund University. The examiner was Max Åhman at the department of environmental and energy systems.

Summary

Conventional Fossil based electricity generation in Sweden is currently being deprecated and is substituted with renewable energy sources. The conversion to a more renewable energy system is already underway since intermittent renewable energy sources, such as wind power, is being installed each year. This conversion brings challenges to the electricity transmission system since supply and demand does not always coincide. Means of flexibility could mitigate these effects and therefore be valuable to electricity system operators. Power-to-heat can potentially be such a flexibility measure.

In this context, power-to-heat is the concept of producing heat in a district heating system under a surplus electrical grid. This surplus energy may, during generation peaks, lead to subscription transgressions due to the limited power transmission capacity. The subscription transgressions mentioned above means exceeding the subscribed level of power transmission from the sub-transmission to the transmission system. The capacity limitation is agreed upon between the system operators through capacity subscriptions for feeding or withdrawing electricity to or from adjacent systems. Transgressions can have high costs and consumer flexibility may at those times be beneficial to electricity system operators.

The purpose of this thesis was to assess the technical, economic and practical aspects of power-to-heat in order to reduce the required transmission capacity at times of high regional electricity generation.

The viability of using power-to-heat was assessed through an investigation of a specific case study in northern Sweden. The case study concerns the sub-transmission electricity system owned by E.ON Elnät and the district heating system in Sollefteå owned by E.ON Värme. Each system was first analyzed individually in able to assess the technical limitations and the practical required prerequisites. The two systems were then combined in order to find the economic benefits and detriments for an overall economic assessment.

There are a few key factors that determines the economic viability of power-to-heat. The economic benefits derives from reducing the transgression energy volume by using it for power-to-heat. The cost reduction is dependent on the subscription cost model. According to the study, energy based subscription models are the most beneficial for power-to-heat, since they depend on the amount of transgression energy rather than the highest power peak, which would be hard to handle using power-to-heat. The economic detriments are almost solely dependent on the electricity price. Since the variable costs are based on the actual energy volume used in power-to-heat, investments do not cause a large impact on the outcome.

It is found that the variable costs for power-to-heat creates an unprofitable business case since the savings derived from the transgression cost reductions are to small.

Although, power-to-heat seem to be a suitable flexibility resource as there are few technical limitations for utilization. The district heating system has internal flexibility mechanisms such as the ability to temporarily store heat. This mechanism may lead to intervals of heat overproduction which potentially may lead to additional heat losses.

The greatest obstacle for power-to-heat in the district heating system is the heat supply temperature. At times with low heat demand and ongoing heat overproduction, the supply temperature may exceed the physical limitations which endangers the system.

There are certain issues regarding the agreement framework and the required prerequisites that needs attention in order to implement power-to-heat. One issue is staff availability, especially a lacking presence on the Nord Pool Intraday market. But also communication transparency, power generation uncertainty and the management of boiler adjustment times. A full transgression sequence ranges from the planning phase before the actual transgression until an ended transgression. To be able to handle a full sequence as well as managing the power-to-heat related issues, two model designs were presented as possible solutions.

It is finally concluded that there is a viability for power-to-heat in all aspects but the economic. The subscription cost model works in favor for power-to-heat and the district heating system seems to have technical potential, although are missing in economic profitability. However, the authors point out that there are parameters that could affect the economic viability such as a more volatile future electricity price and a possible future situation without the possibility of signing temporary subscriptions.

The environmental aspect and consequences of the use of power-to-heat are seemingly positive. An optimized use of the transmission system may lead to more intermittent energy sources being introduced into the Swedish energy system. The opposite may however lead to wind power curtailment.

For future research the authors recommend investigating economic balances more thoroughly for each involved party, and in the long term, research the consequences and possibilities of using several coordinated flexibility resources.

Sammanfattning

Fossilbaserad elproduktion i Sverige fasas ut allt mer och ersätts med förnybara energikällor. Omställningen till ett mer förnybart energisystem fortgår redan nu eftersom intermittenta förnybara energikällor, såsom vindkraft, driftsätts varje år. Denna omvandling innebär utmaningar för elnätet eftersom tillgång och efterfrågan inte alltid sammanfaller. Flexibilitetsåtgärder kan mildra dessa effekter och anses därför vara värdefulla för elnätsoperatörer. Power-to-heat kan potentiellt vara en sådan flexibilitetsåtgärd.

Inom detta sammanhang är power-to-heat ett concept för att producera värme i ett fjärrvärmesystem under ett nät med elektricitetsöverskott. Överskottsenergin kan under elproduktionstoppar leda till en överträdelse av kapacitetesabonnemang på grund av kapacitetsbegränsningar. Dessa kapacitetsabonnemang är avtal mellan elsystemansvariga för inmatning eller uttag av elektricitet till och från det överliggande nätet. Överträdelser har relativt höga kostnader och användarflexibilitet kan vid dessa tillfällen vara fördelaktig för elnätsoperatörer.

Syftet med detta examensarbete är att undersöka den tekniska, ekonomiska och de praktiska aspekterna av power-to-heat för att kunna reducera överföringskapacitetsbehovet under tider med stor lokal elproduktion.

Genomförbarheten av power-to-heat uppskattades genom en specifik fallstudie i norra Sverige. Fallstudien berör sub-transmissionselnätet som E.ON Elnät äger och E.ON Värmes fjärrvärmenät i Sollefteå. De båda systemen var först analyserade separat för att bedömma de tekniska begränsningarna och de nödvändiga praktiska förutsättningarna. De två systempotentialerna var sedan kombinerade för att finna ekonomiska fördelar och nackdelar för en helhetsbedömning av den ekonomiska potentialen.

Det finns ett fåtal nyckelfaktorer som bestämmer den ekonomiska genomförbarheten för power-to-heat. De ekonomiska fördelarna har sitt ursprung i kostnadsreduktioner som följer minskningen av energimängden ovanför abonnemangsgränsen, genom att använda den för power-to-heat. Kostnadsreduktionen är beroende av kapacitetsavtalens kostnadsmodell. Enligt studien är energibaserade avtalsmodeller mest fördelaktiga för power-to-heat. I en sådan modell är kostnaderna kopplade till energimängden som ligger ovanför abonnemangsgränsen, snarare än den högsta effekten. Den energibaserade modellen är mer gynnsam för power-to-heat eftersom energivolymen lättare kan hanteras än effekttoppar. De ekonomiska nackdelarna är nästan uteslutande beroende av elpriset. Eftersom de rörliga kostnaderna är baserade på den faktiska energivolymen använd i power-to-heat, påverkar inte investeringarna resultatet mycket.

Det har visat sig att de rörliga kostnaderna skapar en olönsam affärsmöjlighet eftersom besparingarna från kostnadsreduktion av överträdelserna är för liten.

Power-to-heat ser däremot ut att vara en lämplig flexibilitetsresurs ur ett tekniskt pespektiv eftersom det verkar finnas få hinder vid användning. Fjärrvärmenätet har interna flexibilitetsmekanismer så som möjligheten att tillfälligt lagra värmeenergi. Denna förmåga kan leda till tillfällen med överproduktion av värme som kan potentiellt bidra med ökade förluster.

Det störta hindret för power-to-heat i fjärrvärmenätet är framledningstemperaturen. Under tider med låg värmeefterfrågan samt värmeöverproduktion kan framledningstemperaturen överstiga de fysiska begränsningarna vilket kan vara en fara för systemet.

Det finns utmaningar angående ramavtal och förutsättningar som behöver uppmärksammas för att kunna implementera power-to-heat. Ett problem är personalens tillgänglighet, speciellt den bristande närvaron på Nord Pool's intraday marknad. Tillräcklig insyn, osäkerheten i elproduktion samt hanteringen av värmepannors reglertid är andra utmaningar som bör hanteras. En fulländad överträdelsecykel sträcker sig från planneringsfasen innan en faktiskt överträdelse till och med en avslutad överproduktion. För att kunna hantera en fullständig cykel, samt hantera de power-to-heat relaterade utmaningarna, har två stycken modeller presenterats som möjliga lösningar.

Till slut dras slutsatsen att det finns potential för power-to-heat i samtliga aspekter i fallstudien bortsett den ekonomiska. Kapacitetsavtalsmodellen fungerar i förmån för power-to-heat och fjärrvärmenätet verkar ha teknisk potential, däremot saknas en lönsamhet. Författarna påvisar dock att det finns faktorer som kan påverka lönsamheten så som ett mer volatilt elpris och en möjlig framtida situation utan möjlighet till tillfälliga abonnemang.

Den miljömässiga aspekten och de konsekvenser som följer användandet av power-to-heat verkar vara positiva. Ett optimerat användande av transmissionssystemt kan leda till att mer intermittent elproduktion introduceras i det svenska energisystemet. Motsatsen må däremot leda till begränsningar i befintlig intermittent elproduktion.

För framtida undersökning rekommenderar författarna fortsatt analys av de ekonomiska balanser för varje involverad part, och i långa loppet undersöka konsekvenserna och möjligheterna som följer användandet av flera koordinerade flexibilitetsresurser.

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Nomenclature

CHP Cogeneration or combined heat and power (CHP) uses a heat engine to generate electricity and heat at the same time, page 24

DH District heating - a system of transferring heat generated from a centralized location, page 4

DSO distribution system operator - responsible of operating low, medium and high voltage networks for regional distribution, page 3

EI Energy Markets Inspectorate, page 14

ESA Electricity Settlement Area - ESA is a section of an electricity grid where the transfer volumes in and out of the area are settled and the enclosed losses are calculated, page 3

GHG Green House Gas - a gas that absorbs or emits radiation, page 1

HVDC High Voltage Direct Current, page 13

iRES Intermittent Renewable Energy Sources - RES that produce electricity in a irregular and unpredictable manner, page 1

PtH Power-to-Heat - refers to the generation of heat through use of electricity, page 4

RES Renewable Energy Sources - energy sources that are naturally replenished, page 1

SvK Svenska Kraftnät - the Transmission system operator in Sweden, page 14

TSO Transmission System Operator - the main entity entrusted with transmission of electricity or natural gas, page 3

VBA Visual Basic for Applications (VBA) is an implementation of Microsoft's discontinued event-driven programming language, page 10

Chapter 1

Introduction

This chapter introduces the reader to the technical and environmental issues that are underlying to the project, and gives a short overview of the structures and technology that are related to the project. The chapter also states the purpose, the research questions and the limitations.

1.1 Background

Fossil based electricity generation contributes to global warming through being responsible for the emission of about a quarter of the global anthropogenic green house gases (GHG) and are therefore sought to be replaced by renewable energy sources (RES) (Klimstra 2014). Electricity production from RES like wind, solar, wave and tidal power have a lower climate related impacts relative to fossil based electricity production. A number of issues arise due to the conversion since conventional electricity production is plannable and can be managed to match a certain demand, whereas most RES only produce under certain circumstances i.e. they are intermittent[1] and are called intermittent RES (iRES).

In recent years, such production has increased substantially in Sweden, mostly due to the installation of wind power plants (SCB 2016; Energimyndigheten 2015). The production is neither coupled with the demand, nor can future production be predicted with certainty. This means that future production will result in significant variations of generated electricity which will need to be handled with little or no anticipation. in some cases can this lead to iRES curtailment[2] (Klimstra 2014).

These iRES-related problems are not impossible to solve and there are several options. These options range from energy storage, to reinforcing the grid for more transmission capacity as well as supply and demand management, all helping to balance and stabilize the electricity system (Larsson and Ståhl 2012).

[1] In power systems, intermittency is an irregular or unplannable alternation of electricity generation.
[2] Curtailment - the action of reducing or restricting something.

In the Swedish system, the high share of hydro power constitutes a flexible supply and a balancing resource. Since most of the hydro power plants are located in northern Sweden, the balancing potential relies on the available transmission capacity and the future development of the electricity transmission system. Thus enabling transmission from north to south. The transmission capacity is decided by the physical capacity limit, which have been designed before iRES related problem became a relevant issue. If the future brings more intermittent production with more of these implications, additional measures for managing and optimizing the transmission systems will be required (Svensk Energi 2016).

Recently several other ways and technologies to handle iRES-problems have emerged such as electrical energy storage and power-to-gas which both seem promising. Although they are still waiting for a real breakthrough concerning capacity and cost competitiveness (Larsson and Ståhl 2012). Grid extension, micro production and user/producer flexibility are other concepts that will shape the future and contribute to further balancing the electricity system (Svenska Kraftnät 2016).

Grid extensions will lead to better interconnectivity between countries and areas which may lead to that surplus iRES-production from one area could meet the demand in some other part of the system. This is however expensive, takes time and demands a stable political climate, and is not expanding at the same pace as iRES. Moreover, scenarios assuming a high degree of decentralization with more micro production will increase the complexity of the distribution functions. This by changing the former model of distribution from large plants and small consumers, to a more versatile model where consumers also are producers and the electricity system will need to be able to function both ways.

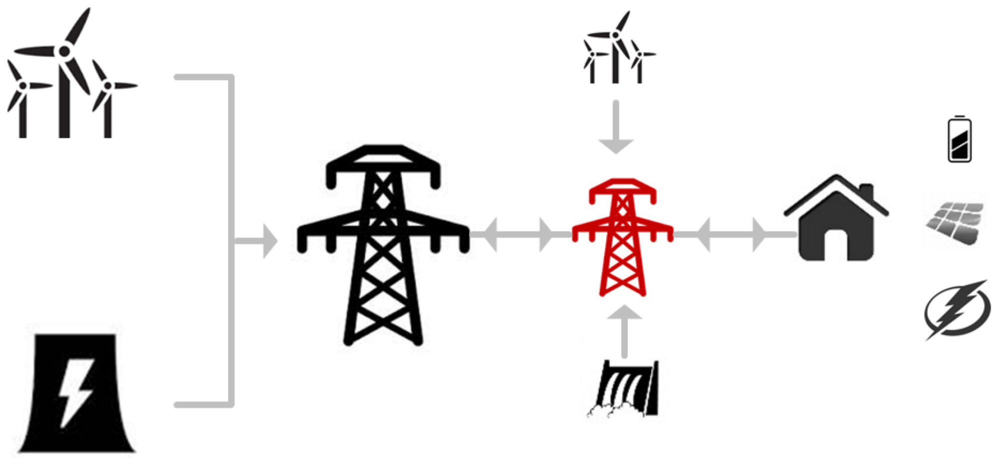


Figure 1.1: A schematic illustration of the role of the DSO. The left part of the illustration show power plants connected to the transmission grid, which in turn is connected to the regional grid (red). The regional grid is in turn connected to local grids, consumers and power generation plants.

This report focus on distribution system related issues and through a distribution system operators (DSO) perspective (marked in red in figure 1.1). The DSO is the operator of the electricity distribution system in a electricity settlement area (ESA).

In a more complex distributory environment, the value of flexibility will increase for the electricity system operators and their customers. The transmission system operator (TSO) is the entity which operates the national grid. In Sweden is the TSO called Svenska Kraftnät.

For a DSO to be able to utilize the transmission system, agreements are signed between the DSO and the TSO. The DSO pays for the reservation of power transmission capacity where different system operators have different cost models.

In this thesis flexibility will be referred to as the possible changes that can be made in planned production and/or consumption to be able to serve the requirements of the energy system as a whole (Klimstra 2014).

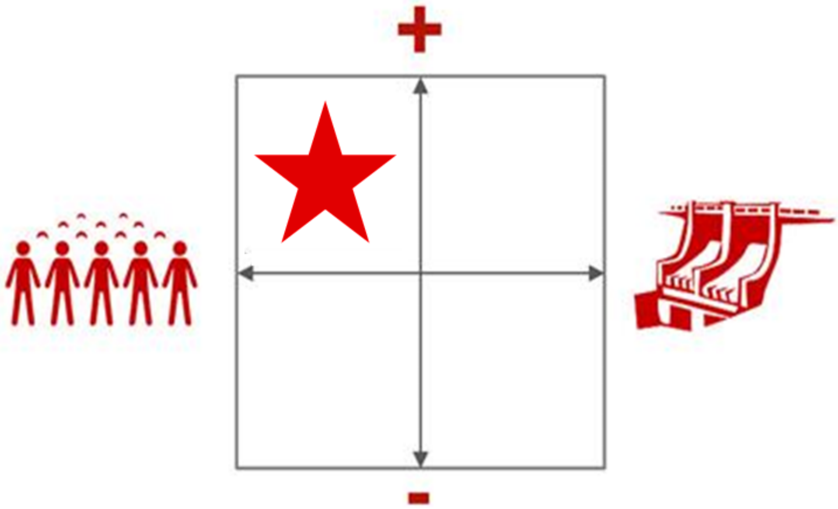


Figure 1.2: An illustration of the four different kinds of flexibility. The horizontal axis indicates producer respectively consumer flexibility, and the vertical axis indicate an increase or an decrease. The star indicates this thesis area of study - increased consumption achieved by increasing demand (source: E.ON Elnät 2016).

Flexibility can be reached by increasing or decreasing planned electricity production, which is illustrated as the right side of the matrix in figure 1.2. This kind of flexibility is needed when more or less balancing power is required. However, flexibility can also be achieved at the consuming end (left side of the matrix), by decreasing or increasing electricity demand at times with limited transmission capacity. This kind of flexibility could be of value to the DSO and the electrical energy system to mitigate the effects of iRES electricity production.

The area indicated with a star in figure 1.2 marks an increased consumer based flexibility. This flexibility can be used at times of large local electricity generation in an ESA and can possibly reduce the need for iRES curtailment and expansion of transmission capacities.

One example of a consumer flexibility resource is the concept of "Power-to-Heat" (PtH), where excess electricity is used to produce heat for the district heating (DH) system instead of being transmitted out of the ESA. This transmission capacity is limited by a physical limit and a subscription limit, the latter which has been decided between system operator and its customers. The idea is that PtH can reduce the transmission power peaks and the transmitted energy volumes by using more electricity locally during electricity generation peaks. This generates lower subscription fees, and may in the long run lead to a higher load factor and a more optimized electricity transmission system. When the limit of a capacity subscription is reached, a transgression occurs and penalty fees are applies (for further description see section 3.3).

A former study of PtH applications in Germany showed problems in finding profitable business cases, especially due to regulatory sub-optimization and high electricity grid tariffs. The study had a slightly different scope which focuses on frequency stability[3] rather than electricity transmission capacity, which is the scope of this report (Böttger et al. 2014).

Besides the technical and economical aspects of PtH, there are also questions of how the flexibility agreement should be designed to make PtH possible for the two involved parties, the DSO and the DH system owner. Challenges lie in the identification of communication frameworks necessary to carry out the operation. Another important aspect is to find and assess the necessary operational prerequisites needed to carry out the sequence. Moreover, other challenges lie in the limited time frames, mutual economic benefits, regulatory issues as well as the pricing and operation of the PtH system.

For the DSO, the challenges related to using PtH as a flexibility resource are many and complex. Challenges range from technical, economic, and regulatory issues, as well as finding a mutually beneficial agreement framework. In this thesis the authors take on the task of assessing the possibilities of finding a potential viability in a case study using PtH.

1.2 Purpose

The purpose of this thesis is to asses the possibility of using PtH as a measure to decrease the need of transmission capacity between a regional sub-transmission electricity grid and the transmission grid, in order to facilitate the introduction of iRES electricity production.

[3] Maintaining the frequency at 50Hz in the electricity grid is the responsibility of the TSO, and is needed to avoid damaging grid infrastructure.

The possibility of using PtH as a flexibility resource is assessed by investigating if there is a viable business case. By a *viable business case* the authors intends the technical and economical potential, as well as the routines and agreement framework associated with PtH implementation. This is assessed through a case study of the regional sub-transmission electricity grid in Ådalen, and the DH system in Sollefteå, which will be referred to as the "base case".

1.3 Research Questions:

The main research question is: Is there a viable business case using PtH for the base case, and what are the key factors?

The research questions can be divided into sub-questions in order to clarify the different aspects of PtH that are important to this report.

- What are the economic and technical potential of using a PtH in Ådalen ESA, and what are the key parameters?
- Is PtH in the DH system of Sollefteå technically and economically suitable, and what are the main features deciding its suitability?
- What are the key aspects regarding the routines and practical prerequisites of reaching PtH flexibility agreements?
- Does PtH in this context have an economic viability, what are the main parameters deciding this viability?

1.4 Delimitations

This thesis studies the PtH concept as a flexibility resource and does not cover other means of reducing transgression costs. The PtH concept is only evaluated through a case study in Sollefteå DH system in the sub-transmission distribution system of Ådalen ESA.

The report does not take into account the potential revenue from the balancing power market, which is a scope that applies to the role of the TSO, who has the responsibility of maintaining the frequency balance of the system.

Since the systems for the reporting of energy volumes has gone through changes during the last years at E.ON Elnät, only the data from year 2015 was available to the authors.

The thesis only investigates PtH in the Swedish context.

Finally, costs of staff education and software upgrades have not been managed in this thesis.

Chapter 2

Methodology

This chapter explain the work process and the methods used. A gantt chart is presented and the choice of case study and its features is presented in order to give the reader an overview on how the report was made.

2.1 Process

As this thesis spans over almost six months the project started with a thorough planning phase in collaboration with the supervisors at E.ON and the Faculty of Engineering at Lund University. The planned process and its phases are represented in a Gantt chart seen below.

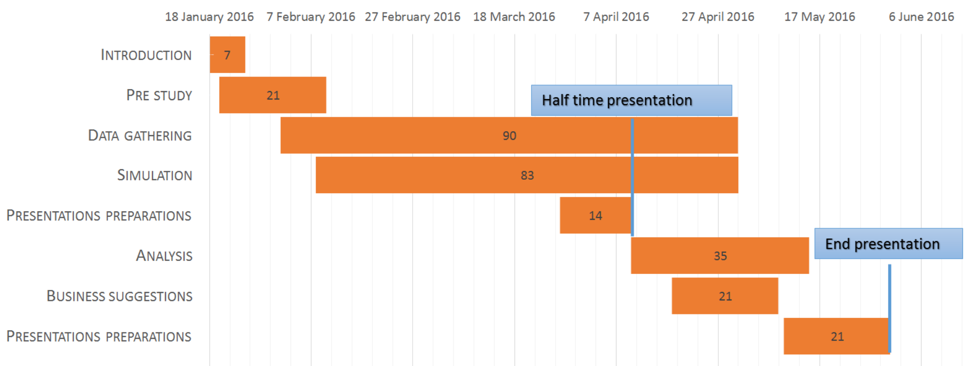


Figure 2.1: The Gantt chart for the thesis project separated in separate tasks.

The most important part during the planning phase was to define the scope of the study and how to assess the information that is collected. As the thesis was part of a bigger project called the DSO flexibility programme (at E.ON Elnät), some points of research were already defined. However, in the introduction phase - a clearer view of the project was stated for all parties involved. The involved parties in this project are E.ON Elnät (also referred to as the DSO), E.ON Värme (also is referred to as the DH system owner) and the authors who represent LTH as thesis students.

2.2 Method

The potential of PtH as a flexibility resource has been assessed through a case study divided into four main parts. The case study is referred to the "base case", and sometimes the "Ådalen case". All information and everything that is done in the report, except the sensitivity analysis, are parts of the base case. In the sensitivity analysis and in the discussion alternatives are explored. The four parts are presented below.

- An assessment of the technical and economical potential of the DH system.
- An assessment of technical and economical potential of the sub-transmission grid.
- An economical assessment where the two systems are combined.
- An investigation of the required prerequisites for the agreement framework for PtH.

The thesis starts with a pre-study/data-gathering with focus on other PtH studies, electricity grid basics, DH basics and current issues that are related to the four main parts.

The economical and technical potential of the two systems are first handled individually and then combined into an economical assessment. An examination of the agreement framework and its required prerequisites are handled after the combination. The four main parts were then analyzed through a sensitivity analysis to assess the key parameters and to highlight the important factors that could change the outcome of the results. See figure 2.2 for a illustration of the thesis method.

2.2.1 Case study - The "base case"

The location of the study was determined from the following parameters:

- The sub-transmission grid had to be owned by E.ON Elnät
- The DH system in the area had to be owned by E.ON Värme
- The settlement area had to be a net surplus grid i.e have higher electricity production than consumption
- The electricity production in the area had to have a significant share of intermittent electricity production.

The location was thereafter set to be Ådalen settlement area due to its significant share of iRES-production. The fact that the DH system in Sollefteå and the electricity distribution system in Ådalen are owned by the E.ON Elnät, was thought to facilitate data collection. Also, due to its relevance as a net surplus ESA with few connection points to other grid owners, the assessment was thought to be easier to manage.

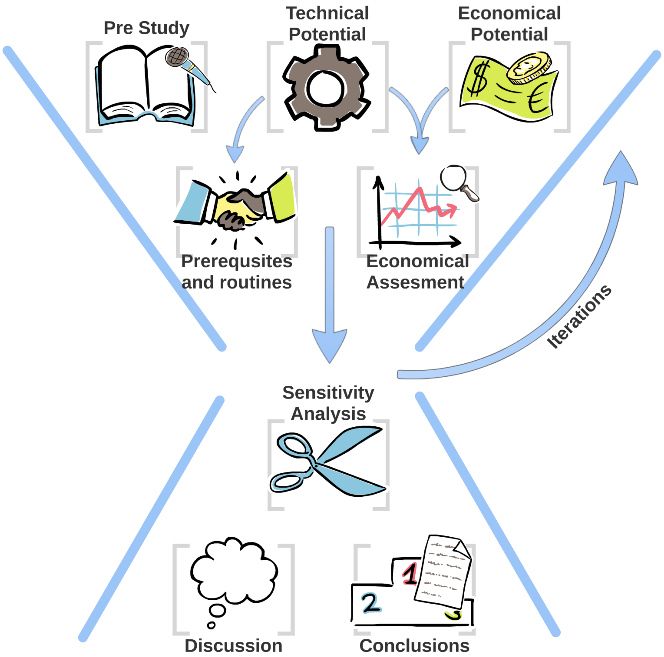


Figure 2.2: Illustration of the methodology used for this thesis. Each symbol is described individually in this chapter.

2.2.2 Pre-study

The main focus for the pre-study and data gathering was topics related to PtH and adjacent topics such as DH, physical commodity markets for electricity, electricity transmission etc.

The electricity system data was gathered from the energy controlling unit in E.ON Elnät. The data is based on the actual measuring stations in Ådalen ESA. The heat production data for the DH system was gathered from the DH production plant in Sollefteå.

2.2.3 Economic and technical potential of PtH in the DH system in Sollefteå

The technical suitability and potential of using the DH system as a flexibility resource were investigated in chapter 4. The aim was to estimate the losses, the energy volumes that could be handled by the DH system and which internal mechanisms it has. This was made through interviews with DH production plant workers. The interviews where done during a visit to the Sollefteå DH production plant. During this visit, the heat production data was gathered and also technical details regarding the equipment of the production plant such as adjustment times of the boilers, size of boilers, fuels used, fuel costs etc.

The gathered data was then analyzed and matched with the data from the energy controlling department at E.ON Elnät in Malmö. The technical and economic potential was derived from matching electricity transgressions with heat production on an hourly basis, to find if there were any technical limitations.

The internal flexibility mechanisms were also analyzed to see the potential of using the DH system as a short time thermal energy storage. This is relevant when supply and demand does not coincide and increases the technical potential of the system.

2.2.4 Economic and technical potential of PtH in the sub-transmission system in Ådalen

The technical potential of the electricity system was estimated through identifying the transgression energy volumes that can be used in PtH instead of being transmitted to the transmission system, see chapter 6.1. The economical potential was determined by calculating the cost reduction that would come with the extraction, depending on the transmission capacity subscription model.

The goal was to find the potential energy volumes that could be extracted with PtH, and to see how the different cost models affected the benefits and detriments for PtH.

This was partly done using Excel Macros in Visual Basic for applications (VBA). The energy transgression volumes constitutes the technical and later economical foundation of the base case.

Normalization

The data was collected during 2015 in Ådalen ESA. During that time significant changes were made in the area which affects the data for this thesis. A relatively large amount of wind power was installed, and significant alterations were made to the capacity subscription types. This made a normalization necessary since the data otherwise would have been unusable. This normalization is further described in section 5.1.4.

2.2.5 Economical assessment

The economical assessment aimed to find the overall economical viability of the base case, and was assessed through comparing the opportunity costs of the base case compared to "business as usual". The base case meaning using PtH under stated conditions (see chapter 5), and "business as usual" meaning normal execution of operations.

The economic viability was calculated through comparing the economic benefits and detriments of using PtH. The economic benefits derived mainly from decreasing transgression energy volumes by using PtH, and the detriments was determined as the opportunity costs due to replacing the energy carrier (replacing biomass with electricity). Also additional heat losses and investments needed for PtH affected the detriments. The electricity price data was collected from the intraday market and was calculated as the mean value during transgression occasions. The yearly investments were calculated through the annuity method (see section 7.4.2).

2.2.6 Prerequisites for the agreement framework

The required prerequisites for the agreement framework were identified for the whole transgression process. For each event, the key factors were identified to assess the challenges and possible solutions of the issues found in the assessment. The recommended solutions and ideas were collected from a seminar held at E.ON Elnät in April 2016 with participants from the internal departments: Grid Operations, Energy Controlling and Products & Services. The participants were told to identify the key factors and prerequisites to enable use of flexibility resources, both in aspects of DH system and the DSO perspective.

2.2.7 Sensitivity Analysis

In order to quantify the impact of certain input parameters, a sensitivity analysis was made. This through changing the value of the different parameters, so that the alternatives to the chosen parameters also could be taken into account. In this chapter also a few alternative cases were explored that deemed interesting for the report by the authors.

2.2.8 Discussion and Conclusions

The findings were then dissected for future potential and challenges dependent on the most sensitive key parameters. These results has been put in a bigger perspective and the validity was questioned.

After the analysis of the four areas of study as well as the sensitivity analysis - the concluding part was written where the main results are presented as well as recommendations for further studies.

2.2.9 Iterations

The process of writing this report and of executing the different tasks have all been an iterative process. The first results of potential economic benefits and detriments were produced in the very beginning of the process, in order to have time for refinement of the products continuously.

2.3 Material

The information sources used for this thesis were mainly primary sources such as internal data gathered from the E.ON group as well as internal interviews with staff and analysts. For the pre-study the sources were authorities (mainly Swedish) regarding electricity distribution and DH such as: Energimyndigheten, OECD, SCB, EI, Svensk fjärrvärme as well as reports and contracts from the TSO in Sweden, Svenska Kraftnät.

The interviews and personal communication were done in person and supplemented over e-mail and telephone. A seminar (or workshop) was also held to further elaborate the information from interviews and together distinguish the required practical prerequisites and limitations to be able to implement PtH.

2.3.1 Reliability of information

All the interview sources used in this thesis are from people with knowledge in their field. As the interviews focuses on certain circumstances in a specific location, and a specific viewpoint (that of the DSO), the only sources available were the interviewees at site.

The pre-study information is gathered from the involved parties such as Nord Pool for market data, and SCB for the Swedish energy profile. The reports used were all published articles or investigations from authorities and are all available online, and are deemed reliable.

Only valid sources have been used and the authors consider themselves to have sufficient knowledge to ensure the validity of the chosen sources.

Chapter 3

The electricity system - infrastructure, production and markets

This chapter contains descriptions of how the grid is managed today on a national, regional and a local level. It also contains information of how the electricity system is utilized regarding power capacity subscriptions and the market where electrical energy is being traded and which laws and regulations that are important as well as the energy production and demand profile of Sweden.

3.1 Electricity grid infrastructure

There are similarities of a power grid and a system of roads. The voltage level (just like the speed limit) decides the transmission capacity where a higher voltage level is used for greater distances. The infrastructure is divided into the national level as well as regional and local levels.

The national grid transfers electricity using high voltage direct current (HVDC) with a voltage level from 220 kV up to 400 kV. By using HVDC, the transmission system reduces its electrical losses[1] and these electrical grid systems can also be more cost efficient than systems using alternating current[2].

The sub-transmission system usually operates using a medium high voltage level which ranges from 40-130 kV (although may range up to 220 kV) and connect local grids and energy-intensive industries such as smelters and paper mills. The sub-transmission system also connect consumers to the main supply in the transmission grid (Nordic Energy Regulators 2011).

Local electricity grids transfers electricity from the Sub-transmission system to smaller industries, households and other users at a voltage level range of 0,4-20 kV. Before the

[1] HVDC transmission losses are lower than the AC losses in most cases (ABB AB n.y.).

[2] Alternating current is an electric current in which the flow of the electric charge periodically reverses direction.

electricity reaches the household customers, it has gradually been transformed down to 230 volts (Nordic Energy Regulators 2011).

3.1.1 System operators

The electricity transmission system has become a natural monopoly, mainly because of the large investments costs which creates a unreasonable entry level for new companies. As a result, it does not make sense, economically, to install parallel electricity grids and it is therefore unreasonable to allow competition (Nordic Energy Regulators 2011). The system operators are divided into two different operating levels. The TSO has the responsibility to manage and operate the transmission system. The DSOs have similar responsibilities, although for management of the sub-transmission system including the local grids (Nordic Energy Regulators 2011).

The TSO is a public enterprise, Svenska Kraftnät (SvK) who owns the national grid in Sweden. The regional systems are however operated by a few major companies, with authorization to operate high voltage wires[3] - E.ON Elnät Sverige, Vattenfall Distribution, and Fortum Distrubution (later called Ellevio) (Svensk Energi 2015; Nordic Energy Regulators 2011). All together there are more than 160 companies with sole responsibility and exclusive right to distribute electricity to their customers in their geographical region (Svensk Energi 2015).

If given authorization, the system operators are liable to report on all consumption and production as well as connecting electrical energy systems in the concession area (Sveriges Riksdag 2015; Nordic Energy Regulators 2011). These formal roles are formulated by a concession duty in order to avoid monopoly surcharges. This is done by laws and regulations such as revenue caps that are determined each year by the controlling governmental institution, the Swedish Energy Market Inspectorate (EI) (Nordic Energy Regulators 2011; Statens Offentliga Utredningar 2007). This is further described in section 3.5.

However, the DSO role might need redefinition to be more similar to that of the TSO, in this case meaning having more responsibility for regulation and coordination than the present situation. This because the challenges on the regional level is becoming similar to the issues on the national level (Svenska Kraftnät 2015b).

3.1.2 Electricity areas

The electricity system in Sweden is divided into four large areas represented in figure 3.1. The two northern areas have a net surplus of electricity, mainly as a result of the large

[3] Authorization to operate high voltages wires is granted by the Swedish Energy Markets Inspectorate

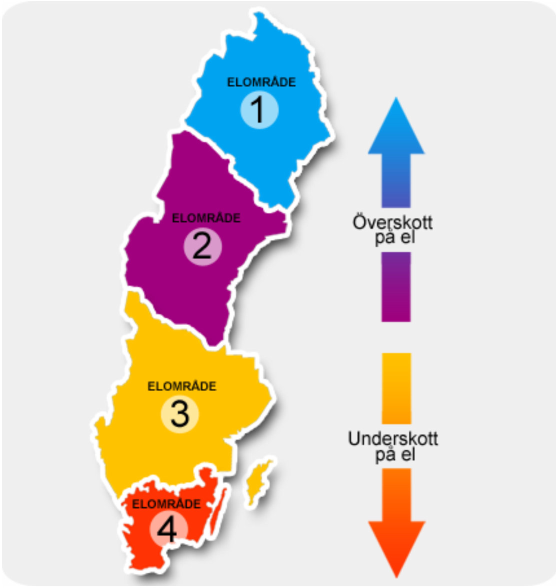


Figure 3.1: Illustration of the different electricity areas in Sweden. The northern regions (SE1 and SE2) of Sweden has a surplus of electrical energy production and the southern parts (SE3 and SE4) has a deficit and thus imports electricity to meet the local demand. (Source: Compricer no date)

capacity of hydro power[4]. The two southern electricity areas have the largest population and the largest electrical energy consumption. Combined with a relative small electrical energy production[5], SE3 and SE4 are areas with a net deficit.

The balancing requirement of meeting supply and demand will result in a power transmission from regions with a power surplus to regions with a deficit. This will cause an electricity transmission flow from regions SE1 and SE2 to the southern regions SE3 and SE4 apart from the energy import from other countries. However, the need for a large power transmission can result in physical capacity limitations called bottleneck effects[6] which will be explained in section 3.3.3.

3.2 Electricity Production Profile

The main Swedish electricity production consists of nuclear- and hydro power which accounts for more than 80 % of total production (SCB 2016). Other power generation

[4]The surplus in the northern parts of Sweden is also a result of the less densely populated area and thus a smaller consumption.

[5]Relative to consumption and nuclear power production where the consumption is larger than production

[6]The bottleneck effect refer to physical limitations in transfer of electrical energy through a medium. In this case, power lines or substations with limited capacity.

originates mainly from wind- and non-nuclear thermal power. In figure 3.2, an increased share of intermittent electrical energy (wind power) is visible as a result of the large introduction of capacity each year. In 2014, 902 MW of wind power capacity was installed. In 2015, wind power accounted for 10 % of the total electricity produced in Sweden (SCB 2016; Energimyndigheten 2015).

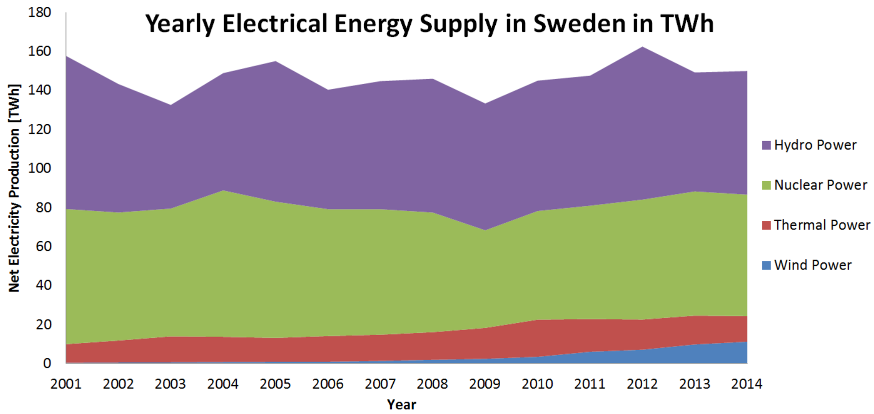


Figure 3.2: Electricity production from common electrical energy sources in Sweden (hydro-, nuclear-, other thermal- and wind power). Wind power has increased market shares in Sweden equal to over 8 % in 2014 with rapid expansion since 2010. (Source: SCB 2015)

3.2.1 Balancing consumption and production

Power systems have the fundamental requirement - supply has to meet demand at every given moment. This means that a sudden change in consumption will require a change in power supply. This relation between consumption[7] and production is always true. The challenge is to maintain a power balance in such way that consumers do not need to be disconnected in order to operate the electricity system properly. It is therefore important to maintain sufficient generation margins so that potential disconnection of customers will not be an issue.

As a result of iRES power generation, the electricity supply will not always coincide the electricity demand. Wind power has limited controllability and is solely dependent on the weather both in short and in long terms. Wind strength projections are often uncertain up until a few hours before operating hours (Söder et al. 2014). In a future with an increasing share of iRES production, more flexible consumption pattern will be required (Lif 2016).

[7] Energy losses is also counted as consumption.

3.3 Grid Utilization

In able to utilize the transmission grid network, agreements are signed between the system operators and their customers. The customers pay for the power capacity reservation per hour and per full year where different system operators have different cost models. The following sections will explain different cost models and the different costs for transgressions.

3.3.1 SvK Subscription Cost Model

SvK has different prices for every individual connection to the transmission system but similar prices in the same grid region. This mostly depending on whether the area is a net import area or an export area. Subscriptions are signed yearly with a cost that follows equation 3.1:

$$P_{cap} \times P_{fee} = S_{cost} \tag{3.1}$$

P_{cap} is the power capacity limit and P_{fee} is the power fee according to SvK's contract which is unique for each transmission point. S_{cost} is the subscription cost which is paid annually to SvK and reserves the capacity for feeding P_{cap} MW every hour for the whole year. The capacity agreement is signed over a year and cannot be changed unless permanent changes in electricity generations has occurred[8] (Svenska Kraftnät 2015a).

Temporary subscriptions

If the maximum power capacity limit in a subscription were to be exceeded, and if there is more available capacity, a temporary capacity subscription may be signed[9]. The costs of such an agreement is divided into two parts. A cost for the extra capacity and a cost for the measured transmission according to equation 3.2 and 3.4. The cost calculations are then added into a single equation - equation 3.5. A temporary subscription is valid for a week and increases the power capacity limit with $P(n)^{+}_{cap}$ MW (Svenska Kraftnät 2015a).

$$\frac{P(n)^{+}_{cap}}{200} \times P_{fee} = T(n)_{cost},\ \ n = [1, 2, 3, .., n] \tag{3.2}$$

[8] Such as large capacity expansion or closure of production sites

[9] In the event of an transgression, the DSO is granted a two hour period to decide if a temporary subscription is necessary or not.

where $P(n)^{+}_{cap}$ is the extra reserved transfer capacity and $T(n)_{cost}$ is the cost of that single temporary subscription. Equation 3.3 describes the total cost for every temporary subscription n booked for a year.

$$\sum_{n} T(n)_{cost}, \ n = [1, 2, 3, .., n] \tag{3.3}$$

The cost for the measured transmission part is calculated using equation 3.4. The measured part is divided into two parts - a power part and an energy part for every measured hour.

$$\frac{P(t)_{obs}}{500} \times P_{fee} + E(t)_{obs} = T(t)_{obs} \tag{3.4}$$

$P(t)_{obs}$ is the observed capacity use and $E(t)_{obs}$ is the cost for energy losses at hour t which is allocated on the transgression[10]. $T(t)_{obs}$ is the cost for the observed transgression energy volume every hour.

Equation 3.2 and equation 3.4 are then combined into the simplified equation 3.5 which is the total cost S_{temp} of the temporary subscription with both the subscription capacity part and the measured energy part for a whole year.

$$\sum_{n} T(n)_{cost} + \int_{0}^{8760} T(t)_{obs} \ dt \tag{3.5}$$

No available transmission capacity

In the event of a subscription transgression and there is no transmission capacity available - a temporary capacity subscription cannot be signed. In this case a different cost model will be used, as represented in equation 3.6.

$$\sum_{t=1}^{2} \frac{T(t)_{obs}}{500} + \sum_{t=3}^{x} \frac{T(t)_{obs}}{50} = S_{temp} \tag{3.6}$$

$T(t)_{obs}$ is the measured transgression at hour t. The transgression time span x ends after the end of the day or after an ended transgression. Equation 3.6 shows a transgression cost that becomes 10 times bigger at the third consecutive hour of transgression during the same day.

[10]The energy cost is paid regardless of a transgression or not, although is removed if being subject to local consumption which will occur with use of PtH

As SvK's subscription cost model is affected by the transgression energy volume throughout a transgression, it is henceforth called an *"energy based"* subscription. This is opposed to *"power based"* subscription cost models which do not have any costs depending on the measured transgression each hour but rather the highest capacity peak.

3.3.2 Other Subscription Cost Models

Subscription cost models for transmission points between two different system operators follow different cost models. Subscriptions cost models between two DSOs are, unlike the SvK cost model, based on power instead of energy. Each cost model[11] is explained in table 3.1.

Table 3.1: Table of the different cost models for subscription transgressions between electricity system operators.

Company	Type	Cost model explanation
SvK	Energy based	Temporary subscriptions is bought (if capacity is available) with a two hours daily deadline for a seven day period. The costs for the temporary subscription is divided into a measured part and a subscription part (see section 3.3.1)
Vattenfall	Power based	The mean value of the two highest peaks in two separate months sets the power level of the year. The difference with the power level and the reserved capacity determines the level of transgression. Temporary subscriptions for a period of seven days or four weeks may be signed, but only between April and October (Vattenfall Eldistribution AB 2016).
Ellevio	Power based	The mean value between the two highest peaks in one week set the cost for transgressions that week. The sum of the costs for all the weekly transgressions is the total cost. Consecutive transgression may be charged retroactively. No temporary subscriptions (Ellevio AB 2016).
E.ON	Power based	The highest peak in the year sets the power level of the year. The difference between the power level and the subscribed level determines the level of transgression. No temporary subscriptions (E.ON Elnät 2016).

[11] There is a fifth cost model, the old SvK cost model, which focuses on temporary subscriptions during transgressions and has neither power costs nor energy costs. It is therefore called a *subscription based* cost model

3.3.3 Bottlenecks

As electrical energy storage is not yet commercialized on a large scale - a balance between supply and demand is necessary as stated in section 3.2. An interconnected power system with means of import and export will therefore improve the market mechanisms and the supply security (Svenska Kraftnät 2015b).

The required transmission of electrical energy as a result of the interconnectivity (explained in section 3.1.2 and figure 3.1), may raise certain capacity issues such as capacity limitations in power stations and temporary shutdowns as a result of maintenance or damages anywhere in the grid system. These issues can severely impact demand satisfaction in other areas. These limitations are known as bottlenecks. The issues of bottlenecks can arise on every level in the electrical system.

The current development which follows an increasing intermittency may result in a less robust system with lowered availability if no counteractions are taken. Many challenges will arise that will increase the risks of smaller marginals in the whole supply chain for all the system operators (Svenska Kraftnät 2015b).

3.4 The electricity markets

Nord Pool is the largest physical commodity exchange market in Europe which exchanges electrical energy. More than 80 % of the total electrical energy consumption in the Nordic market is traded through Nord Pool. The market is owned by the TSOs in Norway, Sweden, Finland, Denmark, Estonia and Latvia, and has the purpose of operating electrical exchange markets such as the day-ahead market and the intraday market called Elbas (Nord Pool Spot AS 2016a).

The Nordic energy market structures mimic the European target model which aims to ensure affordable, secure and sustainable energy for Europe (The European Council 2015).

3.4.1 Day-ahead market

The main marketplace for trading power is the day-ahead market. Contracts are signed between buyers and sellers (called members) before delivery the following day. The trading is driven by planning both the supply and demand the following day which is regulated with hour-to-hour pricing (Nord Pool Spot AS 2016a).

Supply and demand are the key factors for determining the market prices, although, factors as capacity limitations also effect the pricing. Bottleneck effects occur where power connectors are linked to each other, and the congestion is relieved with price rises to reduce the demand (Nord Pool Spot AS 2016b)

3.4.2 Intraday market

The intraday market covers the Nordic, Baltic, German and UK markets and is a supplement to the day-ahead market in matters of securing the balance between supply and demand. Intraday trading occurs within the same trading day, after the deadline of the day ahead market. The intra day market handles all the financial purchases with a time frame between 1-2 hours from the expected physical use (Nord Pool Spot AS 2016c).

With an increasing share of intermittent electricity production the production tends to be more stochastic. This will increase the importance of the intraday market (Svenska Kraftnät 2015b). There will be greater requirements on the capability of addressing forecasting errors. Therefore, counteractions will mainly rely on changes in production with use of balancing power. Moreover, more flexibility will be required on the consuming end (Svenska Kraftnät 2015b; Nord Pool Spot AS 2016c).

3.4.3 Market support systems

Since 2003 Sweden has a support system to stimulate RES called electricity certificates. This system gives a certificate to RES producers for fifteen years which can be sold for additional incomes, apart from the electricity production.

A consequence of this is that the electricity certificate can make electricity production beneficial even though the market prices for electricity were to be negative (Svenska Kraftnät 2015b).

To stimulate demand for the electricity certificates a quota obligation system has been implemented which forces electricity distributors, and some large industries, to buy a certain amount of certificates related to the delivered electricity (Energimyndigheten 2012).

The electricity production sources that are included in the certificate system are wind power, solar power, some biofuels, peat used for thermal power, geothermal energy and wave power.

3.5 Laws and regulations

Because of the natural monopoly described earlier in section 3.1, certain laws and regulations are needed to make sure that grid companies do not surcharge their customers or exclude non-profitable but necessary investments in infrastructure. Necessary investments range from making electricity available for all consumers within the electricity grid area as well as making the electrical energy supply reliable (Sveriges Riksdag 2015). Nevertheless, a structural change of the TSO/DSO may be necessary as a result of the new challenges which follows the capacity limitations in local nets. Also, the national delivery performance needs to be further coordinated between neighboring countries to asses the risks with regards to planning, decisions and management (Svenska Kraftnät 2015b).

Chapter 4

District heating systems

This chapter describes the basics of DH systems. Also, an assessment of the parameters that affect the potential of PtH utilization are described, which depends on mainly on the heat demand and heat production of the DH system.

4.1 District heating systems

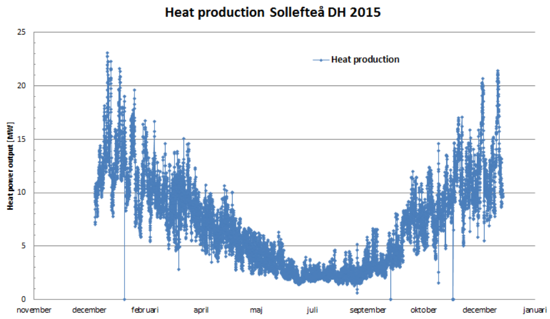
With a total of 50 TWh annual heat production, DH is an important part of the heat supply regarding space heating in Sweden. The customers are multi family dwellings, public premises, industries and singly family houses (Svensk Fjärrvärme 2016).

The basic concept of DH is to transfer heat from local heat production sites to consumers through the DH grid, which is constituted of pipes and a heat medium. In Sweden the medium used in the pipes is cleansed water and in other countries steam is used occasionally. The cleanness of the water is relevant in order to avoid corrosion because of the naturally occurring minerals which promotes corrosion. The advantage of steam is that it can be used in industrial processes because of its high temperature, but the high temperature also contributes to larger heat losses, which has been the reason to decline in use the recent years (Frederiksen and Werner 2013). The heat pipes are connected to heat exchangers at the customer sites where the heat is transferred to another heat medium in a smaller grid – from the distributor side to the consumer side. This is done without mixing the fluids.

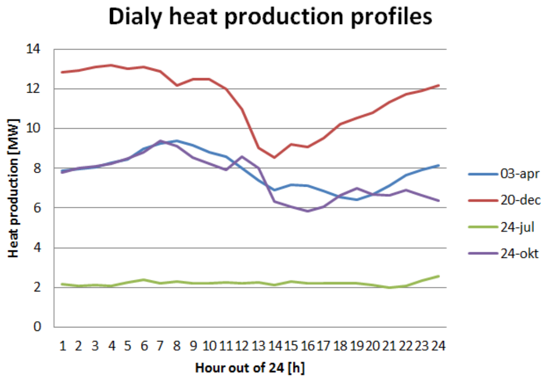
4.2 DH demand and production profiles

The heat production is dependent on demand changes. As the demand for heat vary both yearly and daily so does the production. These changes are illustrated in figures 4.1a and 4.1b.

The daily profile depends on the predominant kind of customers in the grid. The profile of commercial customers is typically higher during the day when shops and businesses



(a) The heat production profile for Sollefteå DH system during 2015. The seasonal change is visible with higher production during cold periods and vice versa.



(b) Daily variation for 4 different days during 2015 in Sollefteå. The seasonal load is visible as of the mean value.

Figure 4.1: Seasonal and daily heat production variation, the data comes from the local DH production site in Sollefteå.

are open. Residential customers have their peak demand during the morning hours when showers are being used and space heating is turned up. Heat load and heat production are therefore coupled by the DH owner to fulfill the needs of the customers (Frederiksen and Werner 2013). As the heat demand peak is somewhat periodical, the DH system usually produces heat in advance e.g two or three hours, and uses the internal inertia in the grid to deliver the heat at the expected peak demand hour. This can also limit the strain on the facility by being proactive and not adjust the boilers with varying heat demand (Frederiksen and Werner 2013; Norén 2016a). The changes over the year, or the seasonal load variation, is shown in figure 4.1a. Also, the heat variability is higher during the winter season compared to the summer season as the load is directly dependent on temperature.

4.3 Heat production sources

The heat production sources for DH systems are local DH plants, excess heat from industries or from combined heat and power plants (CHP). DH plants can use different energy sources to produce heat which ranges from fossil fuels, biomass, waste, and also electricity (Frederiksen and Werner 2013). Electricity is not exactly a fuel, so the term 'energy carrier' will henceforth be used for the energy sources used in DH. The majority of heat produced for DH in Sweden is produced from biomass such as wood chips and branches (around 40%), waste incineration is the second most common (around 20%), followed by industrial residual heat and flue gas condensation which contribute with around 10 % each. (Svensk Fjärrvärme 2016).

4.4 Boilers

There are several kinds of boilers which are used in heat and CHP generation. A fluidized bed boiler has heated sand in the boiler to even out the temperature and thereby the burning process in the chamber. The sand has to be replaced regularly which means the burner has to be shut down. Another kind is a roaster, where the fuels are spun and roasted until completely combusted. Most modern CHP plants, which fire biomass also have flue gas condensers which recover the heat from the water vapour in the flue gases. The energy that was used to heat the water is thereby recovered increasing the efficiency of the plants. Another type is the electric boilers which are flexible and can vary their load quickly between 10-100 % of their capacity (Frederiksen and Werner 2013).

The boilers used in CHP plants and in heat production sites need time for adjustment from initial start up to the optimal steady state operation. There are therefore so called 'merit orders' of the boilers. The merit order is determined by the cost of running the boilers and depends on the relative size of the load and the production of the specific boilers as well as the start-up time and the overall flexibility. Usually big and slow adjusted boilers have lower flexibility but high optimal efficiency, and small boilers are flexible but do not reach the same total efficiency (Löwenham 2016).

The different heat sources are, through the merit order, then used to optimally cover the heat demand in the grid in the cheapest and most practical way possible (Löwenham 2016; Englund 2016). When analyzing the boiler use, the heat production is often represented in a durability chart.

Boilers can be adjusted at to fit a certain demand, and the when the adjustment range is not enough, som boilers can be temporarily shut down to optimize the use. For example when the heat demand becomes low - the merit order changes and excludes the largest boiler as it is ineffective at low heat production. This can be seen in figure 4.2.

4.5 Pipes

The pipes in the DH grid have changed over the years. They used to be laid in concrete culverts and isolated on the spot, whereas now they are pre-fabricated isolated plastic pipes and steel pipes.(Frederiksen and Werner 2013) The pipes are made to handle a certain maximum temperature and pressure. If the temperature is exceeded some materials can change which can create leakages, and if the pressure exceeds maximum the pipes may be damaged (Frederiksen and Werner 2013).

4.5.1 Pressure

The pressure depends mostly on the temperature and the pumping speed of the system. Apart from overseeing that the maximum pressure of the pipes are not exceeded, one

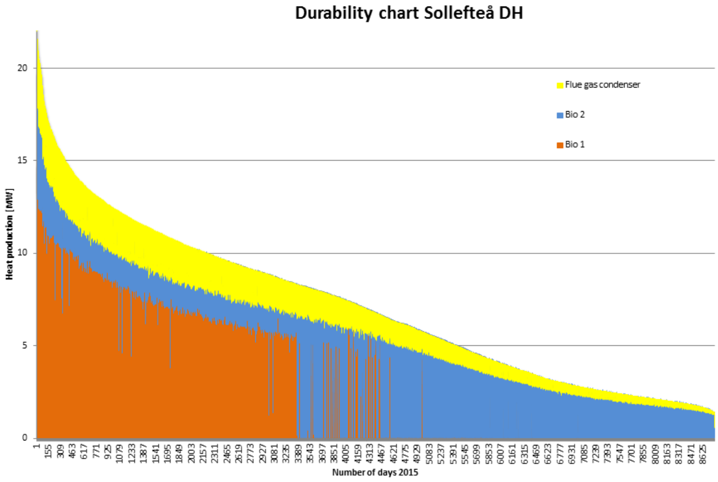


Figure 4.2: Durability chart for Sollefteå heat production/supply, showing the use of two base load boilers (blue and orange) and a flue gas condenser in yellow. The largest production take place at times with high heat demand (usually during the winter season) as opposed to summer with low heat demand and thus low heat production.

must also take the pressure difference of the main DH system and the customer system into account. The pressure difference between supply and return at the heat production site should be around eight bar, and about one bar at the customers substation. The pressure should be considered and constantly monitored by the DH staff when altering the pump speed and temperature of the system (Frederiksen and Werner 2013).

4.6 Concession and economy

Because of the economic ineffectiveness of building parallel grids, DH systems are naturally monopolized and are regulated through concession duty which limits the DH supplier in an area to one agent. DH prices and connection fees are however not regulated, and have been subject to constant increases during the last decade, resulting in a cost of about 0.7-0.9 SEK/kWh(Svensk fjärrvärme 2016). The economic feasibility of DH depends on and the size of the heat load and the geographical density of the customers. The price that customers pay have one fixed yearly part and one variable part depending on the heat used (Energimarknadsinspektionen 2015).

4.7 Linking local energy systems: Power-to-Heat

The simple idea of PtH is to use electricity to produce heat for DH systems, to even the fluctuations in the electricity system. Practically this means using large electric boilers or heat pumps when the electricity grid has large sudden production, which typically occurs at places with a large capacity of wind power. The main historic use of PtH occurred at low electricity prices and was used in Sweden and Norway during the eighties and nineties (Frederiksen and Werner 2013).

Exergy

To produce heat from electricity has been controversial and has been described as "like cutting butter with a chainsaw" (Amory Lovins and the RMI 2011). This relates to the second law of thermodynamics and the exergy losses, meaning that it is a waste to produce low grade heat from electricity. This because electricity can be used for any type of work (has high exergy) whereas low grade heat only can be used for heating and can not become (as much) electricity meaning it has low exergy (Amory Lovins and the RMI 2011).

Chapter 5

Case description: Power-to-Heat in the Ådalen Region

This chapter explains the use of PtH in the Ådalen ESA as a case study. The first sections handles the features of the Ådalen regional system in terms of electricity production profile, electricity transmission, grid ownership as well as subscription type and levels. The DH system of Sollefteå is also described in this chapter regarding the heat production profile, boiler capacities and energy carriers.

5.1 The sub-transmission system of Ådalen ESA

The sub-transmission system analyzed for this case is in the settlement area of Ådalen (ADL). The customers (and connections) of the grid are producers, large-scale users, local grids as well as the transmission system. The Ådalen ESA, managed by the DSO E.ON Elnät, is located in mid northern Sweden. Ådalen is the area along the Ångermanälven river and is located in Electricity Area SE2 and ranges from Härnösand in the east to the Norwegian border in the northwest (see figure 5.1).

The electricity generated in Ådalen ESA is mainly produced from wind and hydro production plants. The generated electricity that is not consumed locally is transferred through three transmission points on three separate locations called Hjälta, Forssa and Storfinnforsen (see figure 5.1). These transmission points are operated by SvK and the subscriptions are revised and set each year.

The power transmission through Hjälta, Forsse and Storfinnforsen are combined into a sum subscription[1] since June 2015. Before June, each individual transmission point had its own agreement and subscription level. The type of subscription changed as a result of the large wind power capacity introduced at Storfinnforsen and because of the meshed structure[2] of the regional and national systems.

[1]Sum subscriptions include the sum of transmissions from two or more transmission points

[2]Because of the nature of electricity, the current will flow through any path to reach its destination. This will result in electricity transmission through the infrastructure (incl. electricity generated elsewhere).

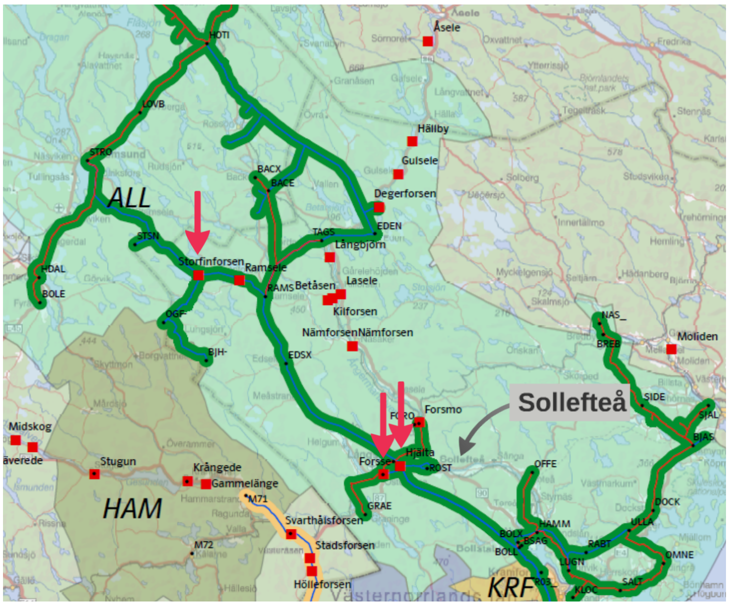


Figure 5.1: Illustration of the Ådalen sub-transmission system. The transmission points, Stofinnforsen, Hjälta and Forsse are marked as red squares (see red arrows). (Figure: E.ON Elnät 2015)

5.1.1 Regional electricity Production

Ådalen ESA has large amounts of wind power capacity installed. During 2015, an additional 162 MW was added. The most notable changes has been at the production sites called Björkhöjden and Ögonfägnaden, owned by Statkraft, where the installed wind power capacity has more than doubled during 2015. Björkhöjden gained 126 MW of wind power in 2015 to a total of 270 MW since 2014, and Ögonfägnaden went from zero to 100 MW (Statkraft 2014). In total, Ådalen ESA has an accumulated amount of 479 MW of wind power capacity and 210 MW of hydro power.

The hourly production in Ådalen ESA can be viewed in figure 5.3. Most notable is the effect of the spring flood[3] where hydro power plants has a requirement to empty the water reserves and produce electricity[4].

5.1.2 Transmission

Figure 5.4 show the measured transmission from Ådalen ESA. Measurements are made locally and at every transmission point to calculate the energy transfer in the ESA at each hour. These observations are then aggregated to present the production from each

[3]The spring flood is the fenomenom where water reserves on land (ice/snow) melts and creates a flood.

[4]The alternative would be to let the water out and thus curtail the electricity production.

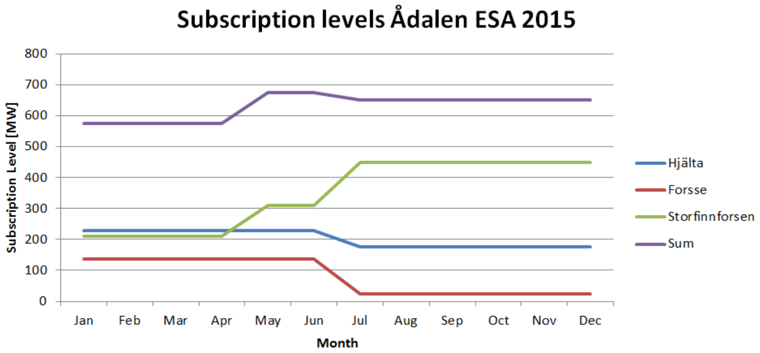


Figure 5.2: Subscription level changes during 2015. Since the first of June, a sum subscription has been implemented.

site as well as the transmission between local grids and other sub-transmission system. The difference observed after the summation shows the consumption (and losses) in the ESA.

5.1.3 Subscriptions

Figure 5.2 shows the subscription levels of each individual transmission point operated by SvK as well as the sum of these three points. Since the first of June the three transmission points have been aggregated to a sum subscription, meaning that from that time their net transmission is aggregated to one collective amount. Exceeding the subscription levels will result in a penalty fee, or additional costs from signing a temporary subscription.

5.1.4 Normalization

Ådalen ESA was changed during 2015 which made an analysis hard to conduct. To be able to analyze the potential for the use of PtH the data had to be normalized. The normalization resulted in a comparable data set, but the changes made to the original data possibly made the results slightly more uncertain. The key issues for the Ådalen ESA are listed below and the resulting normalization:

- Issue 1: Subscription levels had many changes during 2015. For reference see figure 5.2.
- Issue 2: The subscription *type* has changed from three separate subscriptions to one sum subscription for Hjälta, Forsse and Storfinnforsen as of the first of June.
- Issue 3: Installed capacity of wind power increased with 60 % during 2015.

and the resulting normalization.

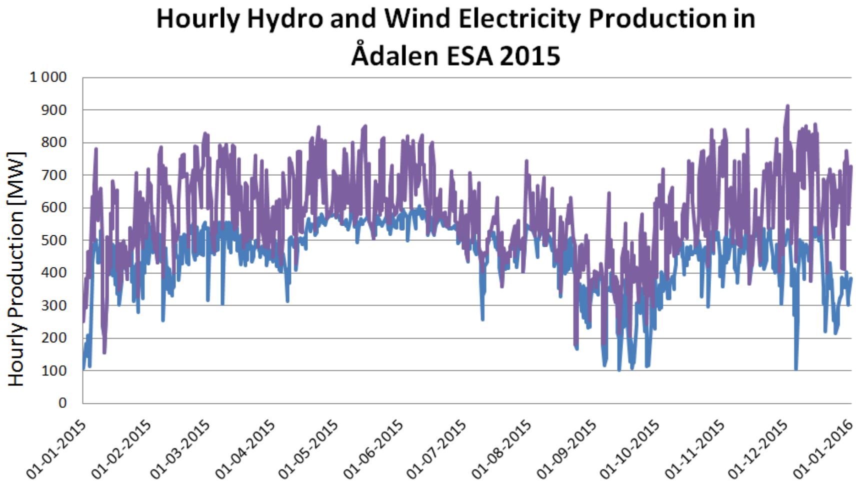


Figure 5.3: Hourly production of Ådalen ESA 2015 from wind- (purple) and hydro (blue) power production. Note the amplitude difference in wind power production and the effects of the spring flood visible during spring.

- Normalization 1: A static subscription level for the whole year.
- Normalization 2: Subscription is interpreted as a sum subscription for the whole year.
- Normalization 3: An retroactively edited wind power production which follows the capacity change dimensioned for each month that was calculated using equation 5.1.

$$Q_n = \frac{P_{real}\ \text{MW}}{\sum P_n\ \text{MW}}, \text{ where } n \in [1, 12] \tag{5.1}$$

Q_n is the normalization fraction for a month n in 2015 and $\sum P_\text{n}$ is the sum of the installed capacity for *all* production site in the Ådalen ESA for *that* month. P_{real} is the *real* installed capacity in all production sites in the Ådalen ESA.

The normalization was carried out based on these assumptions and is represented in figure 5.5 where the *red line* represents the now static subscription level.

5.2 The Sollefteå DH system

The Sollefteå DH system is used for the base case and has about 300 customers in Sollefteå and the grid stretches about 31 km. The customers are mainly commercial and industrial facilities and some are residential (Persson 2016).

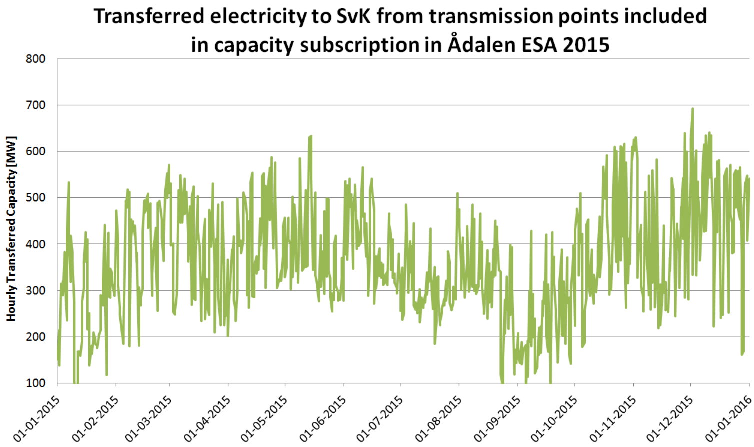


Figure 5.4: Transferred electricity from the subscription including Hjälta, Forsse and Storfinnforsen. The largest measured transmission to SvK was found at the 2nd of December 2015 as seen in the figure.

5.2.1 Heat production

The district heating plant produces 72 GWh of heat annually with a minimal load of 1.2 MW at summer and a maximum load of 30 MW at winter at $-30°$ C ambient temperature. The average oil use in Sollefteå is 1.2 GWh annually (Persson 2016; Norén 2016a).

In figure 5.6 the maximum heat production was around 23 MW and the minimum at 1.3 MW with an average of 7.2 MW. The total production 2015 was 62 GWh (Norén 2016a).

The volume of the DH system is 1050 m^3. The flow speeds ranges between 150 and 400 kg/h. The speed is lower when the heat load is small and close to 400 kg/h at high heat loads (Persson 2016).

5.2.2 Local boilers

There are two main boilers, a fluidized bed boiler and a roaster which are complemented with a flue gas condenser. This setup accounts for 95-100 % of all heat the production in the DH system. The capacities are represented in table 5.1. When the maximum power of the biofuel boilers and the condenser is not enough to meet the demand, oil boilers are used to cover the difference. This could also occur when the demand is so low that the main boilers run at minimum capacity and lower their efficiency as well as during maintenance. In 2015 32 m^3 (320 MWh) oil was used in addition to the regular use of biofuels (Norén 2016a).

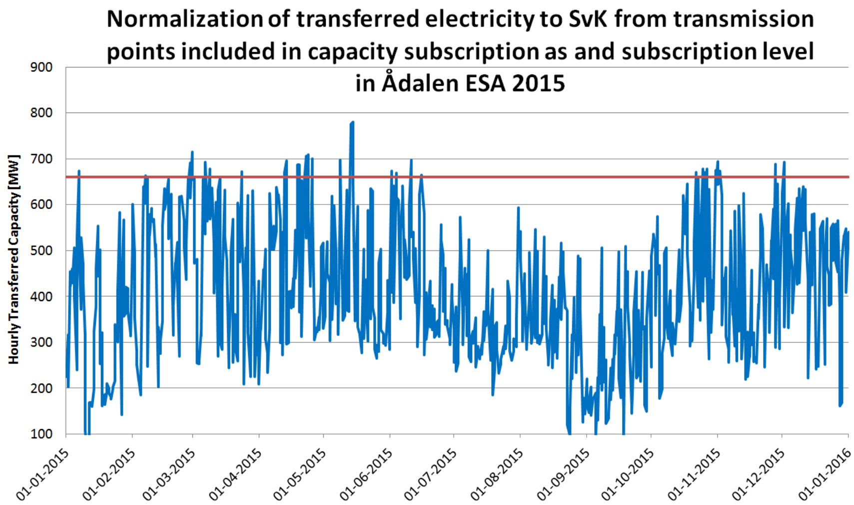


Figure 5.5: Normalized transmission and subscription level in Ådalen ESA. The effects of the spring flood is visible as well as an unedited transmission in December.

The main boilers are fueled by biofuels, or more specifically wood chips from residual wood and sawdust. The two kinds of wood products are mixed to produce the right amount of moisture and temperature. The wood is weighed and loaded into a basin from loading trucks, from where a conveyor belt takes it to the boilers (Persson 2016).

Table 5.1: The maximum and minimum capacities in MW of the boilers and the flue gas condenser at Sollefteå DH production plant.

Production Facility	Max. cap. [MW]	Min. cap. [MW]
L. Biomass boiler	16.0	3.0
S. Biomass boiler	6.0	1.0
Flue gas condenser	3.0	1.0
Electric boiler	9.0	0.5
Total Oil	45.8	0.0

The delivered heat to customers have been 62 GWh/year and the produced heat was around 71.8 GWh/year, of which 70.6 came from biofuels in 2015. The difference comes from the heat losses in the system of almost 10 GWh annually (Persson 2016).

Electricity grid connection - tariffs towards the DSO

The DH system is connected to the local electricity system in Sollefteå. This is important since using PtH will lead to a significantly increased power use for the DH system. This

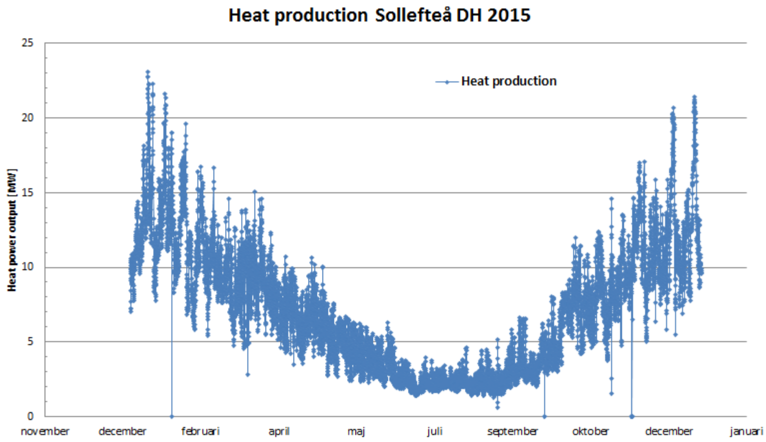


Figure 5.6: The heat production profile for Sollefteå DH system during 2015 (only the main boilers and the flue gas condenser). The highest production value was 23 MW and the lowest was 1.3 MW.

power use has a cost towards the DSO. The tariff is mostly based on power outtake, as the highest power use each month determines the tariff. There is also a small part of the price depending transferred energy volume and reactive power.

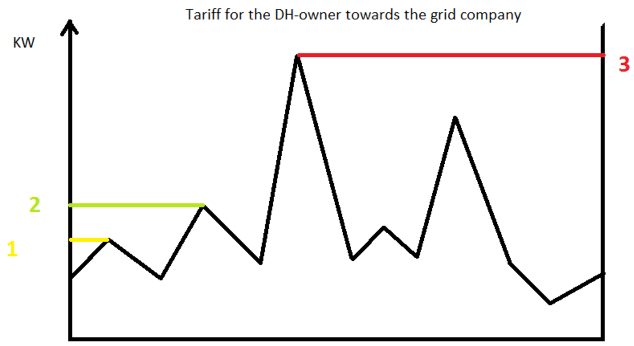


Figure 5.7: Grid tariff schematic that applies to the DH system. Each number represent an example power subscription level for a single month based on the highest power outtake. .

As seen in figure 5.7, the first number shows the first peak which sets the tariff level until it is noted being smaller than the second peak (nbr 2). The last peak is smaller than nbr (3) which leads to that the third peak determines the tariff level.

Chapter 6

Case assessment: PtH in the Ådalen Region

This chapter assesses the use of PtH in Ådalen ESA. The costs of transgressions and the economical potential from reducing the transgression is calculated, as well as the amount of transgression based on the descriptions in earlier chapters. The technical and economical potentials in Sollefteå DH network are also calculated in this chapter.

6.1 Economic potential of PtH in Ådalen sub-transmission system

The main calculations of this section are concerns the savings from decreasing transgressions using the normalized data. To calculate these numbers, some assumptions were necessary, which are stated in section 6.1.1.

6.1.1 Assumptions and key parameters

The assumptions and key parameters used in the following calculations are:

- Normalized wind production data introduced in figure 5.5 is used.
- Temporary subscription will be treated as an insurance and bought regardless use of PtH to reduce transmission costs.
- Flexibility resource size is 9 MW, which is the size of the electric boiler.
- Ideal use of the flexibility resource - i.e the flexibility resource will consume all transgression up to the size of the boiler for each hour of transgression. Further explained in section 6.1.4.
- For the transmission capacity cost model used (SvK 2016), the power fee is 40 SEk/kW and the energy fee is 1,29 SEK/kWh.

6.1.2 Temporary subscription costs

The first transgression in a seven day period is enclosed in a seven days long temporary subscription according to the SvK cost model explained in section 3.3.1. The costs are calculated through programming in VBA which can be viewed in appendix - algorithm A.4. The costs for the temporary subscription are dependent on the subscribed capacity. The temporary subscription are bought in such way that the local maximum is enclosed in the seven days period.

The cost calculation then follows the equation for temporary subscriptions - equation 3.2. The total cost for the transgression is calculated through equation 3.5.

6.1.3 Measured transgression calculation

The most vital part in cost reductions is the reduction of transgression energy, which is a consequence of large local production and small local demand. The surplus of electrical energy is transmitted and sometimes large enough to exceed the subscription limit. For each given hour the transgression amount is calculated using equation 6.1:

$$\sum_{t=1}^{8760} X(t), \text{ where } X(t) = T(t) - S > 0 \tag{6.1}$$

$T(t)$ is the measured transmission at hour t and S is the subscription level. Equation 6.1 will return the sum of the observed transgression in MW which costs is the result of equation 3.4.

6.1.4 Transgression reduction calculation

As stated in section 6.1.1 an *ideal* use of the flexibility resource is assumed which is calculated in equation 6.2.

$$P_{fr} = \sum X(t) - B, \text{ where } 0 \leq B \leq X(t) \text{ and } 0 \leq B \leq 9 \tag{6.2}$$

P_{fr} is the energy volume used in a flexibility resource and B is the used boiler capacity with a maximum of 9 MW. The calculation is done with VBA in algorithm A.5 which also calculates how many hours a year the flexibility resource will be running.

The measured energy use is then evaluated as a cost reduction which follows the same equation as the observed costs of a transgression - equation 3.4.

6.2 The technical and economic potential of PtH in Sollefteå

The technical potential of PtH in the Sollefteå DH system derives out of a few key parameters - availability, responsiveness, storage capacity and the losses. These parameters will set the overall suitability, for both the technical and the economic potentials. As the sub-transmission system handles relatively large volumes and the DH system is a lot smaller in terms of potentially transmitted energy - there will be limitations to the amount of energy that can be displaced in PtH.

6.2.1 Sollefteå DH availability

The differences between the potential electricity displacement volume and the heat demand sets limitations in terms of how much energy can be used for PtH at each given hour. To assess the availability of the DH system as an energy receptor, four scenarios were evaluated (see section 6.2.2). Each scenario is important since they set the foundation of the technical limitations in increasing the supply temperature in an already heated system and the opportunity costs from heat losses[1]. The increased losses determine what the economic consequences and the possibility to use electricity to replace planned heat production.

The availability is assessed using the following assumptions and parameters:

1. Assessing different scenarios for replacing planned heat production as well as scenarios including overproduction with an 9 MW electrical boiler used at full capacity.
2. Brief overproduction can use the inertia of the DH ssytem to store energy, by ”charging” the grid, which can be used later.
3. Overproducing heat will result in extra heat losses dependent on each scenario. The extra heat losses are evaluated out of a combination of all scenario assessments.

6.2.2 PtH scenarios

The four scenarios identified and assessed for this case are: replacement, charging high & low as well as a dumping scenario. The overall assessment is a combination of all four and the additional heat losses are calculated in section 6.2.3. The four scenarios are represented in table 6.2.

The ideal scenario for PtH is the replacement scenario where the whole capacity of the electrical boiler (9MW) can replace planned production. The least ideal scenario is the scenario at times with no or little heat demand. This scenario will result in an

[1] Increasing the supply temperature will result in a larger difference between the heat medium and the ambient temperature which in turn results in a larger loss rate.

Table 6.1: Description of the four scenarios for assessing the availability of PtH as flexibility resource. See figure 6.1 for an graphical illustration.

Scenario	Capacity range (P) [MW]	Comment
Replacement	$P \geq 14$	All the heat production is replaced with the electrical boiler.
Charging high	$14 > P \geq 5$	Overproduction of heat - by using the inertia of DH-grids, energy can be stored briefly with small extra heat losses.
Charging low	$5 > P \geq 2$	Overproduction - by using the inertia of DH-grids, energy can be stored for longer periods with larger heat losses.
Dumping	$P < 2$	Overproduction - no demand for the extra heat results in almost complete heat losses for the overproduction.

overproduction of heat which may put stress on pipes and result in additional heat losses and costs. This scenario is called the dumping scenario. See figure 6.1 for a durability chart with the heat production and each scenario outlined dependent on lowest adjustable boiler capacity.

See the next sections for the assessment of each scenario.

Replacing production

The ideal use of PtH is at times when the heat produced from the the electrical boiler can replace the planned production from the biomass boilers. This scenario occurs when the heat demand is at least 14 MW - i.e the electrical boiler's max capacity[2] of 9 MW plus the lowest adjustable capacity of the biomass boilers of 5 MW as represented in table 5.1. As the lowest adjustable capacity of the main boilers is 5 MW (3+1+1 MW), any heat demand less that 14 MW will result in a scenario where energy will be stored briefly, a scenario will be handled separately.

The only limitation at this time is the responsiveness of the existing boilers. As the electrical boiler can respond almost instantly the adjustment time-span of the main boilers is this scenario's only concern. However, some overproduction at this time is not an issue. As the PtH needed as fast as possible during the adjustment time-span some overproduction may occur.

[2]Full replacement can also occur at times when the electrical boiler is running at capacities lower than the maximum e.g 5 MW electrical results in a replacement scenario at heat demands larger than 10 MW.

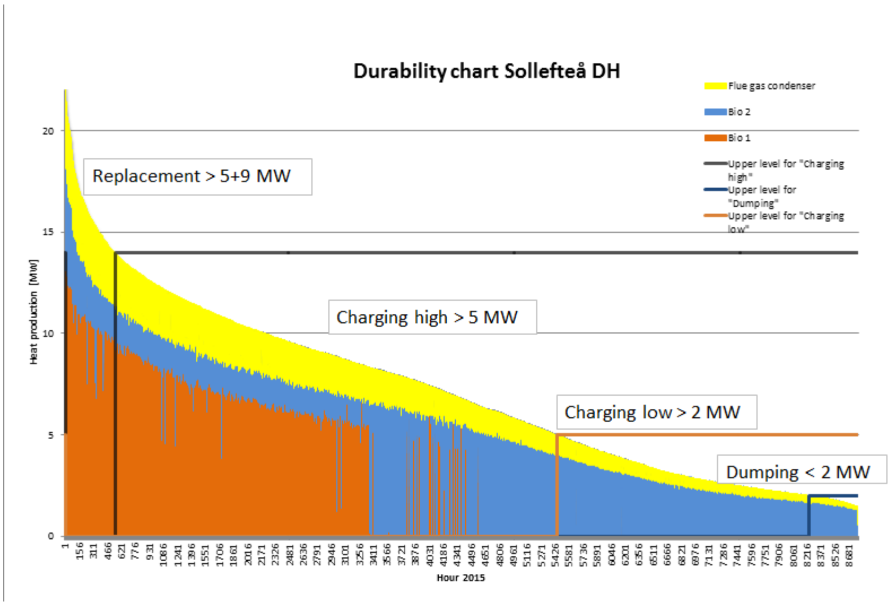


Figure 6.1: The heat production in Sollefteå divided into four scenarios: Replacement, charging high and low and the dumping scenario. The lowest facility capacity sets the lowest foundation for every scenario where 5 MW is the lowest during winter season.

Charging

One other possible scenario is when the heat load is not sufficient to momentarily balance the full PtH production need. During times of PtH need the internal flexibility mechanisms could act as a thermal energy storage. In this scenario the DH grid would be "charged" with energy (by increasing the supply temperature) and then used when the heat load again is increased, or replace later planned production. This will result in higher heat losses than times of a matching heat load.

In this case two separate scenarios have been distinguished - a high heat load scenario and a low heat load scenario (see table 6.2). As the heat load would only be enough to support a part of the electric boiler capacity, only partial replacement will occur. As the lowest capacity is 5 MW or 2 MW[3] every MW larger than the sum of the lowest capacity and the electrical boiler capacity will result in an overproduction. For example if the load would be 8 MW and the minimum production of the biomass boilers is 5 MW, the electric boiler has the potential to replace the 5 MW of the biomass boilers, and "charge" the grid with 3 MW for a number of hours, which later can be used if the load increases due to daily variations.

Due to the thermal storage potential, an increased supply temperature will result in larger heat losses. Although, an already high supply temperature will result in lim-

[3] The lowest capacity depends on if the large biomass boiler is running or not

itations in the amount of energy that can be stored as the capacity is already used. However, the grid can handle certain temperature increases slightly larger than 120° C, although only for a certain time and until a certain pressure around eight hours (Norén 2016a). This can result in a gap which can be valuable for the sub-transmission grid if the DH grid is already at high temperature.

Dumping

The last possibility would be to "dump" heat into the DH grid. This excess heat would not be used at any point and will simply result in heat losses. Here, increasing the energy input means increasing the flow temperature and pressure, which in some cases can be limited. Dumping may thus be limited to a certain amount of consecutive hours as there is no load to compensate for the increased energy input. The DH grid can handle being overcharged for a couple of hours until the facility becomes endangered and high risks of damaging pipes and other infrastructure (Norén 2016a). The dumping scenario may occur during season with low heat demand when the load is equal to or less than the minimum load of the boilers. At these periods, only the small biomass boiler and the flue gas condenser will be used. The minimum production of this equipment is about 2 MW, and any PtH production would result in additional heat production with no corresponding heat demand, or what we refer to as dumping.

6.2.3 Calculating the increased loss factor and estimating the increased losses due to PtH

In section 6.2.2 the different scenarios for heat production and the heat loss factor are presented. The loss factor is the the share of lost heat divided by the produced heat. Losses already occur in the system, but the loss factor calculated here refers to the additional heat losses created by PtH use. The losses are a result of higher return temperatures and larger temperature differences between the heat medium and the ambient temperature.

Replacement can be used for all production above 14 MW and is assumed to yield no additional losses. There are two charging scenarios. The scenario called charging high is at times when the production is between 5 MW and 14 MW and charging low is between 2 MW and 5 MW as the large boiler is shut down. The dumping scenario concerns heat production below 2 MW.

The estimated total additional losses due to PtH are based on the assumption that PtH will be used in the same scenario distribution as a normal annual production. Under this assumption the actual losses from each category were calculated in order to approximate the total additional due to PtH.

Table 6.2: Assumed additional losses during the four scenarios explained in section 6.2.2. The assumptions are based on appreciations of percentages within the intervals of the heat production.

Scenario	Additional losses
Replacement	0 %
Charging high	5 %
Charging low	40 %
Dumping	95 %

Table 6.3: The heat load belonging in each scenario and the assumptions concerning additional losses derived from use of PtH

Heat Production	Dumping	Char. Low	Char. High	Replace.	Total
Tot. prod. energy [MWh]	965	8 886	44 035	8 974	62 860
Loss assumptions [%]	95 %	40 %	5 %	0 %	-
Extra losses [MWh]	916	3554	2202	0	6672
Max. loss factor [%]	14 %	53 %	33 %	0 %	11 %

The total maximum additional losses were calculated using equation 6.3.

$$L = \sum_{s=1}^{4} P_s \times n_s \tag{6.3}$$

L is the increased losses and P_s in MWh is the sum of the heat production in each scenario and n_s is the assumed losses in each category from table 6.3.

The fraction between the total losses (L) and the total production (63 GWh) calculates the increased losses as a percentage which then is multiplied with the flexibility energy volume P_{fr}. The over production is calculated in equation 6.4:

$$P_{over} = \frac{L}{63} \times P_{fr} \tag{6.4}$$

The results of the calculations are presented in table 6.3 This gives the overproduction with use of PtH with the assumptions stated earlier.

6.2.4 Time of introducing energy into the DH system at low loads

In order to assess the time limitations in the DH system i.e the time before a corresponding raise in supply temperature will be observed in the return temperature in a system with no load, the connection between the supply flow speed, the supply temperature and the residence time is examined (see figure 6.2).

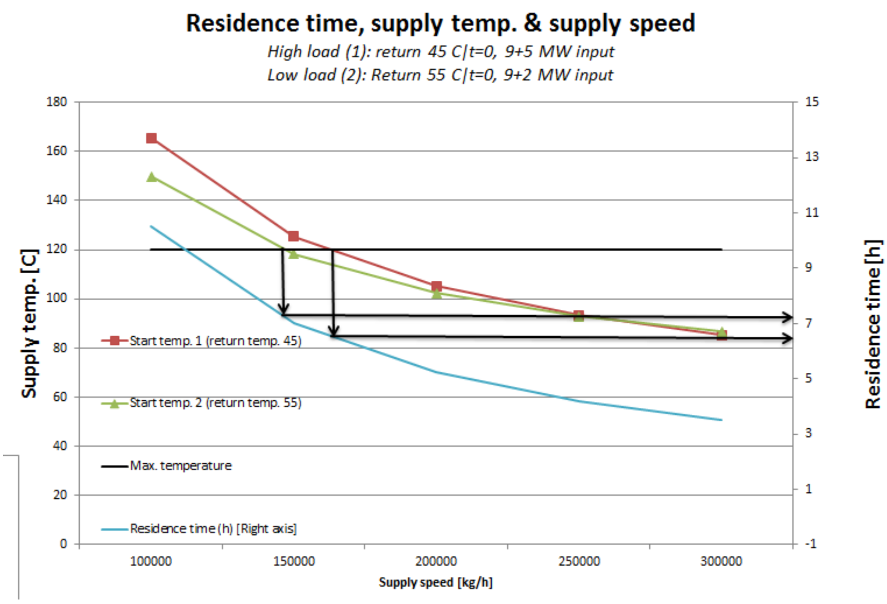


Figure 6.2: The connection between the supply flow speed (left axis), the supply temperature and the residence time (right axis)

Both the residence time and the supply temperature are linearly dependent on the supply flow speed. This implies that a higher flow speed yields a cooler supply temperature, meaning that the faster the flow, the more energy can be introduced to the system. This is coupled with a trade off as the residence time has the reverted dependence. If the flow speed is increased, the residence time is shortened, meaning that the time of possible power input gets shorter when increasing the flow speed, before the return temperature is increased.

If the PtH sequence exceeds the number of hours of the residence time, then the DH system owner will have to assess the situation before continuing the electric boiler over-production, and most probably decrease the power of the electric boiler. The residence time is the average time a single package of water spends in a reservoir, in this case the DH system. The residence time is calculated using:

$$t_{res} = V_{reservoir}/q_{volumetricflow} \tag{6.5}$$

The temperature change of the pumped water in the DH grid was calculated through solving for T_2 in equation 6.6 for energy flow Q' :

$$Q' = m' \times C_P \times (T_2 - T_1) \tag{6.6}$$

the m' is the mass flow, C_P and T_2 and T_1 are the temperatures.

These equations were used to produce figure 6.2.

Chapter 7

Case result - PtH in the Ådalen Region

This chapter analyzes the combination of the electricity and DH system and assesses the overall potential of PtH both with regard technical and economical implications of PtH use. The overall costs are combined and represented through yearly and energy numbers, based on stated assumptions.

7.1 The cost of transgression

The total transgression cost for the base case was calculated to be 0,10 SEK/kWh[1]. Every hour of PtH will use that same amount which will be the foundation for the economical benefits of the base case.

Table 7.1: Table representing the economical benefits due to reduced transgression costs and the potential PtH energy use.

Key parameter	Output	Unit
Measured transgression cost	1.4	[MSEK/yr]
Temp. sub. cost	56	[tSEK/yr]
Potential PtH energy	3.6	[GWh/yr]
Cost reduction	334	[tSEK/yr]

Table 7.1 shows the output derived from calculations done in section 6.1.

7.2 The technical potential of the DH system as a flexibility resource

The result of the PtH potential is assessed in three parameters:

- The ability to replace planned production with PtH

[1]The sum of the costs derived from power and energy costs and the temporary subscriptions (1,456 MSEK/yr) divided by the total transgression volume (15 TWh/yr).

- The possibility for short time storage through raising the supply temperature.
- The maximum increase in the loss rate due to the use of PtH.

The technical suitability to replace planned production seems like a possibility. When the electrical boiler starts the biomass boilers can simply be adjusted to produce less. Although, it takes about 1-2 hours to adjust the capacities, meaning that there will be some excess energy used initially when the electrical boiler is started.

The time of heating without a corresponding load, was deduced from figure 6.2, where the highest allowed temperature (120° C), sets the limit for the lowest flow speed possible, which in turn gives the shortest residence time possible. The time is about 5 to 7 hours for a flow speed of about 160 000 to 200 000 kg/h. After this time the return temperature will rise and thus limit the possibility to overproduce heat.

The maximum increase in heat losses due to PtH use amounts to 11 % of the total production, and the maximum over production amounts to 382 MWh.

7.3 Combining the systems

In earlier sections the technical and economical potential of the Sollefteå DH system as an has been presented. Also, the economical and technical aspects from the sub-transmission system of the Ådalen ESA, have been assessed. The results from a combination of these two systems are now going to be combined - the technical potential of PtH as a flexibility resource and the economical value of this system.

To be able to assess the potential some assumptions are necessary. These assumptions were derived from the conclusions and assumptions from earlier sections and, and are part of what we call the *base case*, all changes and alternatives from the base case are presented in the sensitivity analysis and the discussion. So, the base case assumptions are listed below:

- Assuming ideal use of flexibility resource, saying that all potential PtH energy will be used without adjustment losses as described in section 6.1.4.
- The flexibility resource is an electrical boiler of 9 MW presented in section 4.
- Assuming no extra losses from regulating production of other boilers at the time of production start of flexibility resource.
- The additional heat losses amount to 11% according to section 6.2.2.
- Using the SvK 2016 cost model (see section 3.3.1)
- Using normalized production data according to section 5.1.4.
- Temporary subscriptions will always be bought as an insurance and are always available for purchase.

The technical potential of PtH as a flexibility resource is concluded in 7.3.1 where the system as a whole is evaluated.

7.3.1 The technical potential in a combination of both systems

The key parameters to evaluate the technical potential of PtH as a flexibility resource are controllability of existing heat production and the electrical boiler, the residence time of the DH system, the longest transgression time span, and transgression time span at times with low heat load.

As stated earlier in section 4, PtH can be used as a flexibility resource to replace planned production, act as a short time storage by increasing the supply temperature, and by dumping at times with low heat load. An estimation of the additional losses were made and in the coming section those losses will be recalculated into an economic value (7.3.2).

In section 7.2 the controllability of the existing boilers show limitations with regard to adjustment time and minimum heat production. The minimum heat production is dependent on season, since the different boilers are used for different seasons. At seasons with high heat load (winter), the lowest production possible from the existing boilers is 5 MW. At these times, heat loads with at least 14 MW will result in a full production replacement. High heat load often correlates with times with a larger need of flexibility, since electricity use is correlated with temperature, i.e. is larger during winter. At seasons with low heat load, the minimum production is lowered to 2 MW. The time frame of adjusting the biomass boilers to the right temperature following the adjustment of the electrical boiler is about 1-2 hours.

As stated in section 7.1, the largest consecutive time of transgression is 42 hours, although only 16 hours of these 42 hours are at times with low heat load i.e where the heat loads is lower than 5 MW. As the shortest residence time is around 6-7 hours - this might be a problem for the DH system owner.

7.3.2 Economic potential in a combination of both systems

The economical potential is mainly derived from section 6.1 where the transgression amount is assessed after a normalization. The amount of energy that can potentially be used in PtH is almost 3.6 GWh/yr with a total transmission cost of 0.10 SEK/kWh.

To assess the economical potential of PtH as a flexibility resource the costs that are added to the DH system as a consequence of PtH have to be assessed. The key parameters are: electricity cost, investments costs, cost of additional losses.

7.4 Economic assessment of combining the systems

The assumptions made for the economic *base case* were:

- The electricity price used was the mean price during transgressions on the intraday market: 0.200 SEK/kWh.
- The electricity grid tariff for the DH system owner was determined according to the description in section 7.3.1.
- The costs of staff education and software development are not included.
- 15 years expected lifetime of investments.
- The discount rate used was 5 %.

A simplified economic model for the PtH case where a number of economic flows have been identified (see figure 7.1). The "inflow", or economic benefits is constituted by the reduced cost of transgressions The "outflows", or detriments, are electricity opportunity costs (compared to biomass), the increased heat losses due to PtH, and investment cost necessary to use the electrical boiler. The increase in the electricity grid tariff will has to be included by the agreement design and can be considered, at least partly, an internal flow, which is discussed in section 10. Hence, the overall economic viability is determined by the inflows and outflows, and the internal flows are matters for the design of the PtH agreement.

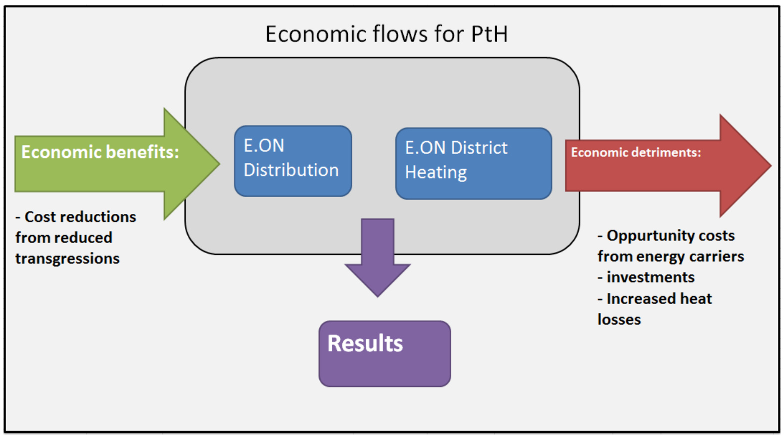


Figure 7.1: The economic flows of PtH. The benefits are cost reductions derives from power transgressions and the detriments are mainly opportunity costs derived from the energy carrier exchange.

7.4.1 The annual economics

The economic balance was calculated as the benefits subtracted by the detriments, see equation 7.1.

$$R(n) = \int_0^n T_{red}(n) - L(n) - I(n) - O(n)dn \tag{7.1}$$

$R(n)$ is the economic result based on the energy amount used in a flexibility resource. T_{red} is the benefits derived from transgression reductions at a cost of 0.10 SEK/kWh and $L(n)$ is the increased losses of 11 % represented as SEK/kWh. I and O are the investments and the opportunity costs derived from using the electrical boiler. See sections below for each calculation. n is the energy transgression volume used in PtH during one year.

7.4.2 Investments

The Sollefteå DH system has an electrical boiler which needs a recommissioning in order to function. The facility manager approximated a cost of 200 tSEK in reinvestment to put it back into commission (Norén 2016a). With the assumption of 15 years lifetime after recommissioning, the yearly investment cost was calculated through the annuity cost model for the investments follow equation 7.2.

$$I = \left[G - \frac{R}{(1+i)^n}\right] \times \mathrm{ann}_{i\%}^{\mathrm{n\ yrs}} \tag{7.2}$$

G is the investment costs for recommissioning of the electrical boiler. i is an estimated internal discount rate of 5 % for n years. R is assumed to be zero after decommissioning the electrical boiler. The annuity factor $\mathrm{ann}_{i\%}^{\mathrm{n\ yrs}}$ is then allocated as of SEK/kWh.

7.4.3 Opportunity costs of energy carriers

The variable costs are mainly constituted of the costs of replacing the normal energy carriers (wood chips and sawdust) with electricity. The electricity price is rather volatile whereas the price of biofuels is more stable. The costs for the relevant energy carriers are listed in table 7.2.

The opportunity cost O associated with the change in energy carrier were calculated as the difference between the cost of electricity and biofuels. The opportunity cost was calculated to be 0.19 SEK/kWh $(0.43 - 0.25)$.

Table 7.2: The variable costs (SEK/kWh) of energy carriers used in the report. The "add-ons" column is different for the three energy carriers where for biofuels add-ons are the cost of the physical handling. For the electricity it's the energy tax and certificates (Persson 2016).

Energy carrier Cost	**Energy carrier price**	**Add-ons**	**Total cost**
Electricity	0.200	0.23	0.43
Biofuel	0.19	0.06	0.25
Heating oil	n/a	n/a	0.82

7.4.4 Costs of increased losses

An overproduction of heat in the DH system will result in additional losses, the losses will result in more production annually compared to a scenario without PtH. The additional cost is the cost of that extra amount produced as electricity.

This overproduction will not be sold and therefore only contribute to additional costs for the transaction. The yearly additional cost (L) was calculated through equation 7.3.

$$L = VC_e \times P_{over} \tag{7.3}$$

VC_e is the electricity price. L_{cost} is then the yearly additional cost for overproduction. If divided with P_{fr}, the potential PtH energy volume, it will give the additional cost for electricity dependent on the increased losses in the assumption. This will give an indication of the costs of overproducing heat with PtH.

7.4.5 Summary

The economic assessment shows that there is no economic viability for PtH in the base case (see table 7.3). The economic benefits derive from decreased costs for transmissions subscriptions and the detriments are higher losses, investment costs and opportunity costs from the change of energy carrier, where the latter is the dominant part.

Table 7.3: The economic viability of PtH in Sollefteå where the benefits and the detriments are shown as well as the result of the base case.

Results	**[SEK/kWh]**
Benefits	0.10
Investments	-0.005
Maximum additional losses	-0.054
Energy carrier opportunity cost	-0.19
Result	-0.152

Chapter 8

Prerequisites for the PtH agreement framework

This chapter presents some important aspects of the practical prerequisites and key factors related to a subscription transgression sequence. The authors view on key factors and prerequisites to be able to reach agreements are presented in this chapter along with the potential issues gathered from the workshop held at E.ON Elnät in April 2016. Two recommendations for the PtH agreement model is presented and its associated framework. Solutions and some visualizations of the suggestions have also been produced.

8.1 The subscription transgression process

Assessing the key factors to reach flexibility agreements are complex and requires thorough attention. In order to organize the issues and solutions, the transgression sequence is presented in figure 8.1 where the sequence is broken down into smaller parts (A-D). The letters in the figure represent certain phases in the process where the challenges, issues and routines needs to be handled separately. The following sections will present certain issues as well as recommendations to manage these issues.

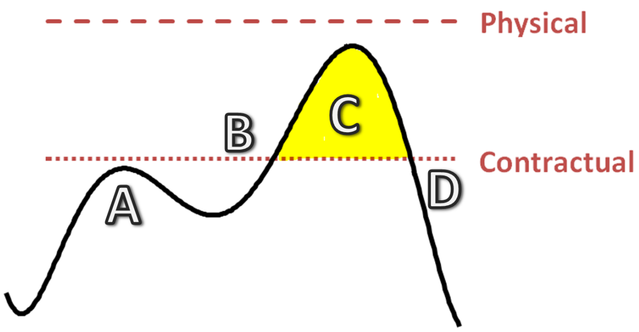


Figure 8.1: The different phases of a transgression sequence where PtH is possible. The yellow area marks a subscription transgression.

Each phase has it own prerequisites and issues. The events are stated below:

A: The event of rapid increase in transmission yet no measured transgression.

B: Being the moment of exceeding the subscription level.

C: The time span during an ongoing transgression where PtH may or may not be used.

D: The moment when the DSO no longer is experiencing a subscription transgression.

8.2 Issues

There are challenges that affect the DSO and other challenges that only the flexibility provider will experience. The issues have been identified through a workshop held at E.ON in April as well as through the authors own thoughts. Below the issues are listed and further explained.

- Transmission uncertainty
- Staff availability
- Communication transparency
- Boiler adjustment time

8.2.1 Uncertainty

A common challenge for the DSO during the whole process (A-D) is the uncertainty of *how much* the transmission will be for the coming hours. The way of predicting transgressions are quite simple but more sophisticated tools for forecasting are under development. Current wind power predictions are dependent on weather forecasts on personal phones and past measurements with a focus on recent days. Other input which helps predict transmission changes are: international connections, expected changes in demand and local wind conditions, as well as daily or weekly periodic changes (Lif 2016).

In event A these challenges are apparent - is the DSO expecting a transgression or not? The challenge regarding uncertainty is equally important throughout the full sequence[1]. At the moment of a transgression in B - the DSO has two hours per day to assess the alternatives. The alternatives can be to acquire a temporary subscription, or to use PtH, or to do both. Signing a temporary subscription can be seen as an insurance, as it has a relatively low cost meaning it can be bought just to be safe, regardless of PtH will be used or not. An other alternative is to manage the transgression with PtH only, but if any of the parties are unable to complete the agreement, the penalties will have to be paid. All alternatives will be affected by the uncertainty, but buying the temporary subscription takes the pressure of the PtH agreement.

[1]For example during the actual transgression (C) is every next hour uncertain in ways of determining the actual transgression for the coming hours.

8.2.2 Staff

An other challenge during the transgression process is the staff, more specifically the staff availability. As the staff at the DH production plant is available only during regular office hours[2] meaning that there is no one who can observe the adjustment of the boilers, as well as supervise fan speeds if a PtH sequence is called for outside the office hours. These issues are most apparent in B and C, but also required in A and D where an agreement is reached as well as stabilization when the agreement has ended.

Also, there are currently no available energy volume broker from the DH system owner acting on the intraday market, which is necessary to purchase the electricity volumes within the stated time frames of 1-2 hours.

8.2.3 Communication transparency

It is important during the whole transgression period that every involved party is informed on how the transgression proceeds and how the alternatives develops as well as the current state of the DH system. As the economical viability is mostly dependent on the electricity price, the prerequisites can change during a transgression as the electricity price can change drastically. Also, if the supply temperature in the DH system is reaching it's limit, the electrical boiler may need to abruptly be shut down to avoid endangering the DH grid's pipes. Therefore, dependent on the agreement framework for PtH, the involved parties need to be informed in a certain way so that the state of the transgression is transparent during the whole sequence.

8.2.4 Boiler adjustment time

Since the biomass boilers are slow in comparison to the electrical boiler - there will be a time-span of heat overproduction. The issue at this point is important in event B and C where an overproduction may endanger the DH system pipes. Also this overproduction will require surveillance of the supply temperature, boiler fans and other aspects regarding the down adjustment of bio-fuel boilers.

8.3 Managing the issues

The issues stated in section 8.2 are challenging abut hopefully manageable. During phase A, the most pressing matter is to assess the alternatives (being temporary subscriptions

[2]Regular office hours for Sollefteå DH plant is 07.00-16.00

or PtH)[3]. As the temporary subscriptions costs are energy based[4] - the most important cost carrier is the energy volume where the subscribed capacity is inexpensive in comparison. The recommendation is therefore to always buy a temporary subscription (if available) and as an insurance. The energy volume can be reduced through use of PtH when the transgression is underway and every energy unit used for PtH will result in a transgression cost reduction.

At the moment of transgression (event B) the DSO has two extra hours to decide on how to proceed with the transgression. The part of the organization which handles the grid operations are informed at the transgression point B. To be able to make the correct decision, forecasts of how the transgression may develop should be made be available. These forecasts should aim to answer the following questions:

- What will be the duration of the transgression?
- What is the expected power peak[5] of the transgression?
- What are the electricity costs?
- What are the weather forecasts for wind in the area? (and perhaps solar insolation)
- Which alternatives are available and which is the most beneficial?

If PtH is economically viable a PtH sequence can be initiated. However, the amount for the PtH sequence is to be inquired is still an issue. To optimize the savings, only the transgression energy should be supplied to PtH. With the previous stated uncertainty - there is no way of predicting how much power production there will be during the next hour which potentially may lead to an overestimation of the PtH volume necessary at the time of reaching an agreement. Suggestions to handle this problem will be stated in section 8.4.

8.4 PtH agreement framework

The transgression during event C can be managed in two different ways. Either the electrical boiler will be adjusted every hour depending on the sub-transmission system needs or a static pre-decided energy volume will be used. Below two different agreement frameworks for how the PtH energy volumes can be inquired are presented:

- Model 1 - hourly regulation of the electrical boiler and active regulation on the hour for every hour during a transgression period depending on opportunity costs.

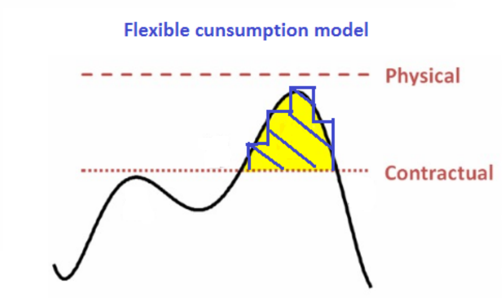
[3] A third alternative may be to curtial the elctricity production.

[4] Meaning that the costs are almost solely dependent on measured transgression volume instead of a single measured power peak.

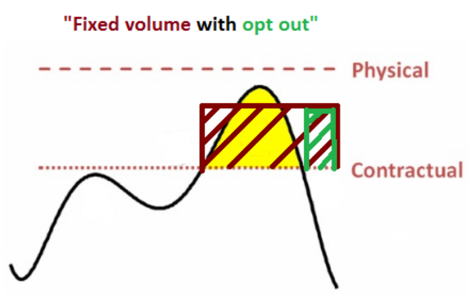
[5] The "power peak" is the highest value of transmitted power for which a production hour will reach.

- Model 2 - A static, pre-decided consumer flexibility with a possibility to "opt-out" (option of ending the agreement) in case the transgression end, DH capacity limitations, unbeneficial electricity price or other reasons.

Both model (1 and 2) have their limitations and possibilities. Model 1 will need active parties during the whole transgression sequence and regulate the consumer flexibility resource in real-time depending on the expected production in the coming hours. This will put pressure on the DH system technicians which will need to be active to monitor frequent regulation of all boilers, and be active on the intraday market. The same goes for the DSO operators where a constant delivery of forecasts would be necessary. Model 2, is an easily managed framework with a pre-decided energy volume, which risk having reduced profitability due to being less agile to change in the prerequisites for the agreement.



(a) Model 1 - The agreement design which is continuously updated according to pricing and technical limitations. This design require an active staff available during the whole transgression process.



(b) Model 2 - The agreement design in which a fixed volume (red) is decided during transgressions. The opt-out option (green) is in case the prerequisites change during the agreed PtH duration.

Figure 8.2: The two agreement designs for handling a transgression through PtH.

Above is an illustration of both concepts where figure 8.2a shows an active presence on the intraday market with an dimensioned transgression energy extraction as opposed to the static framework in 8.2b.

A common issue for both agreement frameworks may be the uncertain energy volume that the DH system requires to buy beforehand from the intraday market in a combination with the transgression uncertainty. Model 1 with a dimensioned consumer flexibility may benefit from the intraday activity to avoid overestimating the PtH energy volume and will depend heavily on the hourly electricity price. These problems will not be an issue in model 2. With a pre-decided energy volume, the profitability will differ depending on the actual transgression energy compared to the predicted. This model will put a larger risk on the buyer but mean less activity for both parties. The risks can be refined with an "opt-out" option, to end the flexibility resource use with e.g a two hour notice to end the sequence or to a certain cost for breaking the agreement.

The faster a flexibility operation can be terminated, after a transgression stops, the better. A transgression sequence with only a temporary subscription will not be an issue. Although, with PtH, the time frame will create a lag that makes the termination decision a bit more complex with risks of overestimation of the PtH energy volume. Again, it would be beneficial to be able to predict the amount of time and volumes at the start of the PtH sequence.

Tariff compensation

Since the increased subscription level will be paid to the DSO from the DH system owner - between the two involved agents, a compensation being paid the other direction during PtH will be necessary (for the economic situation of the base case). This to create a viable agreement for both agents, since the tariff increase is significant in the context. The authors recommendations involve three possible solutions. The first would be to include the monthly tariff increase in the first PtH purchase each month as a fixed cost in event B. Another option would be to have the DSO pay a ”flexibility promotion” in event A, which would have a risk element, but would be lower than the exact amount of the tariff. The risk would be that the transmission would never reach event B that month and therefore being paid unnecessarily. A third option would be to try and spread the amount over an appreciated PtH energy volume for the month.

8.5 Process flow

An imagined process flow is presented in the process flow chart on a separate page below, see figure 8.3. The involved parties are represented in different colors, the DSO in blue, an imagined DH communications central in red and the DH production site in green. The imagined DH central could be the company headquarters, possibly the intraday broker or some other agent, the main issue is to have fast access to the pricing of the market and having a 24 hour availability. At early stages the DH central step could be skipped, to simplify the process.

8.6 Summary

The main issue for a PtH sequence is the uncertainty of the transgression energy volume in the time that follows signing the agreement. However, the uncertainty may be handled through adjusted inquiries through a dimensioned PtH agreement. This framework will require an active staff for the whole sequence and could mean an increased staff work load including out-of-office hours. The second framework proposed in the section is a static inquired energy volume through a, pre-decided PtH agreement model. This framework, simpler and possibly effective, may result in an over(or under)estimation of the PtH energy volume and thus a risk of losing some profitability of the agreement.

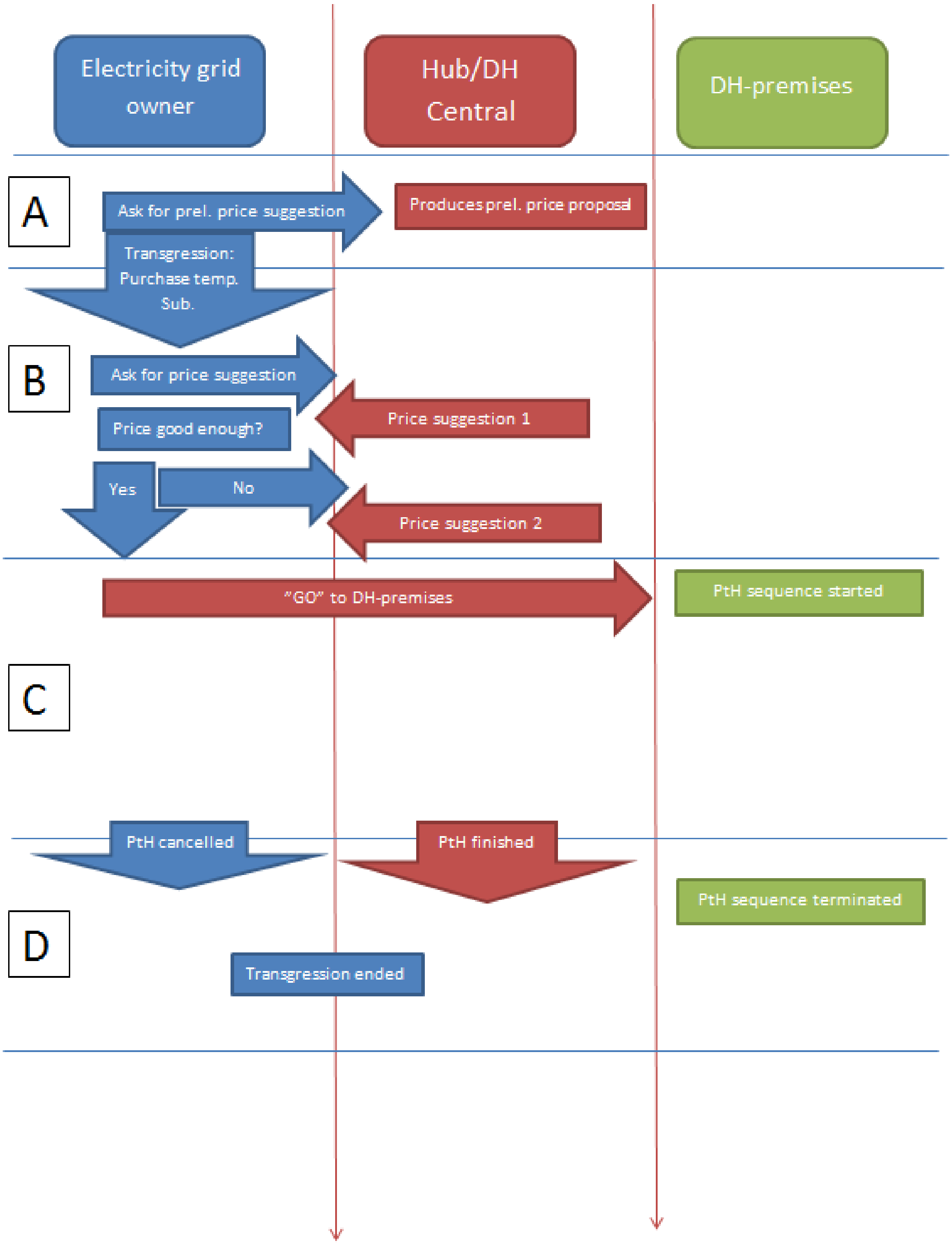


Figure 8.3: In this figure the process flow of the agreement framework is presented. Starting with alerting the parties in section A, making price and volume suggestions in B, considering the opt-out in C, and then terminating or finishing in D.

Chapter 9

Alternative Cases and sensitivity of the results

This chapter presents a sensitivity analysis to assess how the key parameters affects the results of the report. Also, a number of alternative cases are explored to further analyze the business case.

9.1 Sensitivity of the results

In this section a number of important parameters are explored in order to assess their impact on the results. The parameters that depend on the amount of energy will be highly overestimated because the potential use of energy according to the results show the maximum use and not the probable use, because the results of the base case are based on the potential use of energy in PtH i.e. the maximum possible amount of energy, and not an estimation.

9.1.1 Electricity price sensitivity

In this case the influence of the electricity prices are explored in terms of volatility and variable cost. This case is relevant due to the high sensitivity the economical viability has to the energy carriers opportunity cost. It is therefore relevant to examine how alterations of certain parameter affect the overall results. The price is today made up by the market price, energy tax and by certificates to guarantee the quota of RES in the mix (see section 7.3). The market prices vary from day to day and between seasons. this analysis will examine the impacts of lowering or raising the price with 50 % (see table below).

The results show that a 50 % decrease in electricity price is not good enough to find a viability. The "break even" level of the market price is close to zero (about 0,05 SEK/kWh). At low electricity prices (or even negative), there may be a viability for this case. The biofuel prices are also subject to possible changes in the future, and that would affect the viability in this case similarly to that of the electricity price.

Table 9.1: Electricity price sensitivity (excluding "add-ons") - The two first tests ± 50 % assesses the economical viability through an edited electricity price. The "Break even" test calculates at which electricity market price would PtH yield a positive result.

Alteration	Price [SEK/kWh]	Result [SEK/yr]
-50 %	0,10	-198 879
+50 %	0,30	-994 250
"Break even"	0,05	0

9.1.2 Heat losses

The heat losses estimation presented earlier are rough, meaning that it is hard to know how valid the assumptions are. Therefore, the additional losses are analyzed for how sensitive the overall results are to this parameter. The three modifications to the loss parameter are 25 % or 5 % additional losses and a "break even" test (see table 9.2).

Table 9.2: This table show the overall economical results when the heat loss parameter is altered. The "Break even" analysis shows what loss rate would be necessary to yield a positive result.

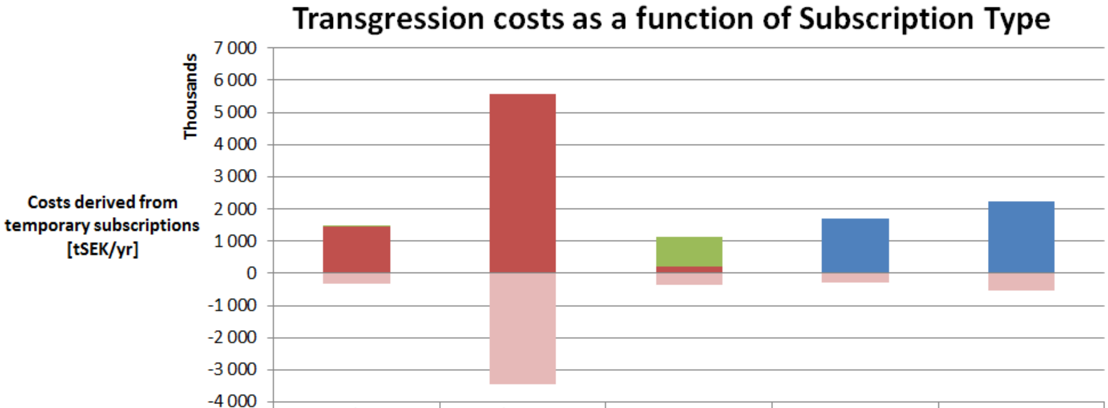
Test name	Losses %	Result[tSEK/yr]
25%	25% (+14%)	-820
5%	5% (-6%)	-509
"Break even"	-28 %	0

The results from this analysis shows that the losses have a significant impact, although alteration in the parameter does not alter the overall viability. The break even calculation shows that "negative losses" would be needed to alter the result outcome.

9.1.3 Alternative subscription model

There are other subscription cost models provided by other DSOs such as Vattenfall and Ellevio. The former SvK model is also assessed to examine a possible potential for PtH with different cost models.

The subscription cost models yields different economical potentials as illustrated in figure 9.1. The most important observation is that of the subscription *type*. We have observed three different types, the *power type* (Ellevio, E.On and Vattenfall) and the new SvK model which is of an *energy type*. The bars to the left are based on the SvK models with or without temporary subscriptions. The cost driver is the amount of energy as opposed to the power cost in the other models.



	SvK (Base Case)	SvK (No temp. Sub.)	SvK OLD	Ellevio	Vattenfall
Potential cost reduction	-333 926	-3 453 087	-347 790	-288 000	-540 000
Temporary subscription cost	55 933	0	932 213	0	0
Energy cost	1 435 052	5 588 606	199 004	0	0
Power cost	0	0	0	1 698 562	2 223 952

Figure 9.1: Transgression costs derived from different subscription cost models. The base case is represented by the bar to the far left and illustrates the "energy based" model. To the right is the cost models of Vattenfall and Ellevio, which are based on power. The former SvK model focuses on temporary subscriptions.

Another important aspect is the manageability of the subscription models. The power based subscriptions are mostly dependent on the peak transmission value within a time-span. To be able to only cut the significant peaks and not the ones that are insignificant, perfect forecasting methods is required. Figure 9.1 shows a best case scenario, with the highest possible savings dependent on reducing only the highest peak[1]. As the cost reduction amount is slightly higher than of the base case but with significantly higher risks - the power based subscription models are in this thesis interpreted as close to unmanageable with PtH.

Also, the possible scenario of not having available temporary subscriptions is examined. This scenario would significantly add to the economical potential of PtH. This could happen if the physical transmission capacity was close to being exceeded, and SvK would not allow temporary subscriptions being purchased.

The results are summarized in table 9.3. The table refers to the best case scenario where as much as possible energy is managed through PtH.

[1]Reducing only the highest peak may result in a "new" peak which is lower than the first peak although within the flexibility resource size's interval. The "real" best case need to handle the initial highest peak and all the new emerging peaks.

Table 9.3: Potential benefits with a 9 MW flexibility resource based on 3,6 GWh annual PtH energy volume (see figure 9.1.)

Subscription model	Economic benefit [tSEK/yr]
SvK Base Case	334 %
SvK No Temp Sub	3 453 %
SvK former	348 %
Ellevio	288 %
Vattenfall	540 %

9.1.4 Cold year case – replacing oil heat production

In this analysis the effects of a cold year are explored. The main effects would be that the heat load would be bigger, yielding smaller additional losses due to PtH. Another difference for this case would be that oil might be used in order to cover production capacity shortages.

Here we assume that the effects of the increased heat load and the transfer capacity are not changed, and focus on oil replacement. Information has been provided that the oil use during a cold year at Sollefteå DH premises is approximately to 1.2 GWh (Norén 2016b). Under the assumption that this amount can be covered by the electric boiler the oil savings could be calculated using equation 9.1

$$(p_{oil} - p_{electricity}) * P_{oil} = S_{oil} \tag{9.1}$$

S_{oil} is the savings from replacing oil, p_{oil} is the price of oil, $p_{electricity}$ the price of electricity and P_{oil} is the annual heat production using oil.

Table 9.4: Cold year case - Replacing oil with electricity for heat production yields yearly savings, a better yearly result and a higher break even price.

Cold year - replacing oil heat production		
Yearly savings	464	tSEK/yr
Yearly total result	-45	tSEK/yr

This means that there is a more beneficial business case for PtH during cold years, when electricity replaces oil.

However, this is not directly a PtH service, since there is no direct electricity system benefit from oil replacement in itself. It does however help the overall business case to partially finance investments, which means it could be a potential benefit for the DH system owner. The income is dependent on the tariffs, since if they were included, replacing oil would not be viable.

Chapter 10

Discussion

This chapter aim to discuss the results in earlier chapters as well as put a different perspective on the issues presented earlier. The validity of the method and data quality will be discussed through a number of headlines. The purpose of this chapter is to assess the overall validity of the results and put the results into a wider context.

10.1 Economic assessment

The benefits from PtH is mainly derived from the cost reductions due to limited transgressions. The subscription cost model is the main entity to enable use of increased consumer demand flexibility methods such as PtH. Power based subscription models[1] i.e the E.ON, Vattenfall and Ellevio models needs flawless forecasting methods and are therefore unsuitable for this kind of consumer demand flexibility. Since SvK's cost model is energy based, every energy unit used in PtH will reduce the overall costs of transgressions. However, each energy unit will also result in an increased opportunity cost for the DH system owner, because electricity is more expensive than biofuels and heat losses will increase. Other possible flexibility resources might have more economically beneficial prerequisites in terms of having lower opportunity costs. Such possible flexibility resources could possibly be sawmills, pulp plants or other industries that can produce in irregular hours.

Under the assumption of always having temporary subscriptions available, the penalty cost for transgression is quite low. The goal is therefore only to reduce the transgression energy volume. Extracting energy that is within the base subscription will probably only result in extra costs[2]. On the contrary, if there is no available temporary subscriptions, every energy unit of transgressed energy has a substantially higher cost. At this point, using energy for PtH beneath the subscription limit may instead be a well invested insurance as a missed production peak may result in a costly transgression.

[1] Models that are solely dependent on a transmission power maximum instead of the total transgression volume.

[2] For example doing 9 MW of PtH when only 5 MW are within a transgression will result in 4 MW

The benefits of PtH would be significantly higher if the availability of temporary subscriptions were to be limited (see sensitivity analysis 9.1.3). This is a quite probable future scenario as the transmission is approaching the physical limit (Lif 2016), especially since the wind power expansion has been ongoing for a number of years in the area.

The majority of the increased opportunity costs derives from the use of electricity instead of biofuels. The costs of the energy carrier switch stands for over 70 % of the total costs. This means that a lower electricity price would result in an economic viability as seen in the energy carrier sensitivity analysis (table 9.1). This is a probable future case since a more volatile electricity price in the future is expected.

About 50 % of the electricity price paid by the DH system owner is the electrical energy tax. It is questionable if the purpose of this tax is fulfilled by taxation of PtH volumes. This, since PtH only consumes energy during production peak hours, and does not compete with any other interests such as efficiency strategies or incentivizing less consumption but adversely, constitutes a systematic benefit. It is the opinion of the authors that PtH electricity volumes should not be included in the taxation. If such change would be made, a much higher share of viable PtH hours would be made available.

Regarding increased tariff compensation the focus of this report has been to find out if PtH is viable for the base case, for the involved parties on a aggregated level. However, some kind of compensation for the increased electricity grid tariff for the DH system owner will need to be to be included in the agreement framework. The issue is delicate since it is subject to possible regulatory inspections. The issue is that the tariff compensation could be seen as a competition infraction related to the concession of the DSO, of not giving the same offer to all customers. The point of allowing it would be that the DSO is paying the DH system owner for the flexibility service they are providing, which according to the authors would be more possible.

10.2 Flexibility suitability of PtH

Using the DH system and an electric boiler as a flexibility resource seem to be a technically possible and suitable option. The features of the system appears to be fitting in terms of boiler adjustments, increased supply temperature possibilities and regarding the size of the flexibility resource.

Even though adjustments are possible, they might be hard to make without temporary over- and/or under production. A higher work load is required during these adjustment times to both monitor and administer the production. The power input must be assessed during the whole process to avoid the risk following to long periods of high supply temperatures[3].

[3] A supply temperature of $120°C$ during a consecutive overproduction of eight hours is considered a very high risks of damages.

According to Böttger et al. 2014 the boiler size should be between 20-50 % of the maximum yearly heat load. The 9 MW electrical boiler (about 30 % of the maximum yearly heat load) seems to be a fitting size. This because the size can be used at most times, partly replacing production and partly for short time storage. However, Böttger et al. 2014 do not consider the yearly variation in heat production but focuses solely on the maximum heat load. Consideration of the yearly average load might perhaps be a more satisfactory measure since it concerns a larger share of the PtH production.

However, the electrical boiler size is not the most important aspect in this case. Since the subscription is energy based, the variable costs and benefits for every produced energy unit are more important. The boiler size is of a higher significance for power based subscriptions and the fixed costs due to the PtH use happens in short intervals with comparably low energy volumes (assuming flawless forecasting methods).

10.2.1 Routines and prerequisites for PtH agreements

The routines and prerequisites for the PtH agreements of the project are complex and hard to assess. Having a solid framework for how to communicate, how to set the price as well as how (and when) to act is crucial to designing a successful framework. Main uncertainties that remain are in the management of the full PtH sequence as well as the increased grid tariff that affects the DH system owner. Also, the organizational parts that will handle the agreements are important, especially for the DH system owners, which have no operational central, meaning that all communication will have to be handled by the local DH technicians. The proposed solutions may deal with these aspects if the right resources and training are supplied. Finally, a key factor is to have a intraday market broker available for the DH system owner.

Handling the uncertainties is a far more complex matter. Exceeding the subscription level is not a big issue because of the low costs for temporary subscriptions. However, when the transgression is abruptly ended, the ability to quickly terminate the PtH sequence will be important.

If no temporary subscriptions would be available, the PtH agreement would include more risks and uncertainties. There would be no insurance to limit the penalties of an abrupt subscription transgression. On the other hand, the benefits of using PtH would be a lot larger since the potential saving would be much higher. This way PtH can be considered a second layer of insurance. Other options available on a systematic scale would be to increase the yearly subscription level (if more capacity is available), or to curtail[4] energy production such as wind or hydro power in the area in order to reduce the penalties costs.

[4]Restrict production, or to limit the maximum supply.

10.3 Data quality validation

The data in the report is of mixed quality. The heat production data is unprocessed and untouched which means it should be objectively unbiased. The electricity system data was extracted from controlled measurements and should thereby be considered to be of high quality. The normalization[5] was necessary in able to make the report comprehensive as well as to handle the calculations. Another option would have been to calculate the actual transgressions to the present subscription levels and conditions. However, that would be a far to time consuming work, and would not say more about the future potential.

The technical information, the information used from the discussion seminar and other input, that have been communicated orally, are deemed to be reliable enough to use in the report. This, mostly because there is no or little literature on these subjects as well as being highly speculative. Since PtH is currently not being used in this exact context there are no objectively correct answers to aspects such as agreement frameworks, and the practical prerequisites and issues. The information used has been subject to continuous scrutiny from fellow workers and external contacts, in order to minimize the risks of mistakes.

The main problem with the data is however the fact that it is only assessed for one year. Since both heat production and and electricity demand is correlated to temperature, a comparatively warm year will show lower heat load (and production) as well as a possible change in amount of transmission capacity needed. This means that there is a possibility that the results only are applicable to relatively warm years and thereby underestimates the potential of PtH. Unfortunately only the data for 2015 was available for use at E.ON Elnät.

10.4 Method reliability

The methods used are deemed satisfactory. Although, one of the main factors is the choice of assessing the maximum potential savings derived from the maximum PtH energy, rather than trying to estimate the actual savings and the energy amount through assumptions. If the opportunity costs of using PtH would have been beneficial - an estimations of the amount of eligible PtH hours could have been used instead in able to assess the "real" potential. The economic potential used in this thesis is therefore interpreted as the best case scenario, which in fact is not very probable at all, but rather an upper boundary for what would be possible. However, one factor for the base case scenario makes the choice justified - there are almost no fixed costs which means that the variable costs are dominant and thus makes changes in energy volume less important.

[5] The normalization was done in able to compensate for installation of wind power in the area during 2015 as well as making the variable subscription level static.

In the case of a larger initial investment, the energy volume is more sensitive to changes in PtH energy volume.

Another part assessed as variable costs are the heat losses due to heat overproduction. These costs were purely speculative but proved to have little effect on the end result. The most important parameter for opportunity costs was the electricity price, which constitutes more than 70 % of the total costs. In conclusion, assuming no additional losses (i.e no overproduction) there was still no economic viability meaning the initial assumption had little effect on the final result.

Another issue was the choice of concentrating on researching the over all viability rather than possible revenue for the involved parties. Assessing the benefits for each involved party would provide a more detailed and solid foundation for the involved parties. This would however require more details in the agreement framework as well as in the calculations which would result in even more speculations. Also, one could argue that it is more interesting to first find out if PtH would create a net value. And if so, go into further detail on how the value creation could be shared between the involved parties as well as what economical risks that applies to the involved parties at which times.

Finally, the seminar held at E.ON to assesses the prerequisites and agreement design could have been more elaborated by being based on standardized questions answered by a larger group of people. This, in order to identify the risks and to be able to analyze information in a more systematic way other than having group discussions/interviews with a few open questions.

10.5 Environmental aspects of PtH

The environmental aspects and consequences of the use of PtH are seemingly positive. An immediate consequence of PtH, which has been mentioned briefly in this report is the optimized use of the existing electricity system (or the higher load factor). Decreasing the power peaks results in less needed transfer capacity, which in turn means that more intermittent power sources can be introduced to the system. If the costs of introducing more RES energy are diminished, more can be developed, and less climate affecting power production sources would have to be used in the long run.

In the case study the possibility of "dumping" is assessed where large heat energy losses are predicted. Considering these facts this would lead to a less effective DH system i.e. producing the same service at a higher energy cost. Dumping would of course only take place at times with very high electricity production, and at times with small heat load. This scenario can only represent a few percent of the total production. However, in the long run, local bottlenecks may limit the electricity supply from local production sites. This limitation can lead to wind and hydro power curtailment[6], which is not more

[6] If curtailing hydro power, water needs to be released without passing the turbines which will result in wasted potential electricity generation. The same goes for the potential energy in the wind which will

desirable than dumping.

Another related topic is the concept of exergy mentioned in section 4.7. Producing heat from electricity is an "exergy loss", which is undesirable in most cases. Using low exergy sources for DH would be more desirable. Although, since the objective of PtH lies in electricity system benefits, which are achieved through the transformation of electricity to heat at certain times. An exergy loss might be a necessary detriment to achieve a larger benefit.

Another factor of the environmental aspects would be through the replacement of biofuels and oil with electricity. Combustion of oil results in airborne emissions such as carbon dioxide, carbon monoxide, nitrogenous oxides and sulfuric oxides and particulate matter (Svensk fjärrvärme 2015). Replacing oil with electricity gives an advantage regarding GHG emissions depending on how the electricity was generated[7]. For Swedish conditions the benefits are substantial due to the low emissions in electricity production (Vattenfall 2015). Different emissions have different effects, i.e. particulate matter have effects close to the emission source and sulfuric oxides mostly affects regional ecosystems through acidification.

Using PtH as a flexibility resource for electricity system purposes will have both negative and positive consequences, of which the benefits of a more flexible and agile electricity system is one important factor, and possibly a necessity for further development of iRES in Sweden.

not be used

[7]The electricity can be generated through oil combustion which of course would not lead to a GHG emission reduction.

Chapter 11

Conclusions

The conclusion chapter answers the thesis purpose in four stated research questions regarding economical benefits, technical suitability, economical assessment and practical prerequisites as well as the overall viability of PtH as a flexibility resource. Finally, this chapter include our recommendations for future studies regarding PtH in Sweden.

11.1 Answering the research questions

The overall research question was: ”Is there a viable business case using PtH for the case study, and what are the key factors?”. This question was divided into four main research questions to clarify the different aspects of PtH that are important to this report. These four research questions are stated in bold text and answered below:

- **What are the economic and technical potentials of using a PtH in Ådalen ESA, and what are the key parameters?**

There may be an economical potential of using a flexibility resource in the Ådalen ESA. The parameters that are most influential on the potential are among others the *type* of the transmission subscription cost model. The subscription that is energy based is dependent on the variable costs per energy unit where the opportunity costs are dependent on electricity price. The possibility to always buy temporary subscriptions renders PtH unprofitable when choosing the alternatives. Although, if there was no possibility for temporary subscriptions - then PtH would be a viable business case.

Power based subscriptions depends solely on high flexibility resource capacity and are not sensitive to variable costs but rather fixed costs. Also, this subscription type is not manageable due to the limited forecasting methods currently available.

- **Is PtH in the DH system of Sollefteå technically and economically suitable, and what are the main features deciding its suitability?**

PtH in the Sollefteå DH system seems to be technically possible. This suitability depends mainly on the internal flexibility mechanisms of the system such as short time energy storage through increased supply temperature and the adjustment range of the currently used biomass boilers. However, these flexibility mechanism will possibly result in larger heat losses.

Regarding the supply temperature - the supply temperature can be raised for at least 5-7 hours without affecting the return temperature, but an assessment of the return is necessary before each PtH cycle to find the minimum flow speed for every power input, without exceeding the temperature limit of the DH system.

- **What are the key aspects regarding the routines and practical prerequisites of reaching PtH flexibility agreements?**

Two of the most important aspects of the prerequisites and routines are the involved time frames. The time frame of the intraday market is about 1-2 hours, which sets a minimum advance for how close to the PtH sequence the deal can be made. Luckily the minimum technical planning time for adjusting the boilers is about 2 hours, which makes them somewhat plannable. However, there are implications at this point since there is no present broker to handle the intraday market purchases of energy at E.ON Värme. Neither is there any staff present at the DH premises outside of office hours meaning that the deals would be limited to business hours or require overtime or jour. These obstacles are not very hard to overcome, although would affect the economical viability as these changes would be allocated to use of PtH. Having low costs for temporary subscriptions helps in this aspect as it may handle the uncertainties of the transgression sequence. If the power transgression rise over the flexibility resource capacity - there will be no penalty costs. This also makes the time frame less sensitive.

Another key factor is the communication framework related to the deal. It would have to be robust and responsive with clear instructions at each sequence. All under the time frames discussed earlier.

- **Does PtH in this context have an economic viability, what are the main parameters deciding this viability?**

The economic viability of PtH for this case study is negative under the base case scenario. The economic benefits of avoiding transgression volumes are out weighed by the detriments of the opportunity costs for energy carriers, the costs for additional losses and the investments. Among the the detriments the electricity price at the intraday market is the most important parameter as it affects both the opportunity costs of energy carriers and the cost of the losses. A higher volatility of the electricity price in the future would change the prerequisites for the viability.

Another factor affecting the economic viability is the replacement of oil with electricity. This swap would generate significant revenue for the DH owner but the use is not strictly to be considered a PtH action as the sole purpose is not related to electricity system issues.

The heat losses are not insignificant but constitute a small part of the overall economic aspects and the investments of the case study are very small in comparison to the other parameters.

– **Does PtH in this context have an overall viabile business case, what are the main parameters affecting this viability?**

The negative economic result for the case study has shown that the case is not economically viable at this point. There is however a possibility that it would be viable at times with low electricity prices and at times where oil is being used as a fuel.

PtH has a technical viability and has definitely a potential regarding routines and practical prerequisites. It does however need further development.

11.2 Authors' recommendations for future studies

Perhaps the most important aspect before PtH implementation would be the management of the agreement frameworks as well as individual economic balances for each involved party. The economic consequences of using PtH needs further investigation. Also, a more detailed framework is required in order to exactly know how the flexibility agreements should be designed. This in able to assess a practical viability, whereas this report only focuses on researching the possibilities of value creation.

If a future possible economic viability is found, communication, and other routines may have to be refined. The investigation should then perhaps lead to a pilot project in able to try and implement PtH in a testing environment so that future transgression penalty costs may be avoided. Or perhaps implemented elsewhere, where a profit is possible.

This testing phase should involve a lot of different stakeholders, including authorities. This will require a lot of coordination. Also, legal matters such as competitive advantages will have to be addressed in order to really implement PtH.

Finally, in a even longer perspective, many flexibility resources may be available through a virtual marketplace, where large quantities of flexibility resource usage is traded. Testing on how this scenario would affect the power system in general would be of great interest for the electricity system as well as the society.

Appendix A

Appendix - Code

A.1 Visual Basic for Applications

A.1.1 Subscription optimization code

Algorithm A.1: Calculates and represents the subscription optimization with varying subscription level.

```
Sub SubOptimization()

    Dim subcriptionLevel As Long, subscriptionChange As Long,
        newSubscriptionLevel As Long, highestPeak As Long, optimalSub As
        Long, newOptimalSub As Long

    Dim iterations As Integer, i As Integer
    Dim visualSheet As Worksheet



    Set visualSheet = ThisWorkbook.Worksheets("Visual")

    With visualSheet

        Columns("AA:AC").ClearContents

        subcriptionLevel = .Cells(6, "O").Value ' Get subscription Level
        subscriptionChange = subcriptionLevel / 100 'A hundreth of the
            Current Subcription Level
        highestPeak = .Cells(34, "O").Value ' The largest power
            transmission
        .Cells(8, "R").Value = 1000000000

        .Cells(7, "O").Value = highestPeak - subcriptionLevel
        subChange = .Cells(7, "O").Value

        For i = 0 To 50 '50 steps

            Select Case .Cells(5, "O").Value
```

```
                Case "SvK"
                    SVKSubscriptionCalc
                Case "SvK Old"
                    SVKSubscriptionCalc

            End Select

            ' Print every subscription level change
             .Cells(1 + i, "AA").Value = .Cells(7, "O").Value / 1000

            ' Calculate subscription savings
            .Cells(1 + i, "AB").Value = .Cells(9, "R").Value ' Savings


                If (i > 2) Then
                    If (.Cells(1 + i, "AB").Value < .Cells(i, "AB").Value
                        ) Then
                        .Cells(8, "R").Value = .Cells(1 + i, "AB").Value
                    End If
                End If

            ' Calculate savings with flexibility Resource
            If .Cells(12, "O").Value = True Then
                PtHCalc
                .Cells(1 + i, "AC").Value = .Cells(17, "R").Value
            End If

            .Cells(7, "O").Value = .Cells(7, "O").Value -
                subscriptionChange

        Next i

        'reset
         .Cells(7, "O").Value = 0



    End With

End Sub
```

A.1.2

Algorithm A.2: Code to calculate the temporary subscription costs in a enclosed subscription á seven days as well as the total costs for the transgression using excel datasheets.

```
    ' This programme calculates the Subscription Cost with the SvK Model.

Public Sub SVKSubscriptionCalc()
```

```
Dim NbrofTempSubscriptions As Byte
Dim lastRowNbr As Double, i As Integer, currentMax As Long
Dim cellStart As String, cellStop As String, cell As Range
Dim powerFee As Double, subscriptionCost As Double
Dim inputSheet As Worksheet, powerCalc As Worksheet, visualSheet As
    Worksheet

Set visualSheet = ThisWorkbook.Worksheets("Visual")
Set transmissionSheet = ThisWorkbook.Worksheets("Transmission")

With visualSheet

    powerFee = .Cells(3, "O").Value ' Get Power Fee

End With

With transmissionSheet

    lastRowNbr = .Cells(.Rows.Count, "B").End(xlUp).Row    ' Counts
        the number of data inputs.

    'Counts rows of sheets with data ant iterates through it
    For i = 3 To lastRowNbr

        ' Finds a power violation (with value larger than zero) and
            stores its cell address and value.
        If (.Cells(i, "J").Value > 0) Then
            currentMax = .Cells(i, "J").Value
            cellStart = .Cells(i, "J").Address
            cellStop = .Cells(i, "J").Offset(24 * 7, 0).Address '
                Jumps 7 days i.e the temporary subscription length

                    For Each cell In Range(cellStart, cellStop)
                        If (currentMax < cell.Value) Then
                        currentMax = cell.Value ' Stores the max
                            value
                        End If
                    Next

            'Calculates the cost of the Temporary Subscriptions and
                the number of Subscriptions
            Select Case visualSheet.Cells(5, "O").Value
                Case "SvK"

                    subscriptionCost = subscriptionCost + (currentMax
                         / 200 * powerFee)
                    NbrofTempSubscriptions = NbrofTempSubscriptions +
                         1
                    i = i + (24 * 7) 'Jumps seven days so that a
                        violation isn't calculated twice

                Case "SvK Old"
```

```
                        subscriptionCost = subscriptionCost + (currentMax
                            / 12 * powerFee)
                        NbrofTempSubscriptions = NbrofTempSubscriptions +
                            1
                        i = i + (24 * 7) 'Jumps seven days so that a
                            violation isn't calculated twice

                End Select

            End If
        Next i
    End With

    ' Stores the data for visualization
    ' TODO (?) - Make the cost calculations in a Makro with the usage of
        a Calculation sheet?
    With visualSheet

        Select Case .Cells(5, "O").Value
            Case "SvK"

                .Cells(3, "R").Value = transmissionSheet.Cells(lastRowNbr
                    + 1, "K").Value
                .Cells(4, "R").Value = transmissionSheet.Cells(lastRowNbr
                    + 1, "L").Value

            Case "SvK Old"
                .Cells(3, "R").Value = 0
                .Cells(4, "R").Value = transmissionSheet.Cells(lastRowNbr
                    + 1, "L").Value

            End Select

        .Cells(5, "R").Value = subscriptionCost          ' Stores the
            Temporary Subscription Cost in Visual-sheet
        .Cells(6, "R").Value = NbrofTempSubscriptions    ' Stores the nbr
            of Temporary Subscriptions in Visual-sheet
        .Cells(7, "R").Value = powerFee * (.Cells(7, "O").Value)
                    ' Calculates Subscription Savings
    End With

End Sub
```

A.1.3 Flexibility resource calculation

Algorithm A.3: Algorithm to calculate the temporary subscription costs in a enclosed subscription á seven days. The local maximum sets the subscription level and its costs.

```
Public Sub PtHCalc()
```

```
Dim boilerSize As Double, lastRowNbr As Double
Dim powerCalc As Worksheet, visualSheet As Worksheet, dhDataSheet As
    Worksheet
Dim i As Integer, consecutiveHours As Integer,
    highRiskConsecutiveHours As Integer, nbrOfHours As Integer
Dim energyVolume As Long


Set transmissionSheet = ThisWorkbook.Worksheets("Transmission")
Set visualSheet = ThisWorkbook.Worksheets("Visual")
Set dhDataSheet = ThisWorkbook.Worksheets("DHData")


'Inputs from Column "O", Outputs on Column "R"
With visualSheet
    boilerSize = .Cells(13, "O").Value ' Get BoilerSize
    .Cells(13, "R").Value = 0
    .Cells(14, "R").Value = 0
    .Cells(15, "R").Value = 0
End With


' Transmission Data on Column "H", Violation Effect on Column "J"
With transmissionSheet
    lastRowNbr = .Cells(.Rows.Count, "H").End(xlUp).Row    ' Counts
        the number of data inputs.

    'Counts rows of sheets with data ant iterates through it
    For i = 3 To lastRowNbr

        ' Finds a value within the treshhold (larger than Zero) which
            can be subject for PtH
        If (.Cells(i, "J").Value > 0) Then

            Select Case .Cells(i, "J").Value
                Case Is >= boilerSize ' The Value of Violation is
                    bigger or equal to boilerSize

                    energyVolume = energyVolume + boilerSize

                    If (dhDataSheet.Cells(i, "E").Value < 5) Then '
                        Column "E" is DH production data
                        highRiskConsecutiveHours =
                            highRiskConsecutiveHours + 1
                    End If

                Case Is < boilerSize

                    energyVolume = energyVolume + .Cells(i, "J").
                        Value

                    If (dhDataSheet.Cells(i, "E").Value < 5) Then
                        highRiskConsecutiveHours =
```

```
                                highRiskConsecutiveHours + 1
                        End If

                End Select

                consecutiveHours = consecutiveHours + 1

                      If (.Cells(i + 1, "J").Value = 0) Then
                        If (consecutiveHours > visualSheet.Cells(14, "R")
                            .Value) Then 'If new consecutive hours is
                            larger than old value.
                            visualSheet.Cells(14, "R").Value =
                                consecutiveHours
                        End If

                        If (consecutiveHours > visualSheet.Cells(15, "R")
                            .Value) Then 'If new high risk consecutive
                            hours is larger than old value.
                            visualSheet.Cells(15, "R").Value =
                                highRiskConsecutiveHours
                        End If

                        consecutiveHours = 0
                        highRiskConsecutiveHours = 0

                    End If
                nbrOfHours = nbrOfHours + 1
            End If
        Next i

    End With

    visualSheet.Cells(13, "R").Value = nbrOfHours
    visualSheet.Cells(12, "R").Value = energyVolume

End Sub
```

A.2 Code Snippet Visual Basic Application [VBA]

Algorithm A.4: Algorithm to calculate the temporary subscription costs in a enclosed subscription á seven days. The local maximum sets the subscription level and its costs.

```
'Finds a power violation (with value larger than zero) and stores its
    cell address and value.
    If (.Cells(i, "J").Value > 0) Then
        currentMax = .Cells(i, "J").Value
        cellStart = .Cells(i, "J").Address
        cellStop = .Cells(i, "J").Offset(24 * 7, 0).Address 'Jump seven
            days (SvK Sub-length)
            For Each cell In Range(cellStart, cellStop)
```

```
                If (currentMax < cell.Value) Then
                    currentMax = cell.Value
                End If
            Next
    -...-
    -...-
    End If
```

Algorithm A.5: Algorithm to calculate the energy volume used in a flexibility resource.

```
            ' Finds a value within the treshhold (larger than Zero) which
                can be subject for PtH
            If (.Cells(i, "J").Value > 0) Then

                Select Case .Cells(i, "J").Value
                    Case Is >= boilerSize ' The Value of Violation is
                        bigger or equal to boilerSize

                        energyVolume = energyVolume + boilerSize

                        If (dhDataSheet.Cells(i, "E").Value < 5) Then '
                            Column "E" is DH production data
                            highRiskConsecutiveHours =
                                highRiskConsecutiveHours + 1
                        End If

                    Case Is < boilerSize

                        energyVolume = energyVolume + .Cells(i, "J").
                            Value

                        If (dhDataSheet.Cells(i, "E").Value < 5) Then
                            highRiskConsecutiveHours =
                                highRiskConsecutiveHours + 1
                        End If

                End Select
    -...-
    -...-
    End If
```

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