CHALMERS
UNIVERSITY OF TECHNOLOGY

EXPLORING THE PATHS

THE TRANSITION TOWARDS A SUSTAINABLE ENERGY SYSTEM FOR A SWEDISH MUNICIPALITY

Master's thesis in Sustainable Energy Systems

JOHN JOHANNESSON

Department of Energy and Environment
CHALMERS UNIVERSITY OF TECHNOLOGY
Göteborg 2016

EXPLORING THE PATHS

The Transition Towards a Sustainable Energy System for a Swedish Municipality

Supervisor: Germán Maldonado
Examiner: Erik Ahlgren

Department of Energy and Environment
Chalmers University of Technology
SE-412 96 Göteborg
Sweden
Telephone + 49 (0)31-772 1000

ABSTRACT

About three fourths of the global anthropogenic greenhouse gas emissions can be linked to energy use. This study aims to identify some driving forces behind the development of an energy system and how these forces can drive the development of a sustainable energy system. The study focuses on a single Swedish municipality, Halmstad. A secondary purpose has been to analyse some concepts of energy system forecasting.

The energy system can be described as a *sociotechnical system*. Three related mechanisms discussed in the study are *learning by doing*, *lock-in* and *technology clusters*. To gain an understanding of the structure and development of the energy system, data and information regarding the import, production and consumption of energy was collected. To make the forecasts in this thesis, the method of *logistic forecasting* has been used.

Halmstad's generation capacity for electricity as of 2015 is 61 MW and consists primarily of wind power (40%), followed by hydropower (36%), combined heat and power generation (22%) and solar photovoltaics (2%). District heating is supplied by two plants: a 68 MW capacity waste-incineration plant, supplemented when needed by a natural gas and wood chip-fired 122 MW capacity plant. Non-renewable energy and electricity were the main energy carriers for end use, at 41% and 35% respectively, in 2013. The use of district heating and biofuels is increasing notably.

Signs of lock-in can be seen with regard to the use of waste incineration. The benefits of learning by doing can be seen with regard to the installations of solar panels made by the municipality. Overall, progress toward a sustainable energy system has been made in some areas, e.g. the residential and public sectors and electricity generation, while others, e.g. the transport sector still have a long way to go.

Keywords: municipal energy system, logistic forecasting, lock-in, learning by doing, technology clusters, Halmstad, sustainable energy transition, energy system overview

TABLE OF CONTENTS

1 INTRODUCTION

1.1 BACKGROUND

The human civilization stands before perhaps its greatest challenge yet. According to the Intergovernmental Panel on Climate Change (IPCC, 2014),

> *Human influence on the climate system is clear, and recent anthropogenic emissions of greenhouse gases are the highest in history. Recent climate changes have had widespread impacts on human and natural systems.*

About three fourths of the global anthropogenic greenhouse gas emissions can be linked to the use of energy[1] (IPCC, 2014). But in spite of these alarms and warnings, the reshaping of our energy system has so far been a slow process, even in those countries which have a seemingly good capability to change their energy systems into entirely renewable ones. With this in mind, this master's thesis aims to identify some of the driving forces behind the development of an energy system and to understand how these forces can drive the development of a sustainable energy system. In order to study these mechanisms on a smaller scale, the majority of the study is focusing on a single Swedish municipality, Halmstad. Halmstad was chosen as the municipality to be studied based on the following qualities: a stated desire to work actively towards a more sustainable energy system (with a special interest in solar energy), being fairly average (and therefore representative) with regards to the geographical size, population size, energy system composition etc., and having not already been the target of numerous other energy system related studies.

1.2 OBJECTIVE OF THIS WORK

The objective of this master's thesis is to study the energy system of Halmstad municipality in a historical perspective to identify and analyse the driving forces behind the development of the energy system, and also to look forward and analyse some possible future developments. A secondary purpose has been to analyse some concepts of energy system forecasting, and to develop computer code to test these.

1.3 LIMITATIONS

The study is confined to a single Swedish municipality, to limit the workload of analysing large parts of the energy system and to enable analysis at a level which the available information and data has permitted.

The study is focused on the import (here 'imported' simply denotes energy which has been produced outside of Halmstad's energy system), local generation, distribution, and use of energy. The focus is on the electric power system, but other parts of the energy system, e.g. district heating and transport, are studied as they interact with the electricity system. The system that is studied in the main part of the thesis is confined to the geographical boundaries of the municipality of Halmstad.

[1] This includes the following categories: *electricity and heat production, industry, transportation, buildings* and *other energy*. The emissions from *agriculture, forestry and other land use* make up the remaining quarter and are considered to be mainly unrelated to the energy system.

1.4 QUESTIONS TO BE ANSWERED

The main questions to be answered by the study are the following:

1. How has the energy system developed from 1990 to 2013?
2. What are some main reasons for the energy system to have developed in the direction that it has? Are these driving forces still in effect?
3. What current and future sustainability issues of the energy system can be identified by analysing the collected data and the forecasting method chosen? How can these issues be tackled?

1.5 DESCRIPTIONS OF THE CHAPTERS

Chapter 2, *Methodology*, begins with an overview of the literature that has inspired and supported the thesis. Thereafter the methods for collection and structuring of information and data, forecasting, and analysing the development of the energy system are presented.

Chapter 3, *Historic overview*, provides some background in the form of a brief accounting of the development of the Swedish energy system, from the middle of the 19th century and onwards, with a focus on electricity. It also provides a brief overview of Halmstad municipality; geography, organisational history, industry etc., as well as some more specific history on the energy system of Halmstad municipality.

Chapter 4, *The energy system in Halmstad municipality*, presents data on Halmstad municipality's energy system, mainly focused on the last quarter-century. The data is presented mainly as diagrams and tables, with accompanying text describing identifiable trends and connections to other parts of the energy system and/or other parts of the surrounding sociotechnical system. The chapter ends with a summary of the key observations made in the chapter.

Chapter 5, *Forecasting*, presents the forecasts made, also here mainly in the form of diagrams with accompanying text.

Chapter 6, *Emerging technologies*, focuses on the two emerging energy technologies of wind and solar power, and specifically their development in Halmstad municipality.

Chapter 7, *Mechanisms shaping the energy system*, first looks at some overall factors that can be seen in the development of the energy system. Later in the chapter we focus on two mechanisms that are deemed interesting: *learning by doing* and *lock-in*, with examples from Halmstad's energy system.

Chapter 8, *Identified current and future sustainability issues of the energy system*, provides a discussion of some current and future sustainability issues identified in the thesis.

Chapter 9, *Conclusions*, presents the conclusions made from the thesis.

2 METHODOLOGY

2.1 LITERATURE OVERVIEW

The energy system can be described as a *sociotechnical system* (Kaijser, Mogren, & Steen, 1988), i.e. a technical system that is closely interlocked with the society in which it is built. This means that the societal aspects, e.g. ownership structures, laws, regulations and political direction are at least as important as the technical ones. Two mechanisms which emerge within the sociotechnical system are *learning by doing* and *lock-in*. Learning by doing (Grübler, 1998; Hogan, 2014; Junginger, Lako, Lensink, Sark, & Weiss, 2008) is the effect where the production and use of a technology generates information and experience which makes further production and use of the same (or related) technologies easier, and therefore cheaper. This effect is significant in the early lifetime of a technology, and is therefore important to consider when studying emerging technologies. Lock-in (Unruh G. C., 2000; 2002) describes how technological, economic, cultural and institutional forces legitimise and give continued support to a system that in reality can be far from optimal. A regional perspective can be found in an article by Corvellec, Campos, & Zapata (2013), on the topic of waste incineration in Göteborg. Kalkuhl, Edenhofer, & Lessmann (2011) explains that due to the almost perfect substitutability of energy as a good, the energy sector has a high vulnerability to lock-in.

Relating to the notion of the sociotechnical system, Unruh (2002) points out that the great challenge in reshaping a system and escaping *lock-in* is not so much in replacing the technology itself as it is in changing the institutions that manage the technology and operate the systems, especially when the reshaping requires parts of the system to be replaced rather than just gradually improved. Another important aspect when studying changes in the energy system (or any technological system) is that of *technology clusters* (Grübler, 1998). A technology cluster is a group of technologies which co-exist at a certain point in time, and through mutual interdependence form the basis of the technological structure at that time, as well as being '…embedded in profound transformations of the social and organizational fabric of society' (Grübler, 1998, p. 120). So far, there has been four clusters, identified by Grübler as *textiles*, *steam*, *heavy engineering* and *mass production & consumption*. Each cluster lasts for about 50 years, and can overlap the preceding cluster by about 20 years. Thus, while technologies belonging to different clusters can co-exist for a limited period of time, in the long term it is problematic or even impossible to replace only one or a few of the technologies making up the cluster (or the institutions governing it); the entire cluster must be replaced by a new one. In a similar vein, Maldonado (1991) writes:

> *'"Technical development usually moves ahead by fits and starts", writes Eriksson*[2]*. This is due to the fact that the technology utilized by a society is interdependent. In order to accomplish great changes in fundamental technical systems (or parts of systems), the prerequisites of technical consistency (in individual systems) and technical uniformity (among different systems in society) have to be fulfilled, and several different technical systems or parts of systems have to be changed or replaced in conjunction. Such changes are usually rather radical and capital intensive processes, which because of their proportions alone can very often not be carried through. Consequently, only such changes that improve existing technical consistency and uniformity can be accepted. Just as old technology can become difficult to handle within the framework of a new, uniform*

[2] Eriksson & Eriksson (1980)

technical system, new technology can become ineffective within a society that has preserved its traditional technical uniformity.

In Sweden, as in other industrial countries, each phase in the development of energy systems has been characterized by the technology available, by the material it has been possible to utilize, by the way production has been designed and organized, and by what kinds of fuel have been predominant. Even though there were (and are) a great many other organizational and social factors that affect the design of production, the demand for technical uniformity and consistency has never been abandoned. In industrial countries, this process has required a balanced and sweeping technical, social, economic and organizational change of the whole society.'

An inspiration to the forecasting part of the study has been Lund & Mathiesen (2007). This article shows suggestions for possible developments for the Danish energy system to reach 50% renewables in the year 2030 and 100% renewables in the year 2050. Methods for modelling and studying future energy systems using the software *EnergyPLAN* are also discussed. Wene & Rydén (1988) talks about the use of computer models (and specifically linear programming) for planning municipal energy systems. The authors describe two aspects of planning that needs to be considered when designing and using such a model: the technical; i.e. how the energy system itself is designed, and the process; i.e. how the planning for the system is made and implemented. To make the forecasts in Chapter 5, the method of *logistic forecasting* has been used. There is considerable evidence to support the theory that goods as well as technologies have a limited life, in which they are introduced, grow, reach maturity and then decline (Maldonado, 1989). Thus, plotting the market share of a certain technology with respect to time often results in an S-shaped (logistic) curve: slow growth at the beginning followed first by an accelerating growth as the technology gains momentum, and then a decelerating growth followed by saturation of the available market (Grübler, 1998, p. 60). Grübler warns however: 'Note though that the [logistic forecasting model] is entirely *descriptive*, it shows how a diffusion/substitution process looks, but does not explain *why* it behaves as it does.' Therefore, more important than the forecast itself is the interpretation of the results and the circumstance in which the model has been used. For example, a trend shown by a logistic forecast will only be valid for as long as the conditions causing the trend are valid (Maldonado, 1989). Different models for logistic forecasting are discussed by Kucharavy & De Guio (2011), there among the *Simple logistic model* and the *Component logistic model*, which were used in this thesis.

2.2 COLLECTION OF DATA AND INFORMATION AND MAPPING THE CURRENT SYSTEM

In order to gain a basic understanding of the structure and development of the energy system, data and information regarding the import, production and consumption of useful energy was collected. Other relevant information related to the energy system has also been collected when such information has been available. Collection and analysis of the data and other information has been performed in an alternating fashion, as studying the available data was often needed in order to realise what additional data and information to look for. In most cases, finding complete and/or perfectly matching data sets has not been possible, affecting the quality of the analysis. In some cases, other available data and/or information has been used either as a direct substitute, or as a way to approximate the missing data[3].

[3] For example, if available data shows that the system uses a total of X GWh of electricity one year, and the in-system generation of electricity is Y GWh that year, it is reasonable to assume that the imported electricity amounts to (X-Y) GWh.

2.2.1 DATA AND INFORMATION SOURCES

The main source of data, providing the bulk of the constructed picture of the energy system has come from Statistics Sweden (*Statistiska centralbyrån*), where regional energy data for Halmstad municipality could be found for the years 1990, 1995 and 2000-2013 (Statistics Sweden, 2015). From 2009 and forward however, the data is less precise with fewer, more general categories, and increasingly incomplete. Data from the Swedish Energy Markets Inspectorate (*Energimarknadsinspektionen*) has been used to fill in some of these gaps. Data for the electricity import and distribution for the years 1930 – 1965 was found in the Municipal Archive of Halmstad (*Kommunarkivet i Halmstad*). For the period from 1966 to 1989 however, no data could be obtained, despite numerous attempts. Information on the various power plants in the municipality come mainly from three different sources; for the CHP/heating plants, information comes mainly from official descriptions from the owner, HEM (*Halmstad energy och miljö*)[4]; for the hydropower plants, the web site *Vattenkraft.info*[5]; for wind power, the Swedish Energy Agency (*Energimyndigheten*)[6]; and for solar power, a document from the Halmstad municipal department of real estate (*Fastighetskontoret*)[7]. For a complete list of data sources, see *Appendix: Data sources*.

Box 1: STRUCTURING THE ENERGY SYSTEM

Any energy system can be described as containing two types of energy: *primary* and *secondary*, as well as three sections: *production*, *conversion* and *use*.

Primary energy describes energy sources found in nature: fuels like coal, oil and biomass, as well as uranium. The kinetic energy captured in hydro- and wind power plants, as well as the solar radiation captured by photovoltaic cells and various solar-thermal plants are also counted as primary energy. Since these sources are less tangible and more difficult to measure directly than fuels, they are considered to be equal to the output of useful energy by the capturing technology, e.g. if a hydropower plant produces 1 GWh of electricity during one year, it is considered to have utilised 1 GWh of primary hydro energy.

Supply of primary energy to the energy system is done during the production stage, e.g. drilling for crude oil or capturing kinetic energy with a wind power plant rotor.

Secondary energy is primary energy which has been converted into a more useful carrier, e.g. gasoline that has been distilled from crude oil, electricity produced from the kinetic energy of a wind power plant rotor via a generator, or hot water produced, along with electricity, from burning coal or biomass in a combined heat and power (CHP) plant. These processes constitute the conversion stage of the energy system. Note, however, that also secondary energy can be used as the input for conversion, e.g. when using a diesel-powered electric generator.

The use stage is where the secondary energy is utilised by the final consumer, e.g. burning gasoline to power a car, using electricity to power a refrigerator or charge a cell phone, or burning wood in a stove to heat a cottage.

2.2.2 STRUCTURING OF DATA

The primary method of structuring the data has been through the use of an *energy matrix*, where all the energy flows through the studied system during a chosen time period (in this case one year) are structured. A sample matrix for Halmstad municipality in 2008[8] can be seen in Table 1.

The columns of the matrix each represent a specific energy carrier (or a sum of several energy carriers). The first rows deal with the supply of energy into the system; import (or utilized influx, in the case of naturally occurring energy carriers such as hydro energy) and in-system production. The sum of import and in-system production gives the net internal supply. The next section of rows handle conversion; here

[4] (Halmstad energi och miljö, A) & (Halmstad energi och miljö, B)
[5] (Kuhlin, Vattenkraft.info, 2015a)
[6] (Swedish Energy Agency, 2015)
[7] (Halmstad municipal department of real estate, 2016)
[8] 2008 was chosen since it is the last year from which the more detailed data is available.

all types of power plants and are listed, and the in- and outputs are noted. A negative number denotes an input of energy to the plant, while a positive number denotes an output. The last section of rows handles the use of energy within the system; here all the consumer groups are listed, and their respective consumption of the different energy types are noted. After summarising the data in energy matrices, the next step was to re-organise the data into more useful structures reflecting the issues that were to be analysed. Many of these tables and figures are presented in Chapter 4.

Table 1: ENERGY MATRIX FOR HALMSTAD MUNICIPALITY IN THE YEAR 2008. The red numbers have been approximated using other available data.

Units: GWh Year: 2008			Natural gas	Gasoline	Diesel	Heating oil 1	Heating oil >1	LPG	Wood chip	Waste*	Total non-renewable	Total renewable	Hydro energy	Waste heat	District heating	Electricity	Others	TOTAL ENERGY	
ENERGY SECTOR	SUPPLY	Import/utilized influx	358	480	663	144	55	1	176	466	1701	642	95	17		1197	16	3026	Total supply
		Total supply	**358**	**480**	**663**	**144**	**55**	**1**	**176**	**466**	1701	642	**95**	**17**	**0**	**1197**	**16**	3026	
		Unutilized													386			386	
		Net internal supply	**358**	**480**	**663**	**144**	**55**	**1**	**176**	**466**	1701	642	**95**	**17**	**-386**	**1197**	**16**	**2640**	
	TRANSFORMATION	Hydropower											-95			95		-95	Transformation losses
		Thermal power plant				-38					-38					12		-26	
		CHP				-4			-112	-466	-4	-578		-17	562			-37	
		Heating plant	-191						-1		-191	-1			182			-10	
		Total transformation	**-191**	**0**	**0**	**-42**			**-113**	**-466**	-233	-579	**-95**	**-17**	**744**	**107**		**-168**	
		Energy sector own use														35		35	Total consumption
		Transmission losses													36	92		128	
CONSUMERS	USE	Agriculture**			23	2					25					29		54	
		Industry & construction	167		14	10	43	1			235				6	433	16	690	
		Public sector			2	7					9				45	127		181	
		Transport		479	613						1092							1092	
		Residential			1	12			62		13	62			41	316		432	
		Others			11	70	11				92				230	272		594	
		Total use	**167**	**479**	**664**	**101**	**54**	**1**	**62**		1466	62			**358**	**1304**	**16**	**3206**	

**Waste is considered to contain 64% renewable and 36% non-renewable carbon. **Including forestry and fishing. Red numbers are approximated.*

2.3 LOGISTIC FORECASTING

2.3.1 INTRODUCTION

In order to be able to use the data collected to also analyse future trends, the logistic forecasting method has been used. This particular forecasting method is chosen because it is well-documented (Grübler, 1998; Kucharavy & De Guio, 2011; Maldonado, 1989) and relatively easy to implement. It was also felt that due to the limited quality and detail of the collected data, using a more complex model would be of little benefit.

The logistic curve (also called the S-curve, in a reference to its shape) can be used to describe the growth of a population or system in a number of different contexts, from the growth of bacteria in a petri dish to the market share of a specific technology (Kucharavy & De Guio, 2011). Using the logistic curve has been the method of forecasting used during this thesis. The computations have been made in MATLAB, so the first step was to adopt the theoretical framework into programming code, as shown in Section 2.3.2. Next, suitable sets of data have been used to generate the forecasts. Not all datasets have been suitable for generating logistic projections; either due to the sets being too limited or incomplete, or simply because there is no sign of logistic growth or recession in the data provided. The results from these failed projection attempts range from projections that seem somewhat unreasonable to the curve-fitting algorithm simply failing to find any match with any logistic curve whatsoever. Of course, even when the available data fits almost perfectly onto the shape of a logistic curve, the resulting projection is no 'magic crystal ball' showing an exact future; at best, they can be a sign pointing out an approximate direction. The results must therefore be carefully analysed to be of any use – this daunting task is attempted in Section 5.1, where the forecasts are presented.

2.3.2 ADOPTING THE LOGISTIC CURVE FOR USE IN A PROGRAMING ENVIRONMENT (MATLAB)

The following section is based on Arnold (2002).

The logistic curve can be written on the form

$$\frac{dx}{dt} = rx\left(1 - \frac{x}{K}\right) \qquad \text{Equation 1}$$

where t is time, $x = x(t)$ is the quantity to be studied and r and K are positive parameters. Solving for x, the equation is rewritten as

$$x(t) = \frac{K}{1 + Ce^{-rt}} \qquad \text{Equation 2}$$

where C is an arbitrary constant.

Next we calculate the second derivative of x with respect to t:

$$x''(t) = \frac{CKr^2e^{rt}(C - e^{rt})}{(C + e^{rt})^3} \qquad \text{Equation 3}$$

The graph of $x = x(t)$ will have a point of inflection where Equation 3 is zero, which occurs when $C = e^{rt}$. By putting $C = e^{rt_0}$, where t_0 is the time when the inflection point occurs and inserting this into Equation 2, we get

$$x(t) = \frac{K}{1 + e^{-r(t-t_0)}} \quad \text{Equation 4}$$

We have now rewritten the equation for the logistic curve on a suitable form. The next step is to fit the logistic curve to the data, meaning that the sum of the difference e for each point of the data set t_i, x_i should be as small as possible. e is defined as the difference between the value of the data point and the value of the logistic curve. To ensure that the error is always positive, we square the error and then minimize the result. In symbols:

$$e = \sum_{i=1}^{n} (x(t_i) - x_i)^2 \quad \text{Equation 5}$$

Now we eliminate one of the three parameters from Equation 4, in order to use Matlab to find an estimate of the least squares problem. Putting

$$x(t) = Kh(t) \quad \text{Equation 6}$$

we get

$$h(t) = \frac{1}{1 + e^{-r(t-t_0)}} \quad \text{Equation 7}$$

thus eliminating K. To be able to use Matlab to produce a numerical solution, we create the vectors

$$\boldsymbol{H} = \langle h(t_1), h(t_2), \ldots, h(t_n) \rangle$$

and

$$\boldsymbol{X} = \langle x_1, x_2, \ldots, x_n \rangle$$

Rewriting Equation 5 using these vectors and inserting Equation 6, we get

$$e = K^2 \langle \boldsymbol{H}, \boldsymbol{H} \rangle - 2K \langle \boldsymbol{H}, \boldsymbol{X} \rangle + \langle \boldsymbol{X}, \boldsymbol{X} \rangle \quad \text{Equation 8}$$

where $\langle a, b \rangle$ is the dot product of a and b

Equation 8 still contains the three parameters K, r and t_0. We need to adjust these parameters to minimize e. This is done by setting the partial derivative with respect to K to zero and solving for K.

$$\frac{\partial e}{\partial K} = 0$$

$$2K \langle \boldsymbol{H}, \boldsymbol{H} \rangle - 2 \langle \boldsymbol{H}, \boldsymbol{X} \rangle = 0$$

$$K = \frac{\langle \boldsymbol{H}, \boldsymbol{X} \rangle}{\langle \boldsymbol{H}, \boldsymbol{H} \rangle} \quad \text{Equation 9}$$

Substituting this into Equation 8, we get

$$e = \langle \boldsymbol{X}, \boldsymbol{X} \rangle - \frac{\langle \boldsymbol{H}, \boldsymbol{X} \rangle^2}{\langle \boldsymbol{H}, \boldsymbol{H} \rangle} \quad \text{Equation 10}$$

This equation contains only two parameters, r and t_0, making it much easier to deal with. A graph of e, as defined by Equation 10, can now be plotted as a function of r and t_0. First we define the domain in the $r - t_0$ –plane. The limits of t_0 are the endpoints of the time data. For r, we use the interval of $-1 \leq r \leq 1$. Although the logistic curve is defined for values of r from $-\infty$ to ∞, values of $|r|$ much larger than 1 produce a very ’square’ curve, more akin to a (backwards) ‘Z’ than an ‘S’, and thus of limited potential in representing an actual growth pattern.

Now, using Matlab, a contour plot of the error varying with the parameters r and t_0 can be made. The curve with the closest approximation will have the parameters corresponding to the smallest error. In this example, we are forecasting the total electricity use per year for Halmstad municipality.

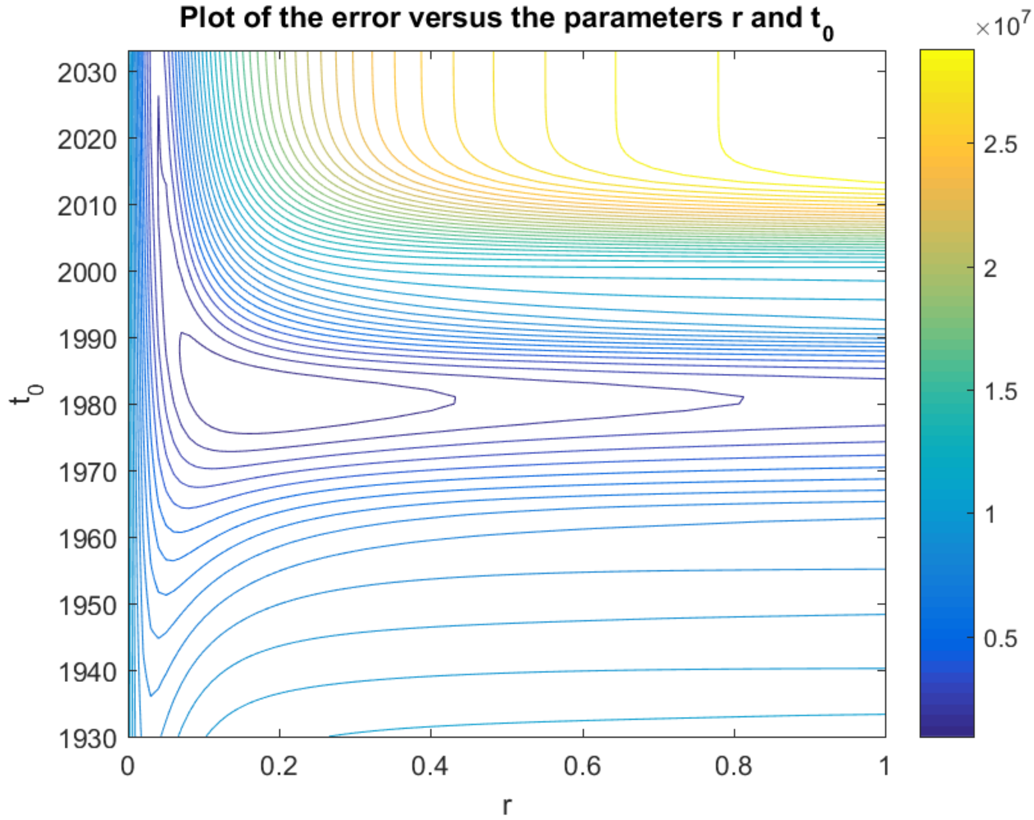

Figure 1: PLOT OF THE ERROR VERSUS THE PARAMETERS r AND t_0. The error is smallest in the region around $r = 0.2, t_0 = 1981$.

The parameters t_0 and r are thus defining our logistic curve. The parameter t_0 is, as stated previously, the point of inflection, i.e. the year in which the rate of growth of the electricity use becomes zero. In other words, according to the model the electricity use will grow faster and faster until 1981, at which point the growth is less and less every year as the system moves towards its maximum value. The parameter r determines the steepness of the curve, with a larger number producing a steeper curve. In this example, r takes the value of approximately 0.2. Negative values of r denotes a declining curve.

Having computed this data, it is a simple task for the computer to find the smallest value of e and the corresponding values of t_0 and r. In this example these parameters are $t_0 \approx 1981$ and $r \approx 0.17$. The resulting curve is the calculated using Equation 4.

The parameter K determines the asymptote (the maximum value that the curve approaches). If this asymptote is known beforehand, we can force the logistic curve to approach this value by setting K to a specific value. Since K is then known, Equation 4 can be calculated directly for every value in the vector $\boldsymbol{T} = \langle t_1, t_2, \dots, t_n \rangle$, producing a vector

$$\boldsymbol{X_{calc}} = \langle x(t_1), x(t_2), \dots, x(t_n) \rangle \qquad \text{Equation 11}$$

$\boldsymbol{X_{calc}}$ is also dependant on the values of t_0 and r, and by using Equation 5 to calculate the error for each combination of values of t_0 and r, we can let the computer find the optimum values of these parameters, just like in the previous method. The forecasting curve can then be calculated using Equation 4. For the projections made in this thesis however, the asymptote is always unknown, so this method is not used.

2.3.3 FILLING IN GAPS IN THE DATA

Before the complete curve in our example can be calculated, another issue has to be solved: we are, unfortunately, working with an incomplete data set. As the data for the years 1966 to 1989 is missing, these values must first be approximated. Fortunately, the forecasting model can help us fill in this gap. To do this, the forecasting model is first run with the values for the years 1930 to 1965 and is instructed to calculate the values for the missing period. The approximation of the missing data can be seen in Figure 2.

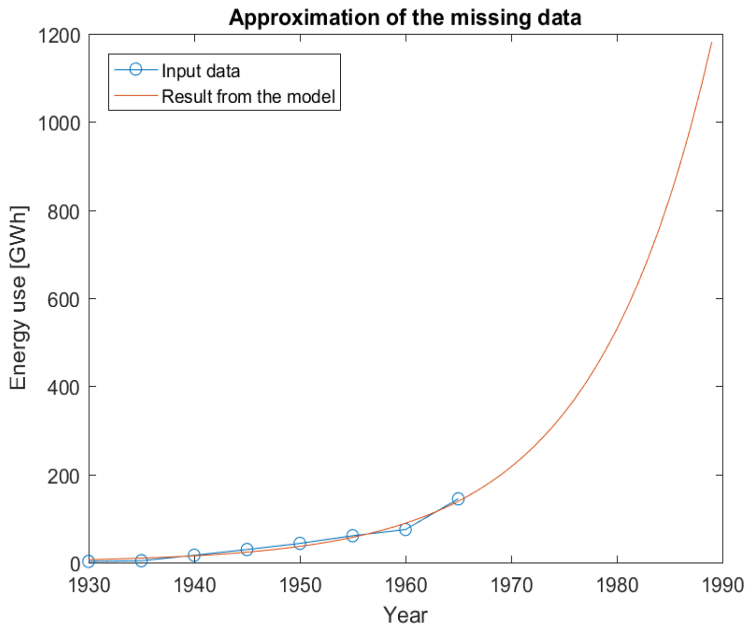

Figure 2: APPROXIMATION OF THE MISSING DATA. The model's value for 1990 is 1292 GWh while the actual value is 1125 GWh, giving an error of 15%.

The approximated data hits the mark almost surprisingly well, but has to be adjusted down by 15% to give the same value in 1990 as the actual value in the reported data. The approximated values are then inserted into the gap in the data and the whole series is fed back into the model for the forecasting calculation. The result can be seen in Figure 3. Looking at the result of this simple forecasting model, we see that the electricity use is projected to grow until around the year 2020, after which it will stabilize at around 1200 GWh per year. But for how long? Here, the forecast gives no answers; the logistic curve will continue at the same level forever, but reason tells us that this is unlikely the case for the electricity use.

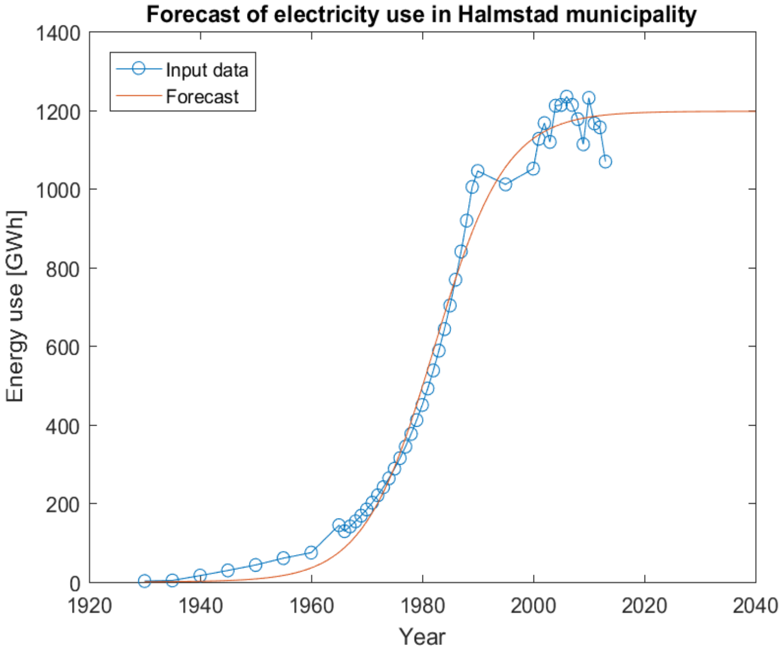

Figure 3: FORECAST OF ELECTRICITY USE IN HALMSTAD MUNICIPALITY

2.3.4 A MORE ADVANCED MODEL: THE COMPONENT LOGISTIC MODEL

In order to generate a more detailed (although not necessarily more accurate) forecast, it is beneficial to divide the quantity that is to be forecasted into separate subdivisions (Kucharavy & De Guio, 2011). These subdivisions can then be forecasted individually, and the produced forecasts can then be summed to produce a more detailed forecast for the overall quantity. For example, to more accurately forecast the electricity use, instead of making a forecast using the data for the total electricity use, forecasts for each of the user categories (residential, industry & construction, etc.) are made. By forecasting the end use of each user category separately, trends in individual categories, which would be lost in the total use data, can be forecasted. The individual forecasts are then summed into a forecast for the total electricity end use. Figure 17 shows such a forecast, for the electricity end use.

2.4 COST OF SOLAR ELECTRICITY

The cost of electricity produced by the solar photovoltaic panels installed by Halmstad municipality (presented in section 6.2.2) is taken directly from the data source (Halmstad municipal department of real estate, 2016) where it is presented without any explanation of how it is calculated. In order to provide such an explanation here, a likely formula has been 'reverse-engineered' to provide the same cost as in the source. The formula chosen as the best match is

$$C_E = \frac{C_{Inv}}{A_{t,r} * E} \qquad \text{Equation 12}$$

where C_E is the cost of the electricity produced, C_{Inv} is the investment cost, E is the amount of electricity produced by the panels in one year, and $A_{t,r}$ is the equivalent annual cost-factor.

$A_{t,r}$ is calculated as

$$A_{t,r} = \frac{1 - \frac{1}{(1+r)^t}}{r}$$ Equation 13

where t is the expected lifetime of the solar panels and r is the assumed discount rate. The lifetime is set to 25 years, as this number is referenced in the data source as the assumed lifetime when calculating the panels' environmental impact. The discount rate is then adjusted so that the formula gives results matching those found in the data source, in this case giving $r = 3\%$.

2.5 MECHANISMS SHAPING THE ENERGY SYSTEM

In order to further explain the development of the energy system in Chapter 7, two mechanisms deemed important are presented, and their effects studied: *learning by doing* and *lock-in*.

2.5.1 LEARNING BY DOING

Learning by doing is the effect where the production and use of a technology generates information and experience which makes further production and use of the same (or related) technologies easier, and therefore cheaper. Grübler (1998, pp. 81-86) gives the formula

$$y = ax^{-b}$$ Equation 14

where y is the amount of labour, or associated cost of producing the xth unit, a is the labour or cost of the first unit, and b is a constant describing the amount of learning gained for each unit produced.

2.5.2 LOCK-IN

Lock-in occurs when a technical system becomes so integrated in a society that large parts of the society (expectations, preferences, routines; as well as policies, industry standards and even culture) becomes adapted to this technology to the degree that the technology is no longer judged only on its own (economical, environmental, utilitarian etc.) merits. A good example of a locked-in technology is the (internal combustion engine-powered) automobile[9]. Table 2 provides a list of sources of technological lock-in, according to Unruh (2002).

Table 2: SOURCES OF LOCK-IN. Taken from Unruh (2002).

Lock-in source	Examples
Technological	Dominant design, standard technological architectures and components, compatibility.
Organizational	Routines, training, departmentalization, customer-supplier relations.
Industrial	Industry standards, technological inter-relatedness, co-specialized assets.
Societal	System socialization, adaptation of preferences and expectations.
Institutional	Government policy intervention, legal frameworks, departments/ministries.

[9] Many pages could be spent listing the ways in which modern society is created around the automobile (rather than the other way around), but this exercise is left to the reader.

3 HISTORIC OVERVIEW

Before we start looking at Halmstad's energy system, the following chapter will provide some background; first a brief history of the development of the modern energy system in Sweden, and then some general information on Halmstad municipality.

3.1 A BRIEF HISTORY OF THE SWEDISH ENERGY SYSTEM WITH FOCUS ON ELECTRICITY

During the 20th century, Sweden has had many energy-intensive industries, as well as a large potential for hydropower, but very limited fossil fuel resources. During the 1890s a synergetic development of electricity production, electro-technical equipment and electricity use in the industry began. This became a driving force for Sweden's industrial breakthrough and has affected the structure of the industry since. Electricity and electro-technology has been a more important factor in the energy use and industrial direction in Sweden than in many other industrialised countries. Since 1890 the productivity of an industrial worker has increased by roughly 3.5% per year. This is partly coupled to an increased use of energy; the amount of energy used per hour of work has increased by 1.5% per year (Schön, 1993).

The industrial revolution began in Sweden around the year 1850, and with it came both a drastic increase in the use of energy and the introduction of new energy sources and carriers. As a consequence, the Swedish energy system went from being almost self-sufficient to becoming more and more dependent on imported energy, mainly in the form of coal and, later on, oil (Peterson, 1990). In 1850, the total energy use was around 11 TWh and 80-90% of this energy came from domestic sources, mostly wood. In 1900, the energy use had grown to around 35 TWh[10], and only about half of this energy came from domestic sources; still mostly wood, but also from an increasing production of domestic coal (from 50 000 tonnes in 1850 to 200 000 tonnes in 1900) (Peterson, 1990). One of the solutions suggested to reduce the dependence on imported energy was to start producing electricity from hydropower, then considered an almost limitless resource (Peterson, 1990). It took around 40 years for hydropower to totally dominate the electric power production; in 1880, 18% of the electricity was generated in hydropower plants, and 82% in thermal power plants. By 1900, the share of hydropower had grown to 60% (Schön, 1993). By 1923, Sweden's yearly electricity generation amounted to roughly 2.5 TWh, with 95% of the electricity coming from hydropower and 5% coming from thermal power plants (Borgquist, 1923).

Up until the 1880s, industry in Sweden had grown mainly in the countryside, near sources of raw materials and energy; wood, iron ore and rivers and streams suited for hydropower utilisation. During the 1880s however, cities began to grow and new types of industries (some producing electro-technology) were developed. At the same time, structural problems plagued the traditional iron industry. A financial crisis struck in the early 1890s, and even though the cause of the crisis was unrelated to the energy field, the resulting disturbance of the traditional energy sources provided an opportunity for electricity to have a breakthrough as an energy source for industrial applications. At first, electrification was dominated by the heavy industry sector: these plants were already located close to sources of hydropower, and their energy demand was great enough to warrant the construction of power plants supplying a single factory; the only alternative as a more extensive distribution network was not yet in place. With the electrification came a concentrated effort from the involved actors and institutions, which would come to greatly affect the development of the modern industrialised society. Development of new technology – adapted to the needs of the growing industry – played an important role, mainly in

[10] For comparison, today Sweden's total energy consumption is roughly 160 TWh per year (Statistics Sweden, 2016).

newly formed *ASEA* (now part of *ABB, a Swedish-Swiss multinational company with headquarters in Zürich*). After a while the Swedish state also took a greater interest into the development of the electricity sector, mainly through the state-owned company *Vattenfall.* This concentration of effort can be explained partly due to the large capital needs, and partly due to the threat of competition from German companies such as *AEG* and *Siemens* which saw Scandinavia as a natural expansion of their markets. The payoff was that Sweden soon took up a position at the forefront of electricity production and electro-technology (Schön, 1993).

With this development came at the turn of the century the preconditions for a more extensive electrification. During a span of roughly 10 years, both the price of electricity and electric motors halved. This meant that electrification could be used also in less energy-intense industry, and support the structural change that had already begun. No longer requiring a nearby source of power, factories could be located anywhere, and industrial cities began growing more quickly. This meant that the still scarce resource of modern industrial know-how was concentrated and could be utilised more efficiently. The growing cities also supported a growing market for consumer goods (Schön, 1993).

Electrification of the countryside started around 1915, with a moderate progress at first (Borgquist, 1922). Because of the intensifying First World War, the import of coal (which came mainly from England and Germany) dropped from 4 036 thousand tonnes in 1916 to only 1 504 thousand tonnes in 1917 (Peterson, 1990). The following year, driven at least partly by this shortage of fuel, the rate of the electrification increased drastically. This quickened pace continued around 1920, when all easily electrified areas had already been connected to the grid. The quick expansion during the war is even more remarkable considering that the cost of expansion during the war is estimated to have been 2.5 times more expensive than before the war (Borgquist, 1922). A graph of the expansion can be found in Figure 4; note the 'S'-shape characterising logistic growth.

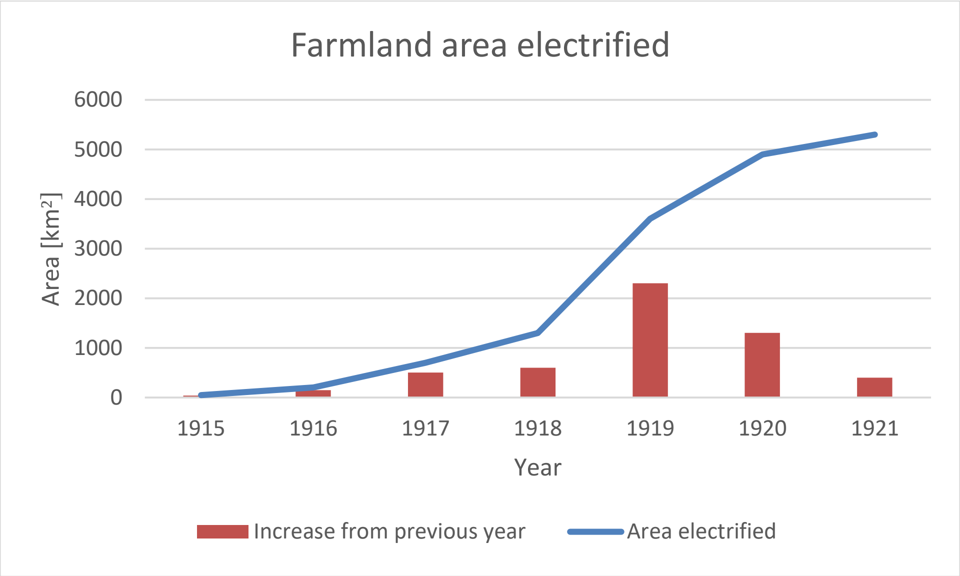

Figure 4: FARMLAND AREA ELECTRIFIED. Farmland connected to the grid owned by Vattenfallsstyrelsen, 1915 – 1921. Adapted from chart in Borgquist (1922).

During the 1920s, international competition meant an increasing pressure for the industry to increase efficiency, and together with fewer investments in new plants this meant that the specific energy use of industry no longer continued to increase. At the same time, electrification spread to both households and public utilities such as railroads, and no longer would the industrial sector be the sole dominating electricity user (Schön, 1993).

Fast-forward to the 1950s, and the electro-technical industry is once again central to the development of society in two ways. Firstly, in order to utilise the large potentials for hydropower located in northern Sweden, new technology for long distance electricity transfer was required, and rising to the challenge, *ASEA* would soon become world leading in high voltage technology, made possible by the development of transformers and the use of alternating current[11]. Secondly, an improved supply of small electric motors gave new possibilities for using electricity both in industrial applications and in the home. Having started in the 1920s, in the 1950s came the real breakthrough of electricity in the home – electric cooking stoves, refrigerators, washing machines and vacuum cleaners. As well as providing another market for the growing industry, the decreased workload in the home led to a dramatic increase in the share of women working in industry and the rapidly growing service sector. Another development that would further consolidate electricity as the main power source for industry was the introduction of electronics and computers, and the automation of entire industrial processes that followed. Here, electricity as an energy carrier met electricity as a carrier of information, and once again a synergy between industrial growth and the new technology was formed, not unlike the one during the initial electrification (Schön, 1993).

In the 1960s and 70s, nuclear power was introduced to the Swedish power grid, enabled by the development of control engineering in the previous decades. With a large base load capacity consisting of low-variable-cost hydro and nuclear power, Sweden was set for a bright future of low electricity prices and world-leading electro-technical and power-producing industry. With the oil crisis in 1973 however, things changed both on the international and domestic markets and another structural crisis hit the Swedish industry, which during the 1960s had become, both directly and indirectly, increasingly dependent on oil. During previous structural crises strong forces of change and renewal, with electrification as a chief component, had stood ready to take industry in a new direction, but this time the direction had already been decided: an expansion of nuclear power. While this meant that the availability of cheap electricity increased dramatically, paradoxically the crisis also made the future of nuclear power, and thus the future of the electricity supply, more uncertain. In spite of this uncertainty, from the middle of the 1970s the specific electricity use of the industry increased significantly, while the specific use of fuels decreased. However, only a small part of this substitution can be explained by changes in relative prices between electricity and fuel. The major reason for change was yet again the introduction of new products and production methods, as well as new work environments and ways of organisation which benefited from the properties of electricity. An example of this is the increasing share of workers' wages as a cost of production, giving incentive to further automate production (thereby reducing the number of employees), which in turn increased the use of electricity (Schön, 1993).

Schön identifies three distinct periods since the middle of the 19th century. The periods are defined by three structural crises, in the 1890s, 1930s and 1970s. After each of the crises, a period of 15 – 25 years where the relative amount of total income used for investments have increased dramatically, especially long-term investments. As the rate of growth reaches its peak, a period of focus on increased efficiency in already constructed facilities and short term investments begins, lasting for 10-15 years and leading up to the next structural crisis[12] (Schön, 1993).

[11] ASEA was also a pioneer in using HVDC (high voltage direct current) transmission, building a HVDC link between mainland Sweden and the island of Gotland in 1954.

[12] Following this pattern, the decade of the next structural crisis is the 2010s – and with the 2007-08 financial crisis regarded by many as the worst economic collapse since the great depression, this may very well be the case. On the other hand, this also suggests that the coming decades will contain the next 'investment phase' – this time hopefully focused on sustainable technologies.

3.2 HALMSTAD MUNICIPALITY

Located on Sweden's west coast, about 130 kilometres south of Göteborg, Halmstad municipality is Sweden's 19th most populous municipality with around 100 000 inhabitants (Halmstad municipality, 2015). The municipality shares its name with the largest city and seat of the municipality, Halmstad [13], which has about 60 000 inhabitants. The municipality was formed in 1974 through a merger of several smaller municipalities with the city of Halmstad.

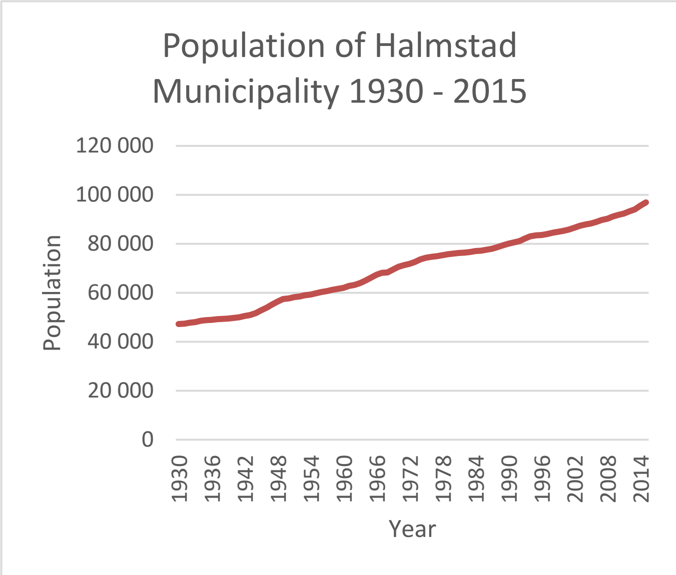

Figure 5: POPULATION OF HALMSTAD MUNICIPALITY 1930 – 2015. As can be seen, the population has grown in a roughly linear fashion throughout this period. The data represents the population living in the geographical area that Halmstad municipality covers today.

A municipality-owned company, *HEM* (Halmstad Energi och Miljö – *Halmstad Energy and Environment*) handles all production and distribution of district heating, all distribution and some production of electricity, as well as waste collection and incineration. The company owns two district heating plants: the natural gas and wood chip-fired *Oceanen* and *Kristinehedsverket*, a waste incineration plant. Both plants also have some co-production of electricity. In 2014 the company built a 500 kW solar photovoltaics plant on *Skedalahed*, a former landfill.

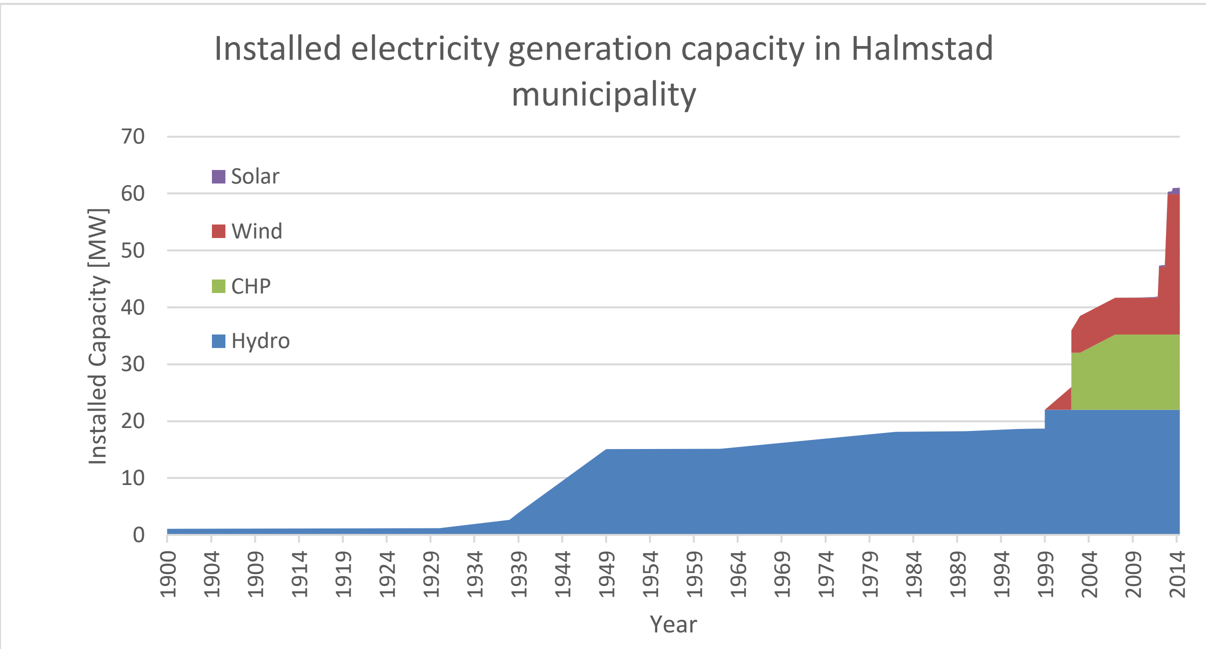

Figure 6: INSTALLED ELECTRICITY GENERATION CAPACITY IN HALMSTAD MUNICIPALITY. Note that only plants that are still operating are included in the data. *CHP* denotes the electricity produced from combined heat and power plants.

[13] Throughout this document, unless specified otherwise, 'Halmstad' will be used to refer to the municipality of Halmstad.

The municipal electricity system traces its roots back to 1890 when the first streetlights were lit in Halmstad. Shows the growth of electricity generating capacity within the municipality, from 1900 to 2015[14]. Three distinct periods of growth can be seen: The first is between 1939 and 1950 when the majority of the hydropower plants were built. The second period spans from 2000 to 2008, and consists of some further expansion of the hydropower capacity, as well as introduction of both combined heat and power (CHP) generation (with the construction of new boilers and co-generation turbines in already existing heating plants) and wind power. The third expansion began in 2013 and consists of a large expansion of the wind power capacity, as well as some solar power.

In 1974, a municipal waste-handling company was formed to service the newly-formed municipality. In order to combat the problem of bulging landfills, *Kristinehedsverket* was completed in 1972. At first constructed simply for waste incineration, 1984 the plant started supplying heat to Halmstad's district heating system, which during the 1980's was built to supply much of central Halmstad with heat. HEM was formed in 2006 through a merger of the former municipal energy company (*Energiverken*) and waste handling company (*Renhållningsbolaget*). The company has around 240 employees and provides roughly 45 000 customers with energy and waste-handling services (Halmstad energi och miljö, 2014).

3.3 LOCAL INDUSTRY

The city's first major industry was Wallbergs Fabriks AB; a textile factory, founded in 1823 and expanded throughout the 19th century. After moving to the site of a former water-driven gristmill in 1850, power from the waterfall in the river Nissan was used both directly as mechanical energy and converted to electricity to be utilised by the factory. At the same site a brick factory was built, at first to provide building material for rebuilding the main factory but later producing bricks that were sold across Sweden. The brick factory continued production throughout the 20th century but was closed down in 1994 (Wikipedia, 2015). The textile factory closed its main production in the early 1970s, but production of textile for use in the paper industry continued until 1990 when it was taken over by Nordiskafilt AB, another company specialised in textiles for the paper industry that was founded in Halmstad in 1904. Nordiskafilt AB has in turn merged with U.S.-based Albany Felt, and production continues in a factory in Halmstad today under the name Albany International AB. In 1916 a steel mill was built in Halmstad to produce steel from scraps. Originally equipped with open hearth furnaces, these were exchanged for electric arc furnaces in the 1960. Today the mill is owned by Höganäs AB and produces atomized iron powder that is further refined at a plant in Höganäs, Sweden (Wikipedia, 2013). In 1956 Duni, a producer of disposable tableware, napkins and packaging, moved production to Halmstad. Production was expanded in several steps, but was closed down in 2004. Another major local industry was Pilkington, which produced sheet glass in Halmstad from 1976 until 2013, when production was shut down (Pilkington, 2014). The factory buildings were bought by Stena Recycling, and will be turned into a plant for recycling various types of industrial and consumer materials (Stena, 2014).

[14] The diagram starts at 1900 due to a limitation in the software used; the first power plant was actually built in 1890 (see Table 5)

4 THE ENERGY SYSTEM IN HALMSTAD MUNICIPALITY: IMPORT & PRODUCTION, CONVERSION AND USE

This chapter presents data on Halmstad municipality's energy system, focused on the last quarter-century. The data is presented mainly as diagrams and tables, with accompanying text describing identifiable trends and connections to other parts of the energy system and/or other parts of the surrounding sociotechnical system. The aim is to answer the first question asked in Section 1.4; 'How has the energy system developed from 1990 to 2013?', as well as provide a basis for answering the other two questions. The chapter will follow the structure of the energy system outlined in Box 1 (found on p. 5); starting with the supply of energy to the system, continuing with the conversion of energy within the system, and finishing with the end use of energy.

4.1 ENERGY IMPORT AND LOCAL PRODUCTION

The journey through the energy system begins with the supply of energy to the system through import and local production[15]. Halmstad municipality imports most of its energy; about 85% of the electricity as well as all fossil fuels, mostly in the form of gasoline, diesel and heating oils. For biofuels, no information could be found regarding the share of local production vs. import, but according to a municipal strategy document (Halmstad municipality, 2015), small-scale local production of biofuels is an 'interesting area of development for the region'. Primary energy produced within the municipality is hydro, wind and solar energy, as well as some, but not all, of the waste used as fuel for the waste incineration plant (no data on the share of waste imported could be found, however)[16]. Secondary energy produced within the municipality is presented in Section 4.2.

Year	Supplied to the system [GWh]	Inserted for conversion [GWh]	Output from conversion [GWh]	End use [GWh]	System losses [GWh]
1990	3587	338	323	3477	110
1995	3614	430	419	3497	117
2000	3768	480	452	3614	154
2001	3623	344	316	3490	133
2002	3917	544	292	3526	391
2003	3592	629	543	3361	231
2004	3484	559	561	3327	157
2005	3456	635	599	3243	213
2006	3369	627	616	3193	176
2007	3534	779	641	3132	402
2008	3668	924	851	3043	625
2009	3748	813	701	3596	152
2010	4032	942	765	3852	180
2011	3872	862	748	3555	317
2012	3792	887	788	3651	141
2013	3221	853	803	3021	200

Table 3: TOTAL ENERGY PASSING THROUGH THE ENERGY SYSTEM. Column 1 represents the total energy that enters the system, both in the form of imported electricity and fuel and e.g. utilised hydro energy. A part of this energy is inserted for conversion in one of the municipality's power plants; the size of this part is shown in column 2. Column 3 shows the output of useful energy from this conversion. Column 4 shows the total end use of energy, and Column 5 shows the difference between columns 1 and 4, representing the total system losses.

In Figure 7 we can see the total supply of energy to the system. The amount of energy supplied has been roughly constant throughout the period at around 3.5 TWh, but reached a peak of 4 TWh in 2010, and then decreased to 3.2 TWh in 2013. Some of this energy is converted to secondary energy in one of the power plants within the system, but the majority is used directly by end

[15]The term 'local production' here includes the local utilisation of naturally occurring resources such as biomass and hydro-, wind- and solar energy. 'Import' references energy produced outside Halmstad's energy system.

[16]The production of waste is normally not included as a part of the energy system, but will here be considered as an energy source.

users. Table 3 shows these various amounts. The percentage of the supplied energy that is inserted for transformation has increased from 9% in 1990 to 26% in 2013.

Going back to Figure 7, we see that the majority of the energy supplied is in the form of non-renewable liquid fuel. Overall, the total import of non-renewable liquid fuel has decreased from 1863 GWh in 1990 to 1192 GWh in 2013. Looking at more detailed data available for this category from 1990 to 2008, it can be seen that in 1990, roughly equal amounts of heating oil and motor fuels were imported. By 2008, the amount of heating oil imported had decreased by roughly 80%, while the import of motor fuels had increased by 20% (consisting solely of an increase in diesel import; import of gasoline had declined).

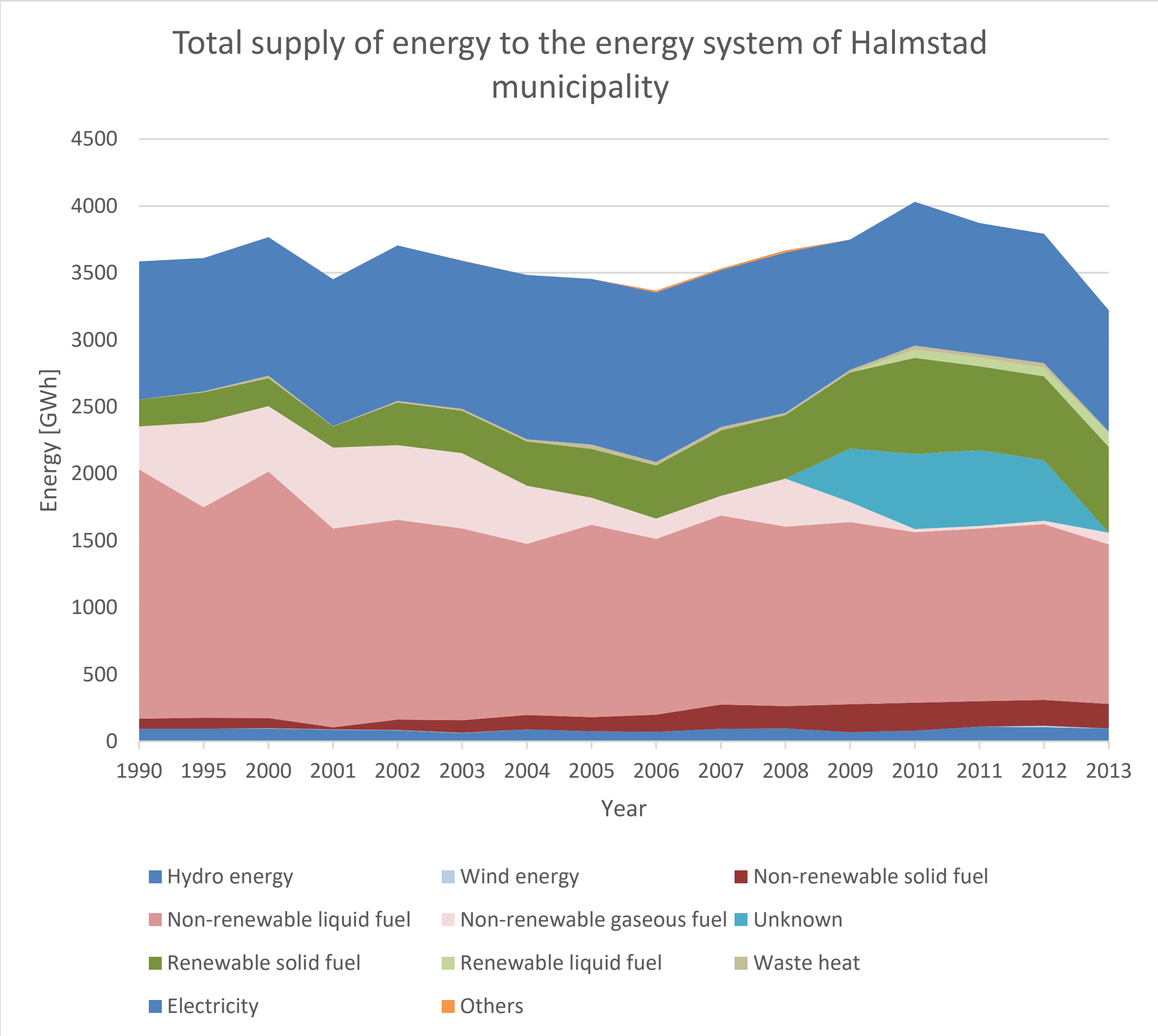

Figure 7: TOTAL SUPPLY OF ENERGY TO THE ENERGY SYSTEM OF HALMSTAD MUNICIPALITY. The 'unknown' category likely consists of non-renewable energy used by the industry & construction sector; the reason for this category is explained in Section 4.3.2.3. The *Wind energy*, *waste heat* and *others*- categories are represented only by small slivers in the diagram.

Other trends that can be noted are: a slightly decreasing import of electricity; an almost completely ended dependence on non-renewable gaseous fuels; and an increase in the supply of both renewable and non-renewable solid fuel, mostly reflecting an increasing supply of waste which is assumed to consist of 64% renewable and 36% non-renewable solid fuel (Avfall Sverige, 2012).

Table 4 shows the respective shares of electricity generated within the municipality and imported from the rest of Sweden. The trend shows an increase in electricity generated in-system in the later years, almost doubling from 93 GWh (8.3%) in 1990 to 163 GWh (15.2%) in 2013. The amount of electricity imported increased from 1032 GWh in 1990 to 1341 GWh in 2006, but has since then decreased again, reaching 906 GWh in 2013.

4.2 ENERGY CONVERSION

The next major stage of the energy system is the conversion of energy from primary energy carriers, such as hydro energy, waste, and biomass, into secondary energy carriers, in this case heat and electricity (note however that, as can be seen in Table 3, in the case of Halmstad only a minor fraction of the supplied energy is converted within the system). This in-system conversion produces all of the hot water used in the district heating system, as well as roughly 15% of the electricity used within the municipality.

4.2.1 GENERATION CAPACITY

We start our examination of the conversion stage by looking at the generation capacity, i.e. the different power plants within the municipality. We will start by looking at the capacity for electricity generation, and then look at the capacity for generating heat.

The generation capacity for electricity consists primarily of wind power (40%), followed by hydropower (36%), condensing power as part of combined heat and power (CHP) generation (22%) and solar photovoltaics (2%). However, since the capacity factor for the wind power plants is significantly lower than for both hydropower and CHP (see Section 4.2.2), as we will see in Section 4.2.4 the largest share of the electricity generated within the municipality does not come from wind power.

Table 4: ELECTRICITY, GENERATED IN-SYSTEM VS. IMPORTED

Year	Generated in-system [GWh]	Imported [GWh]	Percent generated in-system
1990	93	1032	8.3%
1995	94	997	8.6%
2000	107	1037	9.4%
2001	101	1098	8.4%
2002	110	1163	8.6%
2003	111	1107	9.1%
2004	91	1227	6.9%
2005	95	1238	7.1%
2006	74	1267	5.5%
2007	166	1172	12.4%
2008	107	1197	8.2%
2009	141	972	12.7%
2010	155	1076	12.6%
2011	186	980	16.0%
2012	190	966	16.4%
2013	163	906	15.2%

Table 5 lists all the plants currently producing electricity in Halmstad municipality. A clear divide can be seen when looking at the years of construction, with hydropower dams built from 1890 until 2000, and wind power and CHP turbines built mainly from 2003 and onward[17]. For the hydropower, ownership is divided between several companies and even private owners. The two CHP plants are both owned by

Table 5: PLANTS CURRENTLY PRODUCING ELECTRICITY IN HALMSTAD MUNICIPALITY

Type	Name	Built	Nominal power [MW]	Owner	Primary fuel
Hydropower	Oskarström övre	1890	1.1	Varberg Energimarknad AB	Hydro
	Lingforsen	1931	0.08	Lingforsen Kraft AB	Hydro
	Oskarström nedre	1939	1.5	Varberg Energimarknad AB	Hydro
	Slottsmöllan	1940	1.2	Slottmöllans Fastighets AB	Hydro
	Nissaström	1950	11.2	Statkraft Sverige AB	Hydro
	Mostorps gård	1963	0.045	Mostorps Gård AB	Hydro
	Maredsfors	1983	2.98	Varberg Energimarknad AB	Hydro
	Årnilt	1991	0.125	Årnilts Kraftstation HB	Hydro
	Linneberga	1997	0.4	Laholms Stenhuggeri AB	Hydro
	Lindoms kvarn	1999	0.037	Private	Hydro
	Fyllinge kvarn	2000	0.048	Private	Hydro
	Marbäck	2000	0.35	Sperlingsholms Holding AB	Hydro
	Sperlingsholm	2000	2.92	Sperlingsholms Holding AB	Hydro
	Tönnersa	2000	0.04	Private	Hydro
	Subtotal		**22.0**		
Wind power	[8 plants]	2003*	3.955	Various	Wind
	[2 plants]	2004	2.52	Various	Wind
	[3 plants]	2013	5.4	Various	Wind
	[8 plants]	2014	12.8	Various	Wind
	Subtotal: 21 plants		**24.7**		
Condensing (as part of CHP generation)	Kristinehedsverket, boiler 3	2003	10	HEM AB	Waste
	Oceanen, boiler 5	2008	3.2	HEM AB	Wood chip
	Subtotal		**13.2**		
Solar	**Total cap. as of 2015****		**1.1**	Various	Solar
Total capacity, all plants			**61.0**		

**Built 2003 or prior*

***For more details, see Section 6.2*

HEM. The wind power plants are also owned by several companies, with the company Arise being a major owner, owning at least 10.8 MW of installed capacity (Vindkraftsnyheter.se, 2014).

District heating is supplied by the two plants owned by HEM. *Kristinehedsverket* (68 MW capacity) is a waste-incineration plant and is used to provide base-load heat, and is supplemented when needed by natural gas and wood chip-fired *Oceanen* (122 MW capacity) (Halmstad energi och miljö, A), (Halmstad energi och miljö, B). The sheet-glass factory owned by Pilkington supplied about 5-9 MW of waste heat

[17]Halmstad did get its first 3 wind turbines in 1992.

before closing down in 2013 (Bernhardsen, 2011). Both *Kristinehedsverket* and *Oceanen* have been expanded with additional boilers, with the latest expansions adding CHP capacity to both *Kristinehedsverket* (in 2003) and *Oceanen* (in 2008) Details of the district heating production plants can be found in Table 6 below.

Table 6: PLANTS CURRENTLY PRODUCING HEAT FOR THE DISTRICT HEATING NETWORK IN HALMSTAD

Type	Name	Built	Nominal power [MW]	Owner	Primary fuel
Heating plant	Kristinehedsverket, boiler 1	1984	13	HEM AB	Waste
	Kristinehedsverket, boiler 2	1984	13	HEM AB	Waste
	Oceanen, boiler 1	1994	25	HEM AB	Natural gas
	Oceanen, boiler 2	1994	25	HEM AB	Natural gas
	Oceanen, boiler 3	1994	25	HEM AB	Natural gas
	Oceanen, boiler 4	2000	32.5	HEM AB	Wood chip
	Kristinehedsverket, boiler 3*	2003	42	HEM AB	Waste
	Oceanen, boiler 5*	2008	14.3	HEM AB	Wood chip
	Total capacity		**189.8**		

**Boilers with CHP capacity*

4.2.2 Capacity growth and capacity factors

Having listed all of the power plants in the system, we can now look at how the capacity for generating electricity and heat has changed over the years. Table 7 shows the total installed capacity for each year, for district heating and electricity, respectively. The capacity for electricity generation has roughly doubled since 1990, while the capacity for district heating generation has increased by almost 150% since 1995 (or almost tenfold since 1990 according to the available data – however, the number for 1990 is unsure; see footnote 18 below).

The last two columns of Table 7 show the capacity factor; a number between zero and one describing the usage of the generating capacity, with zero being no utilisation and one being utilisation at full capacity for every single hour of the year. The yearly capacity factor is calculated as $cf = E_{prod}/(C_{inst} * 8760)$, where cf is the capacity factor, E_{prod} is the energy produced in a year (in watt-hours), C_{inst} is the installed capacity (in watts) and 8760 is the number of hours in a year.

Table 7: GENERATION CAPACITY AND CAPACITY FACTORS PER YEAR

Year	Capacity [MW]		Capacity factor	
	Electricity	District heating	Electricity	District heating
1990	18.105	26	0.61	~~1.01~~
1995	18.23	101	0.60	0.37
2000	22.025	133.5	0.55	0.30
2001	22.025	133.5	0.52	0.18
2002	22.025	133.5	0.58	0.16
2003	35.98	217.5	0.36	0.23
2004	38.5	217.5	0.27	0.25
2005	38.5	217.5	0.28	0.26
2006	38.5	217.5	0.22	0.28
2007	38.5	217.5	0.49	0.25
2008	41.7	246.1	0.29	0.35
2009	41.7	246.1	0.39	0.26
2010	41.7	246.1	0.42	0.28
2011	41.7	246.1	0.51	0.26
2012	41.7	246.1	0.53	0.28
2013	47.1	246.1	0.40*	0.30

**Lower number at least partly due to missing data for electricity produced from wind power.*

As can be seen in the table, the calculated capacity factor for district heating in 1990 is unreasonably high, which is a result of incomplete or incorrect data[18].

The capacity factor can be a measure of how efficiently the generating capacity is utilised, with higher numbers meaning a higher degree of utilisation. A low capacity factor can suggest that the system has excessive generation capacity (resulting in unnecessarily high costs), while a very high capacity factor on the other hand can suggest that the system will not have enough capacity to respond to high demand peaks. In Halmstad's case, the ability to handle peaks is more important for the district heating generation, where the option of importing energy from outside the system to handle peaks does not exist. The supply of electricity on the other hand can, and does, depend on imports to meet the demand. This is reflected in the types of plants for each system. For heat production, Halmstad uses (as mentioned in the previous section) both a base load plant with a smaller capacity and a high utilisation and a peak load plant with a large capacity, but lower utilisation. This is contrasted by the electricity generation where all four types of plants used either have very low variable costs (hydro, wind and solar), or are producing electricity as a 'by-product' (CHP). This means that these plants typically will be utilised as much as possible, leading to a higher overall capacity factor.

Box 2: INACCURACIES IN THE REPORTED DATA

Figure 8 below shows the reported production and use of district heating, and since the district heating system in Halmstad is a closed system with no import or export of energy (in contrast to, e.g. the electric grid), production and consumption should match each other closely (with production being slightly larger than consumption to cover e.g. transmission losses). As can be seen in Figure 8, for the reported data this is not the case. Since the reported data suggests, among other things, that production is more than twice as large as the use in 2008 (which is very unlikely) and that the use is almost twice as large as the production in 2002 (which of course is impossible), the only reasonable assumption is that the data reported for the production and/or consumption is inaccurate.

This example uses data for district heating, but it is reasonable to assume that much of the data contains similar inaccuracies.

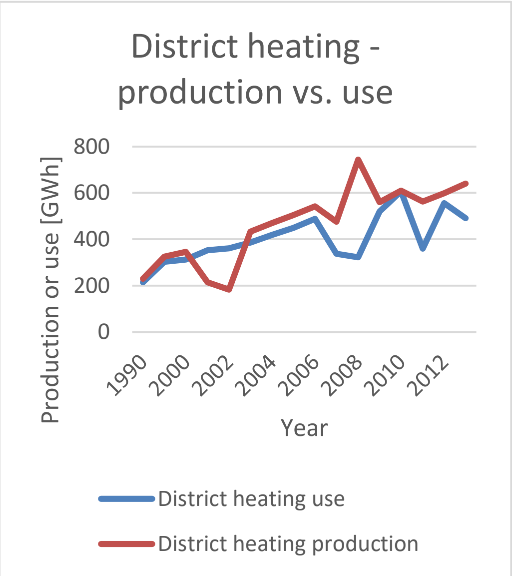

Figure 8: DISTRICT HEATING - PRODUCTION VS. USE

A special case regarding capacity factors is so-called *intermittent* energy sources, here represented by wind, solar, and, to an extent, hydropower plants. These power plants cannot directly control their output; instead the output is coupled to the available input, i.e. wind power plants will produce electricity in relation to how much the wind is blowing and solar panels will produce electricity in relation to how much the sun is shining. Intermittent energy sources are therefore often characterised by relatively low capacity factors, as they can only utilise their maximum capacity when the input source permits. Most hydropower plants have built-in storage capacity in the form of dams storing the available water, which can then be utilised to meet the present demand. This storage capacity raises the capacity factor. However, the output is still coupled

[18]The most fitting missing piece of the puzzle is an additional heat-producing plant in operation in 1990, but no information on such a plant could be found.

to the inflow of hydro energy, as the dam only can store a certain amount of water.

For the electricity system, we see that the capacity factor has gone from around 0.5 – 0.6 from 1990 to 2002, reflecting use of high-capacity factor generation (hydro and condensing power), to around 0.2 – 0.3 for most of the period 2003 – 2008, reflecting the introduction of wind power, which has a significantly lower capacity factor. For the period 2009 – 2012 however, the capacity factor grew steadily, reaching 0.53 in 2012, despite a growing share of installed wind power. This increase can be traced to an increase in the capacity factors of all the generating technologies, in turn reflecting an increased energy output. The drop to an overall capacity factor of 0.40 in 2013 is at least partly due to missing data for the amount of electricity produced by wind power that year.

In the district heating system, we can observe that the addition of a boiler in the *Oceanen* power plant in 2000 (adding 32.5 MW of capacity), combined with low production during 2001 and 2002 brought the overall capacity factor for district heating down from 0.37 – 0.30 to 0.18 – 0.16. The later expansions of the generating capacity (42 MW in 2003 and 14.3 MW in 2008) has had little effect on the capacity factor; meaning that the demand (and therefore production) of heat has grown at the same pace as the capacity expansion; from the 2001 – 2002 dip the capacity factor increased steadily to 0.28 in 2006 and has remained at around that level since.

Looking at the capacity factors for the individual generation technologies, for district heat generation the average capacity factor is 0.69 for combined heat and power generation and 0.21 for heat-only generating capacity. This suggests that the CHP-capable boilers are used primarily. For electricity generation, the factors are 0.46 for hydropower, 0.11 for wind power (this number is very unsure however, since data on wind power generation is severely lacking), and 0.45 for combined heat and power. For Sweden in general, capacity factors are 0.45 for hydropower (Kuhlin, 2015a) and 0.22 for wind power (Boccard, 2008).

In addition to the expansion of the district heating generation capacity, another measure of the expansion of the district heating system is the number of new district heating connections made each year. Figure 9 shows the number of connections to the district heating system of Halmstad municipality, since 2005. The system has grown by roughly 180 new connections per year from 2005 to 2011, but since 2012 and onward, the pace has slowed to about 100 new connections per year. 1753 new connections have been made since 2005, resulting in a total of 4792 connections. About 83% of the connections made since 2005 are to residential buildings, 5% to commercial buildings, 3% to public buildings and 1% to industrial buildings (for the remaining 8% no data could be found). For 40% of the connections, data could be obtained on the type of system replaced by the new district heating connection. Out of these, 45% of the connections

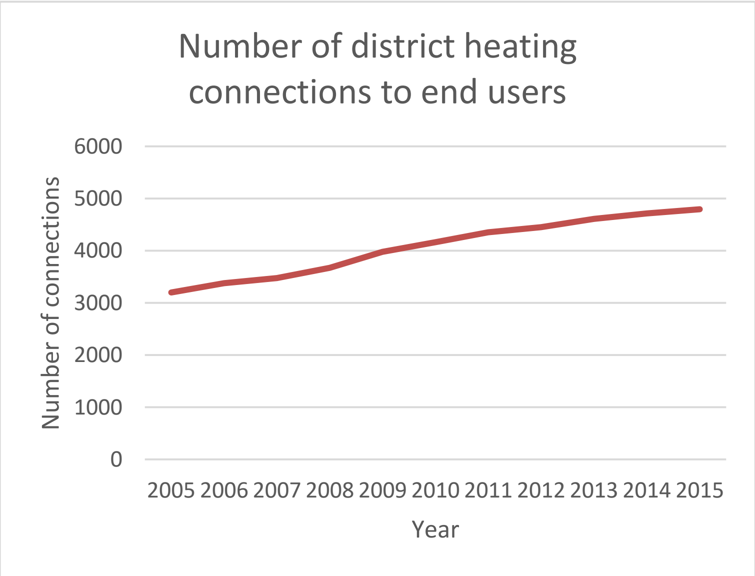

Figure 9: NUMBER OF DISTRICT HEATING CONNECTIONS TO END USERS. One connection typically represents e.g. one house, although larger customers (typically industrial buildings) can have multiple connections to the same site.

replaced oil-fired heating systems, 45% replaced electric heating, and 10% of the connections were made to newly constructed buildings.

4.2.3 ENERGY INSERTED FOR CONVERSION

Now that we have studied the power plants used for conversion, the natural next step is to take a closer look at the energy inserted for conversion in these plants.

Figure 10 shows the total energy inserted for conversion in power plants. Hydro energy has been converted into electricity at an almost constant level of around 95 GWh per year throughout the period (changing with yearly variations in precipitation, rather than changes in the production capacity). Data on wind energy is lacking for much of the period, but in the years 2000 – 2004 around 2 GWh was converted and by 2012 this number had grown to 10 GWh. The use of wood chip-type fuels has grown from practically not-existent in 1990 – 1995 to 207 GWh in 2013. Waste was the main fuel used already in 1990 (then supplying 167 GWh, almost half of the total energy), and use has since then roughly trippled, reaching 509 GWh in 2013 (almost 60% of the total energy). Natural gas use peaked at around 95 GWh per year in 2000 – 2001, and has since then seen a decrease, appart from a second peak in 2008. The use in 2013 was 28 GWh. The use of heating oil peaked in 2003 at 143 GWh, and has since also decreased to only 5 GWh in 2013. Overall, the ammount of non-renewable energy inserted for conversion increased from 130 GWh in 1990 to 209 GWh in 2000, but has since then remained fairly constant at around 200 GWh per year throughout the period (with the use of traditional fossil fuels decreasing, but the ammount of waste incinerated increasing). However, since the total ammount of energy inserted for conversion has increased, the share of non-renewables inserted for conversion has decreased from 28% in 1990 to 13% in 2013.

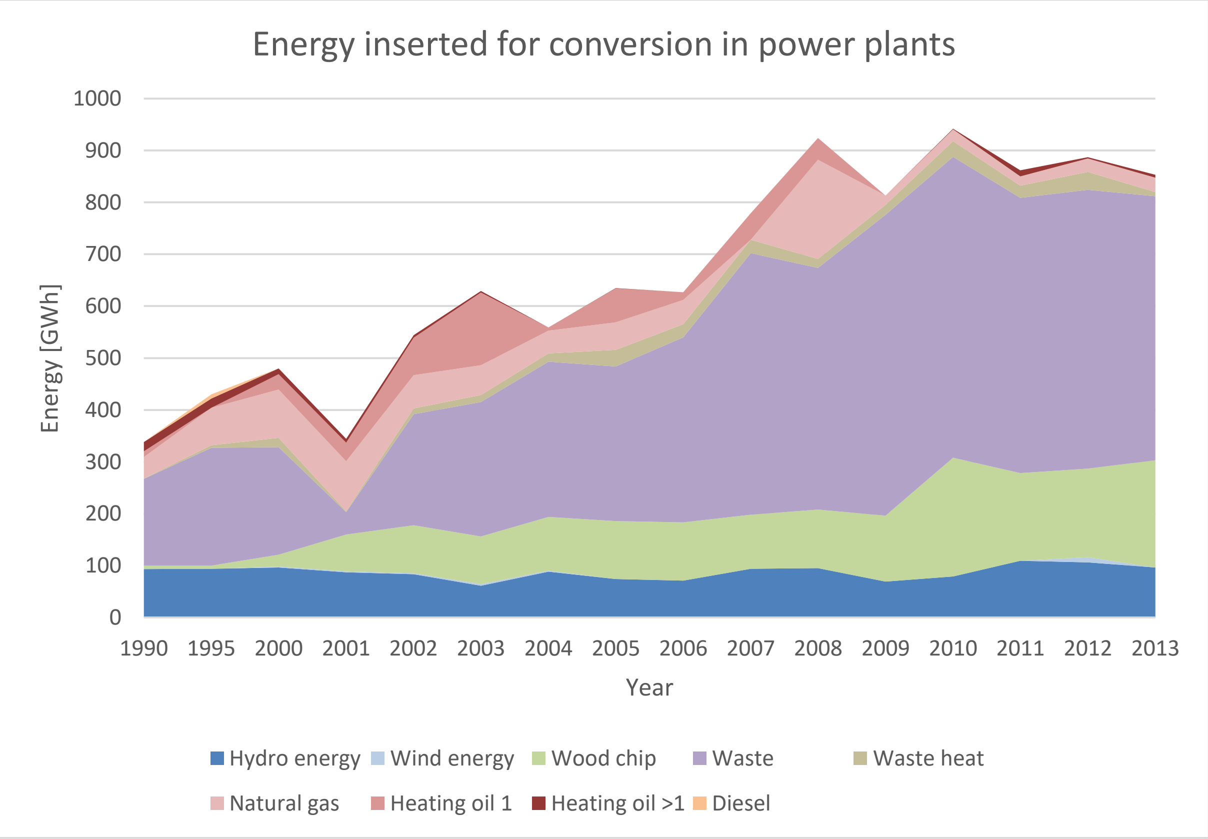

Figure 10: ENERGY INSERTED FOR CONVERSION IN POWER PLANTS IN HALMSTAD MUNICIPALITY. The figure shows energy inserted both for producing electricity and heat. The *wind energy* and *diesel* categories are very small, and thus hard to note in the diagram.

4.2.4 Conversion output

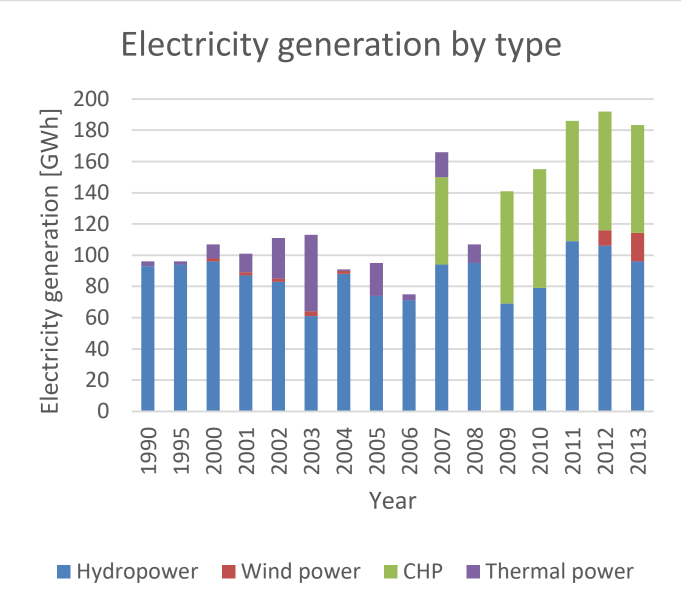

Figure 11: ELECTRICITY GENERATION BY TYPE. The values for hydropower generation in 2000 and 2013 are equal to the reported normal year production (Kuhlin, Vattenkraft.info, 2015 B). This is due to missing data for 2013 and a reported value for 2000 at 2.5 times the average level, which is considered unreasonable. The value for wind power in 2013 has been estimated using the capacity factor for 2012 and the installed capacity for 2013.

Studying the generation capacity 'sets the stage', so to speak – showing us what properties and capabilities the energy system has. Studying the energy inserted reveals the requirements of the energy conversion – what we have to supply to get what we want. The concluding step when studying the conversion then becomes to look at the actual production for each year – what utility we get from the system.

Figure 11 shows the electricity production. As can be seen, the majority of the electricity produced comes from hydropower, with an increasing share of electricity from CHP generation in later years. It is reasonable to assume that use of CHP generation began already in 2003, when the first CHP boiler was introduced to the system, but for 2003 – 2006, this has either been reported as 'thermal power' or for some reason been excluded from the statistics altogether. The share of electricity from wind power in later years is hard to judge, since for the years 2005 – 2014, only data for 2012 is available. However, since the installed capacity of wind power was about 3.8 times as large in 2014 as in 2012, a similar increase in electricity production can be assumed. This would mean that wind power produced around 38 GWh of electricity in 2014. The total generation was around 100 GWh per year from 1990 – 2006 (however, as discussed previously, data for CHP generation could be missing for 2003 – 2006). From 2007 and onward, the total generation rose to around 150 GWh, nearing 200 GWh in 2011 – 2012.

Figure 12 shows the district heat production. Overall, a growing trend can be seen; the amount of heat produced has almost tripled from 230 GWh in 1990 to 640 GWh in 2013. Up until 2003 all heat was produced in heat-only boilers, but in 2003 the first CHP capacity boiler was introduced. Since then it is reasonable to assume that the majority of the heat is co-produced with electricity in CHP boilers. Data from 2008 – 2013 supports this, but for 2003 – 2007 the heat produced with CHP boilers is reported as zero.

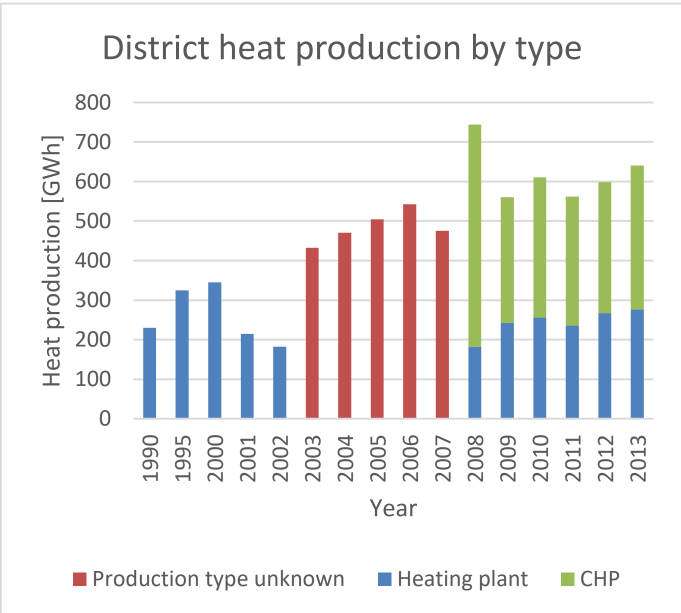

Figure 12: DISTRICT HEAT PRODUCTION BY TYPE. For the years 2003 – 2007, no distinction between heat-only and CHP production is made due to lacking data quality.

4.3 ENERGY CONSUMPTION

The final stage of the energy system, where the main utility of the system is obtained, is the end use phase. Here both imported (as is the case for e.g. the majority of the electricity and all fossil fuels) and locally generated (e.g. the district heating hot water) energy is consumed. In this section the focus will first be on the use of different energy carriers over time, and then on the energy use of each user sector (residential, transport, industry & construction etc.) in more detail.

Looking at the total end use of energy from 1990 to 2013 in Figure 13, we see that the total energy use reached a peak of 3614 GWh in the year 2000, and then decreased by about 60 GWh per year for nine years until 2008, reaching 3043 GWh. Then the energy use increased again, reaching 3852 GWh in 2010. After this peak, energy use has again decreased, reaching 3021 GWh in 2013. As we shall see in the following section, this 2009 – 2012 peak can be linked primarily to increases in the use of energy in the industry & construction and residential sectors.

4.3.1 END USE BY ENERGY CARRIER

The first step of our analysis is to look at the different energy carriers. The major patterns become clear right away: the use of non-renewable energy is decreasing, while the use of renewable energy and district heating is slowly increasing, and the use of electricity is remaining more or less constant over the period.

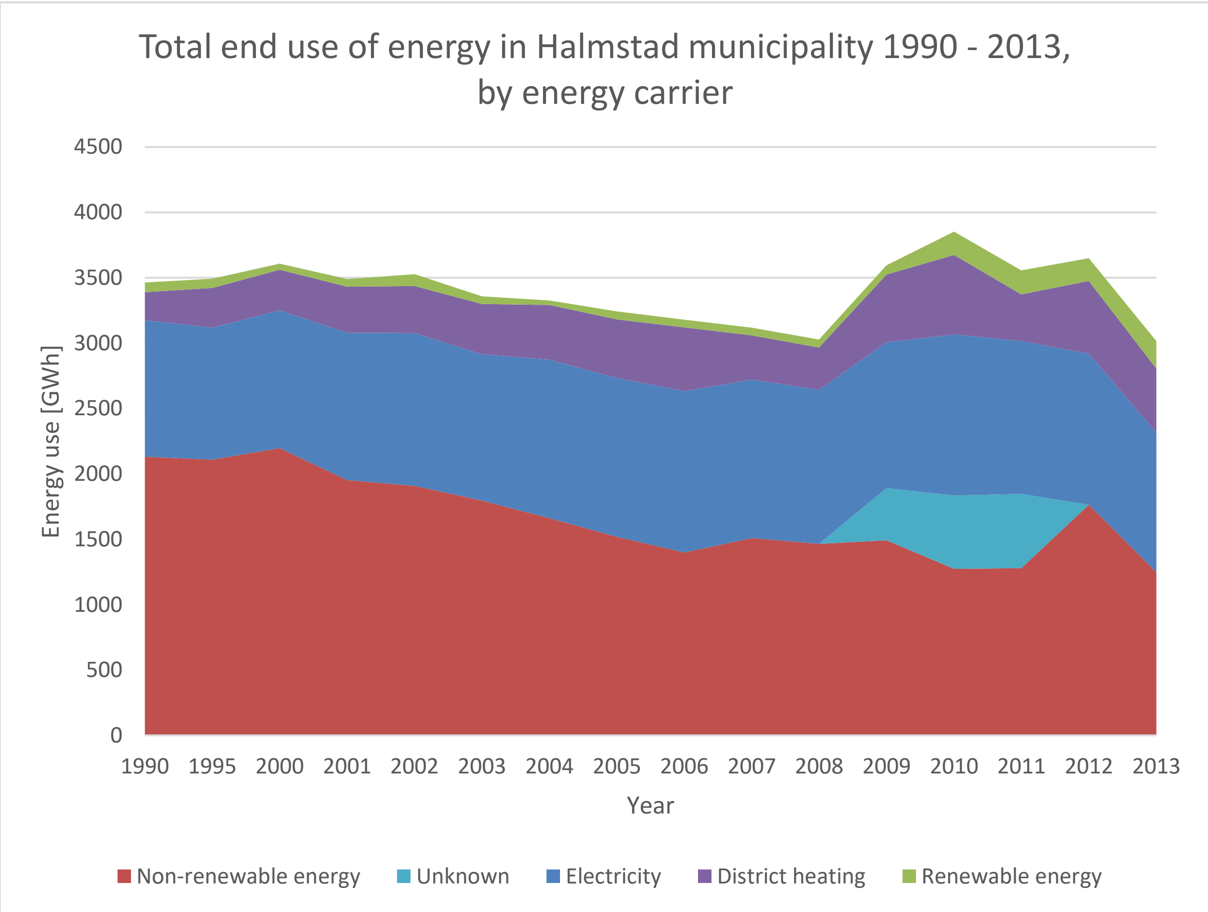

Figure 13: TOTAL END USE OF ENERGY IN HALMSTAD MUNICIPALITY 1990 – 2013, BY ENERGY CARRIER. The 'unknown' category likely consists of non-renewable energy; see Section 4.3.2.3.

Looking in more detail, we see that the use of non-renewable energy reached a peak of 2198 GWh in the year 2000. From 2001 to 2006, use decreased considerably, reaching 1399 GWh in 2006. For the period 2007 – 2012, there was likely an increase (see Section 4.3.2.3). In 2013 however, the use decreased again to 1246 GWh, the lowest number for the studied period. The use of electricity has increased from 1045 GWh in 1990, to 1234 GWh in 2006 and, after a slight decrease 2007 – 2009, saw another peak of 1231 GWh in 2010. Since then use has again decreased, reaching 1069 GWh in 2013. District heating use grew with about 3% per year from 215 GWh in 1990 to 488 GWh in 2006. Thereafter the reported use fluctuates greatly, while showing a continuing growing trend overall. The fluctuations are likely due to inaccuracies in the reported data; see Box 2. The use of renewable energy remained roughly constant at around 60 GWh per year from 1990 to 2009. In 2010 the use suddenly increased to 179 GWh, and remained at this level until 2013, when use increased again, to 211 GWh.

4.3.2 End use by sector

We now know what types of energy is used; now it is time to see who is using the energy. Figure 14 again shows the total end use of energy within Halmstad municipality, but this time subdivided by sector[19]. Comparing the shares of energy use of the different sectors for the years 1990 and 2013, we see that in 1990, the industry & construction sector was the largest energy consumer at 1162 GWh, followed by the residential sector (986 GWh) and transport (903 GWh). These three largest sectors then made up 88% of the total energy end use (3477 GWh). In 2013, the transport sector had grown to become the largest energy user at 1172 GWh, followed by the residential sector (773 GWh); the industry & construction sector had decreased its consumption to become the third-largest at 515 GWh. In 2013, these three largest sectors made up 81% of the total use (3021 GWh).

[19] The sectors are categorised as following (Rehn, 2012):
Agriculture: agriculture, forestry, fishing.
Industry & construction: manufacturing industry and extraction of minerals, as well as the construction sector (consumption of electricity only).
Public sector: public administration, defence, education, research and development, healthcare and social services, culture and recreation, streetlights, waterworks, waste handling and recycling.
Transport: all fuels distributed through petrol stations, rail transport, public transport.
Others: Electricity distributed to offices, warehouses etc., distribution of gaseous fuels via pipe networks, distribution of heating and cooling, wholesale and retail stores, hotels and restaurants, storage and other services supporting the transport sector, post and curriers, finance and insurance businesses, misc. business services, other services, information and communication.
Residential: Single-apartment houses, multi-apartment houses, holiday homes.

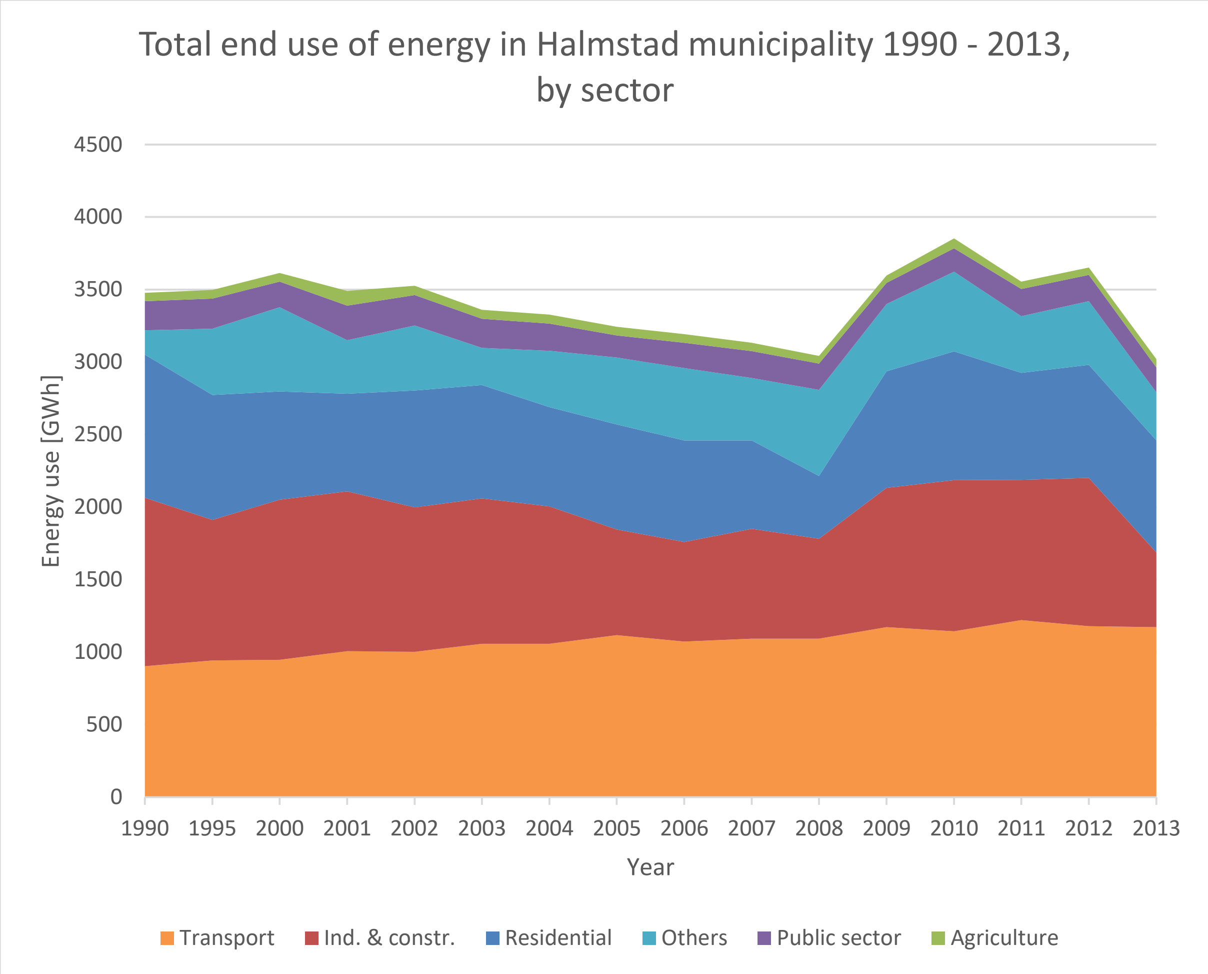

Figure 14: TOTAL END USE OF ENERGY IN HALMSTAD MUNICIPALITY 1990 – 2013, BY SECTOR

4.3.2.1 TRANSPORT

The transport sector was the largest energy end user in 2013, responsible for 39% of the total end use. The sector has grown steadily with about 11 GWh per year throughout the studied period, reaching 1172 GWh in 2013. Looking at the different energy carriers utilised by the sector (Figure 16), we see that non-renewable energy dominates, amounting to 1068 GWh in 2013 (91% of the total use of the sector), but renewable energy become noticeable in 2010 and saw a notable increase in 2013, reaching 103 GWh that year (9% of the total use).

However, since this category includes all motor fuels sold within the municipality – all of which are not necessarily used within the municipality – this data does not necessarily reflect the development of the transport sector of Halmstad municipality specifically, but rather that of the larger region (i.e. south-west Sweden). This is especially likely since the major highway of Sweden's west coast, the E6, which connects the Köbenhavn/Malmö region with both Göteborg and Oslo, passes through the municipality. On the other hand, this highlights the fact that investments aimed at supplying sustainable transport fuels in Halmstad municipality (e.g. biofuel/biogas filling stations and electric charging points) also have a potential to provide benefits to the region at large[20].

[20]For example, Halmstad is situated almost exactly at the midpoint of the ~290 km journey from Göteborg to Köbenhavn, so electric charging points in the city reduces the required range for battery-electric vehicles to about ~145 km in order to manage the journey.

4.3.2.2 RESIDENTIAL

The residential sector was the second largest energy end user in 2013, responsible for 26% of the total end use. Looking at the total energy consumption of the residential sector we see a decrease in energy consumption from 986 GWh in 1990 to less than half, 432 GWh, in 2008, coinciding with the financial crisis. However, this dip can be traced to a very large dip in the use of district heating, which might be at least partly due to inaccuracies in the reported data. In 2009 energy consumption had again increased to 803 GWh, and the number stays at around 800 GWh until 2013.

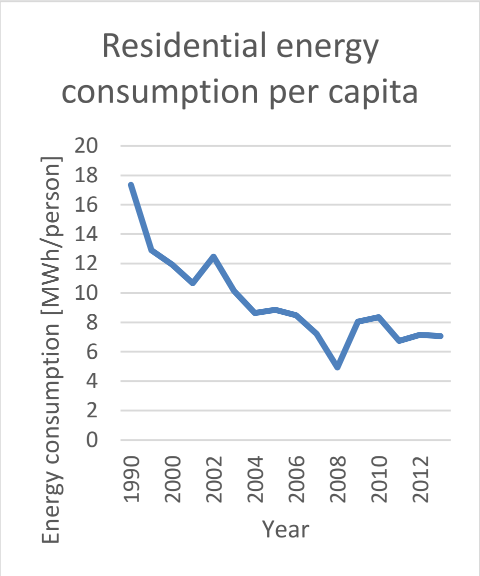

Figure 15: RESIDENTIAL ENERGY CONSUMPTION PER CAPITA

Looking at the consumption by energy carrier (Figure 16), first of all we can note a clear shift from non-renewable energy (predominantly heating oil) to district heating around the year 2003. Comparing 2002 and 2003, non-renewable energy decreased by 170 GWh (to 104 GWh), while district heating increased by 193 GWh (to 267 GWh). Looking further back in time, a shift from non-renewable energy to district heating can also be seen from 1990 to 1995, but from 1995 to 2002 the development is reversed, i.e. district heating consumption decreases and consumption of non-renewable energy increases.

Electricity use has been fairly constant throughout the period, at around 350 GWh per year. The use of renewable energy was around 65 GWh per year from 1990 to 2009, and in 2010 the use increased to 120 GWh, and has remained at that level for the years 2011 – 2013.

Looking at the energy consumption per capita (Figure 15), we see that it has decreased from roughly 12 MWh per person in 1990 to 8 MWh per person in 2001. Since then, the consumption has varied from year to year, but no long-term trends can be seen.

4.3.2.3 INDUSTRY & CONSTRUCTION

The industry & construction sector was the largest end user of energy until 2002, using roughly 1100 GWh/year from 1990 to 2004. After this, there is a dip in energy use to about 700 GWh/year for the years 2005 – 2008. After increasing again to about 1000 GWh/year for 2009 – 2012, the use shows a dramatic decrease in 2013 to only 515 GWh, likely due to the closing down of the Pilkington sheet glass factory, which has been described as '…being responsible for almost 30% of the CO_2 emissions [of the municipality].' (Halmstad municipality, 2015). Thus, in 2013 this sector was the third largest end user, responsible for 17 % of the total energy end use.

Looking at the individual energy carriers for the sector (Figure 16), we see that non-renewable energy dominates from 1990 to around 2005 (with about 600 GWh per year consumed). In the following years, up until 2008, non-renewable energy use is about 250 GWh per year, and electricity takes over as the dominating energy carrier. For the years 2009 – 2011, part or all of the data on the use of fuels for the industry & construction sector is missing, but since data on the total energy use, as well as electricity and district heating use, is still available, an 'unknown' category can be introduced. This category most likely consists of non-renewable energy use, but could also potentially contain the use of renewable energy. For 2009, this unknown use amounts to 400 GWh (the reported non-renewable energy use is 130 GWh, making 530 GWh in total). For 2010 – 2011, the unknown use is around 565 GWh per year. For 2012, data for non-renewable energy use is again available, and amounts to 554 GWh. In 2013 it had dropped to only 84 GWh, again probably due to the closing of the Pilkington plant.

The electricity use for the industry & construction sector has been roughly constant throughout the period at around 400 GWh per year, with a peak of 485 GWh in 2007 and a dip to 336 GWh in 2009. However, use of electricity also decreased in 2013, reaching a new low of 307 GWh. Use of district heating is reported at around 10 GWh per year for the period 1990 – 2008, with the exception of 2000 – 2001, where the use increased to around 55 GWh/year. In 2009 use suddenly increased to 96 GWh, and has grown steadily to 122 GWh in 2013 (except for an anomalous dip to 6 GWh in 2011).

Box 3: THE CASE OF MISSING DATA

Much of the data presented as ‘missing’ is absent from the source at Statistics Sweden due to issues of confidentiality. According to the user guide accompanying Statistics Sweden’s municipal energy statistics (Rehn, 2012): ‘It should not be possible to identify single objects [power plants, end users etc.] … A cell is identified as sensitive if the addition from any single object can be approximated closer than [with a certainty of *p* %], and must then be marked as confidential.’* This is especially a problem for statistics on a municipal level, where e.g. a large factory can be responsible for a major part of the energy use of a certain category.

**Quote translated from Swedish by the author.*

4.3.2.4 Other users

The miscellaneous category was the fourth largest energy end user in 2013, responsible for 11% of the total end use. The energy use of this category has been roughly 400 GWh per year. After a peak of 594 GWh in 2008, the energy use shows a declining trend, reaching 331 GWh in 2013. Looking at individual energy carriers, the most utilised carrier is electricity, which also shows an increasing trend 1990 – 2010 (doubling from 144 GWh in 1990 to 289 GWh in 2010). From 2011 to 2013 however, the use of electricity has decreased somewhat, reaching 266 GWh in 2013. Use of non-renewable energy saw a large peak in 1995 – 2000, reaching about 270 GWh per year, but then decreased dramatically to levels below 60 GWh per year for 2001 – 2006. 2007 – 2009 use increased again, reaching a peak of 161 GWh in 2009. From thereon, levels have decreased again, reaching 65 GWh in 2013. Use of district heating increased from 11 GWh in 1990 to 209 GWh in 2002, and has varied substantially since then: For the period 2003 – 2008, the use has varied between 47 and 230 GWh per year. From 2009 to 2012, use has been lower, varying between 20 and 114 GWh per year. For 2013, the reported use of district heating was 0.

4.3.2.5 Public sector

The public sector was the fifth largest energy end user in 2013, responsible for 6% of the total end use. Total energy use for the sector has decreased somewhat over the period, from 200 GWh in 1990 to 171 GWh in 2013. Electricity held the largest share of the total use, going from 102 GWh in 1990 to a peak of 170 GWh in 2001. From there use again reached 103 GWh in 2004, and for the 2006 – 2013 period stabilised at around 125 GWh per year. Use of district heating has varied between roughly 20 and 60 GWh per year, but the overall trend shows a stable use at around 40 GWh. Use of non-renewable energy has gone from 73 GWh in 1990 to virtually zero for the years 2011 – 2013.

4.3.2.6 Agriculture

The sector with the lowest use of energy for the entire period studied was the agricultural sector, in 2013 responsible for 2% of the total energy end use. Use of electricity was around 18 GWh per year for 1990

– 2000 but reached a sudden peak of 61 GWh in 2001, and has thereafter stabilised at around 30 GWh per year. Use of non-renewable energy has decreased steadily from 40 GWh in 1990 to 18 GWh in 2012. In 2013 however, use increased to 26 GWh.

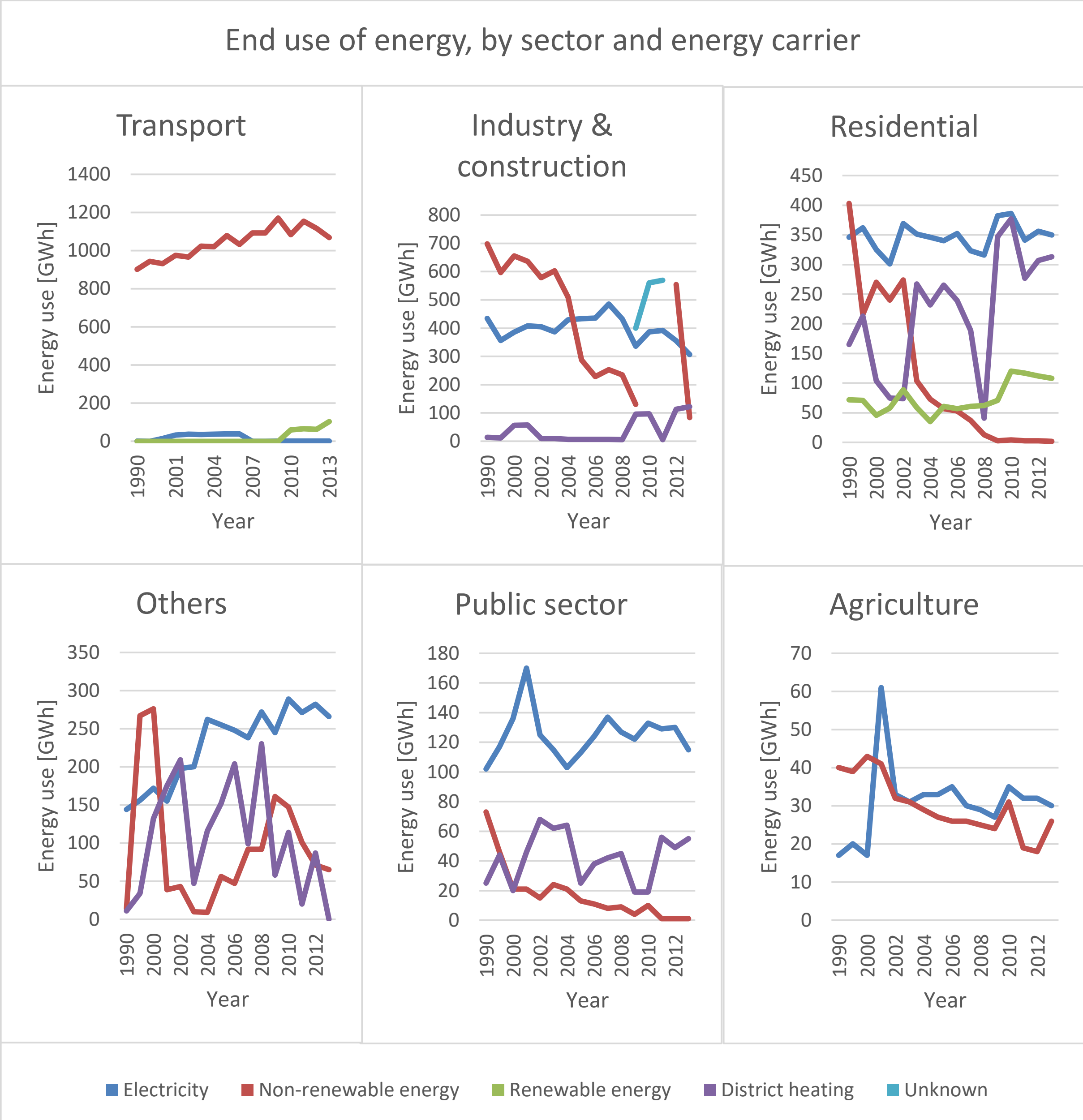

Figure 16: END USE OF ENERGY, BY SECTOR AND ENERGY CARRIER

We end this section with Figure 16, showing the end use by energy carrier for each sector. As can be seen, displayed at this 'highest resolution', much of the data shows very large yearly variations. Thus, the accuracy of the data can be questioned. Nevertheless, the general trends seen in the data (and presented in this chapter) should be more reliable than the year-to-year values.

4.4 Summary

Non-renewable energy and electricity were the main energy carriers for end use, at 41% and 35% respectively, in 2013. Use of non-renewable energy likely saw a peak around 2010, but has since decreased dramatically, while the use of both district heating and biofuels is increasing.

The use of electricity has remained fairly constant throughout the period studied (1990 – 2013). An increase in the end use of electricity is observed in the 'others' category, while a decrease is observed in the industry & construction sector (since 2008). For the other sectors, use has been fairly constant. A 160% growth of the electricity generating capacity over the period has resulted in almost doubling the amount of electricity produced within the municipality. Combined with a somewhat lowered amount of imported electricity, the share of electricity produced in-system has roughly doubled, reaching 15% in 2013. The capacity factor has dropped somewhat over the period; this can be partly traced to the introduction of wind power into the system.

The production capacity in the district heating system has seen a similar increase over the period, having grown with about 150%. At the same time, production and use of heat has increased by about 180%. A majority of the increased use can be traced to the residential sector. In total, 1753 new connections to the district heating system have been made since 2005, with a majority being to residential buildings.

Overall, the energy inserted for conversion (for production of both electricity and heat) in the municipality has increased by 140%, dominated by increases in waste and biofuel. This is to be expected, as the period has seen the capacity of waste-fired *Kristinehedsverket* increased by 160%, from 26 to 68 MW, as well as the construction of 122 MW, biofuel-fired *Oceanen*. Both plants are mainly for producing heat, but have partial CHP capacity. In addition, about 12 MW of wind power has been built during the period (with an additional 13 MW constructed in 2014).

A decrease in the use of non-renewable energy is seen in all sectors except the transport sector. Especially of note are the residential and public sectors which have gone from relying significantly on the use of non-renewable energy in 1990 to having completely phased them out in 2013. This has been achieved by a combination of increased use of district heating, combined with a decreased energy use overall. The decrease in total energy use for the residential sector has happened in spite of an increasing population within the municipality.

The transport sector was the largest energy end user in 2013, responsible for 39% of the total end use. The sector is also the only one showing a steady growth in energy use, as well as the sector where non-renewable energy dominates the most, supplying 91% of the sector's energy in 2013. This means that the transport sector provides the largest challenge (but also the largest potential) for the decrease of non-renewable energy use.

In the industry & construction sector, the end use of energy, especially non-renewable energy, has seen two major decreases: one from 2004 to 2005 of about 220 GWh per year, and one from 2012 to 2013. The second decrease can be linked with some certainty to the closing of the Pilkington sheet glass plant. The first decrease is harder to link with a specific event, but coincides with the closing of the Duni disposable tableware plant in 2004. The 2008 financial crisis however seems to have had little noticeable effect on the energy use of the sector.

Finally, as a crude analysis of the transition towards a carbon-neutral energy system, we can compare 1990 and 2013, assuming that all changes in the energy system have had the intention of reducing the amount of non-renewable energy used.

Looking first at the end use we see that the use of electricity has increased by 24 GWh, the use of district heating has increased by 275 GWh, and the use of renewable energy has increased by 129 GWh; totalling an increase of 428 GWh of energy that can replace the use of non-renewable energy. Another way of reducing the use of non-renewable energy is of course to simply reduce the overall use of energy; the decrease in total end use of energy is 456 GWh. Adding these together, we get 884 GWh of non-renewable energy reducing potential, matching the reported decrease in non-renewable energy end use. This means that replacement of non-renewables with electricity accounts for 3%, replacement with renewables accounts for 15%, replacement with district heating accounts for 31%, and reduction of the total energy use accounts for 52% of the total reduction of non-renewables.

Looking instead at the supply of energy into the system, we see that the supply of non-renewable energy has instead decreased by 797 GWh from 1990 to 2013 (the lower number than for the end use reflecting the increased amount of non-renewables inserted for conversion). The supply of electricity has decreased as well, by 126 GWh. This reduction has been covered by an increased supply of biofuels (549 GWh, covering 59%) and a decrease of the total energy supply (366 GWh, covering 40%), as well as a minor increase in the supply of hydro energy and waste heat (together 8 GWh, covering 1%). This adds up to 923 GWh, again matching the decrease in the reported supply of non-renewables and electricity.

5 FORECASTING: WHAT DOES THE PAST TELL ABOUT THE FUTURE?

Having studied the past in the previous chapters, we will now use the data and knowledge gathered to peer into the future; but first, a few words of caution. No forecast, no matter how advanced, can with complete certainty predict the future. However, like most things the development of an energy system follows certain patterns, and by identifying these in the available data we can project them into the future, identifying a likely path for the development to take. In order to do this, we will assume that the studied technologies (approximately) follow a logistic curve, both when expanding and receding. In the following chapter, we will first introduce the concept of *logistic forecasting* and how it has been applied in this thesis. Later, the resulting forecasts will be presented, along with the underlying data.

5.1 FORECASTS

Looking at the forecast in Figure 17, we can note two trends that were missing from the previous forecast. Firstly, the end use of the 'others' category is projected to increase throughout the period, however with a diminishing rate. Secondly, the end use for the industry & construction category is projected to reach close to zero around 2020. This second prediction is of course very unlikely, and shows one of the weaknesses of using logistic forecasting, especially for limited sets of data: if the majority of the data set roughly follows a straight, horizontal line (matching one of the horizontal parts of the logistic curve), even a relatively minor increase or decrease at the end will trigger the exponential part of the logistic curve, producing the dramatic decrease seen.

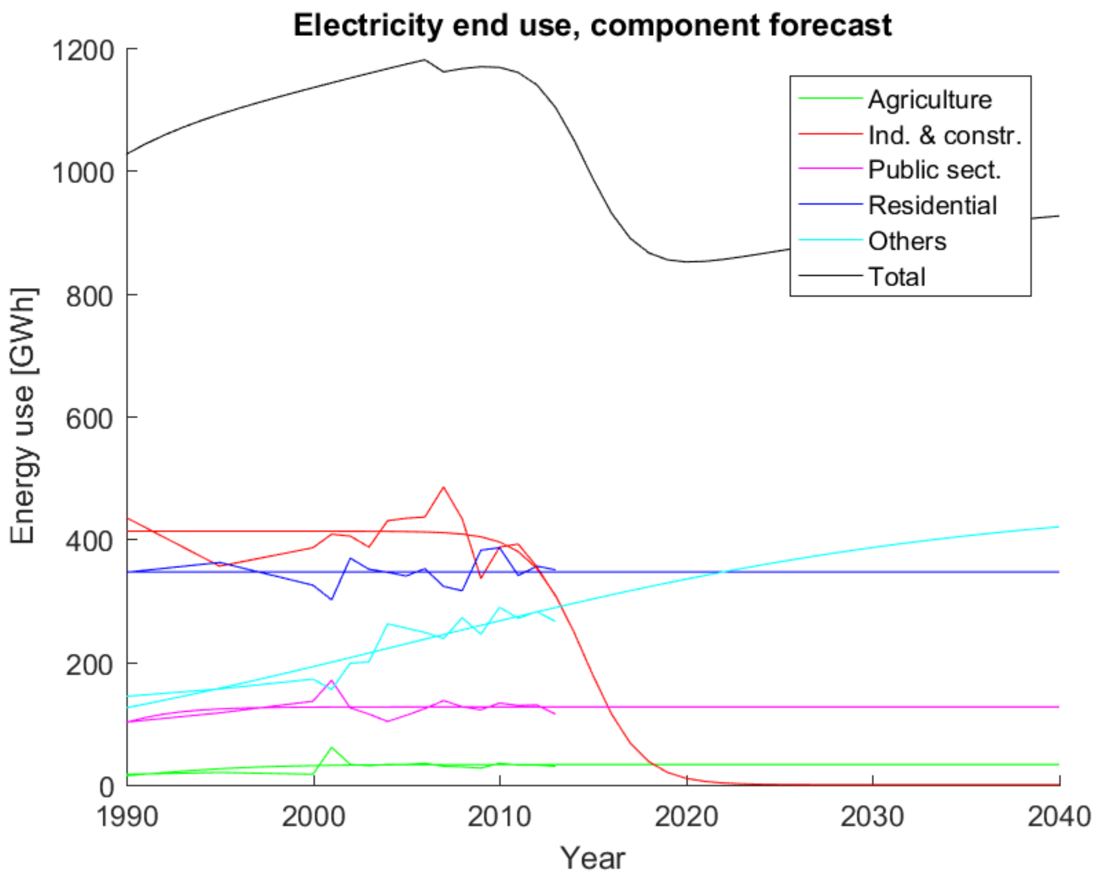

Figure 17: ELECTRICITY END USE, COMPONENT FORECAST. The graph shows the available data (jagged lines) and forecasts (smooth curves) of the total end use of electricity for the different sectors, as well as the sum of all sectors' forecasted values (black curve). The plot for *transport* has been omitted from the graph due to very small values for this category, but is included in the calculation of the total energy use.

Another thing missing from this simple forecasting model (but which could be implemented in more advanced models) is the knowledge of planned future events which will impact the energy system. One such event is the planned opening of a large scale recycling plant in Halmstad municipality in the near future (Stena, 2014), which can be expected to impact e.g. the electricity use of the industry & construction sector.

Going back to the results in Figure 17 and looking at the total electricity end use, we see that the electricity use is projected to drop until around 2020, due to a reduced electricity use in the industry & construction sector (although, as previously mentioned, the extent of this reduction is likely greatly exaggerated; indeed, intuition tells us that an increase in the electricity use during this period is probably more likely). From 2020 onwards, the total electricity use is projected to increase due to the increasing electricity demands of the 'others' sector (for a definition of this sector, see Footnote 19).

Moving on to the district heating system, we start by forecasting the projected demand for district heat. Unfortunately, the data for the individual sectors has some extreme variations from year to year which causes the component forecasting to fail. Thus, a forecast made only with data on the total district heating use will have to suffice. The later data points also suffer from large yearly variations, but the algorithm manages to produce a forecast in spite of this. Since no data is available for the time before 1990, we also add a data point representing when the use was 10% of the use in 2013, to mark the point where the major expansion of the system starts. According to the history of the district heating network (presented in Section 3.2), the first major expansion of the district heating system was during the 1980's, so 1980 is chosen as this point.

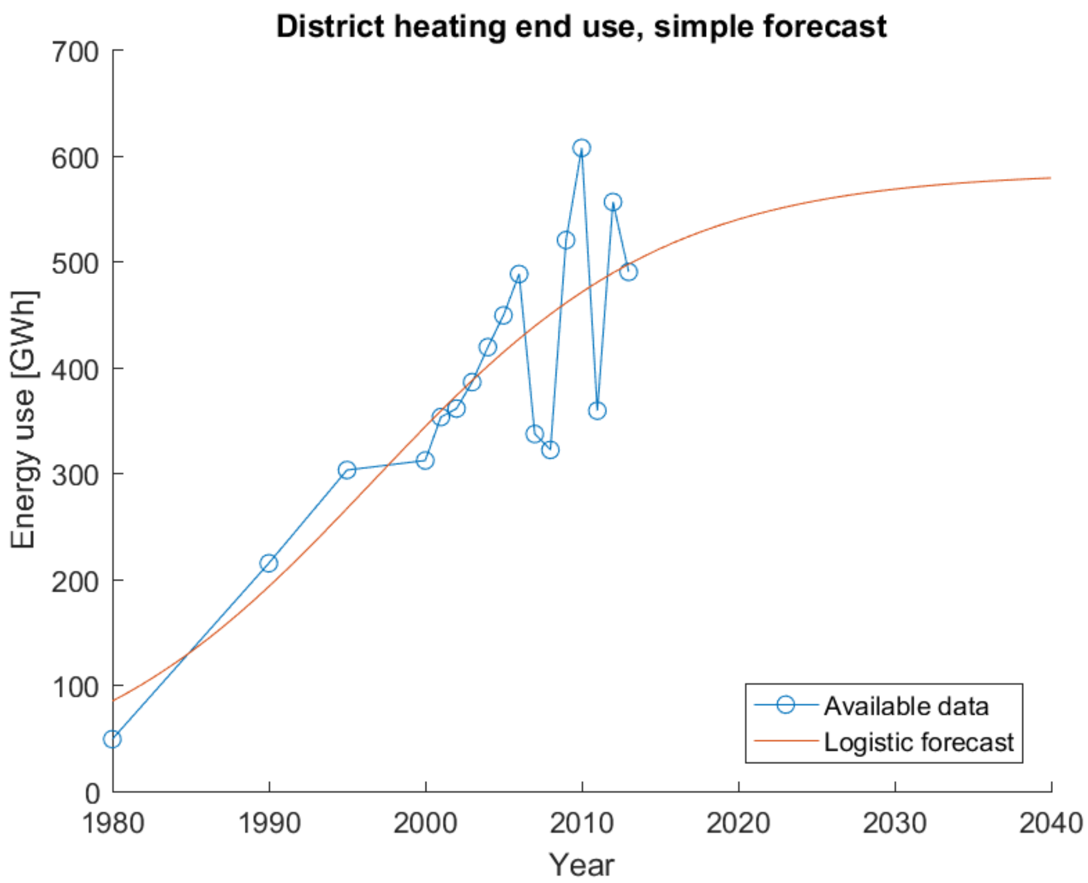

Figure 18: DISTRICT HEATING END USE, SIMPLE FORECAST

The forecast, shown in Figure 18, shows a continued growth in the use of district heat, but with a diminished rate of growth. Around the year 2040, the demand for district heat is projected to be nearing its peak, reaching almost 600 GWh per year; roughly 20% above the current level.

Another way to follow the growth of the district heating system is to look at how the number of end point connections of the system (i.e. the number of buildings connected to the district heating system) has changed over the years. Forecasting this quantity (Figure 19), a similar prediction as in the previous forecast is seen – the number of end point connections nearing its peak around 2040, again at a level roughly 20% above today's. Following the logistic forecast curve backwards in time, we can note that it also here roughly matches the curve in the previous forecast, reaching near zero in 1980.

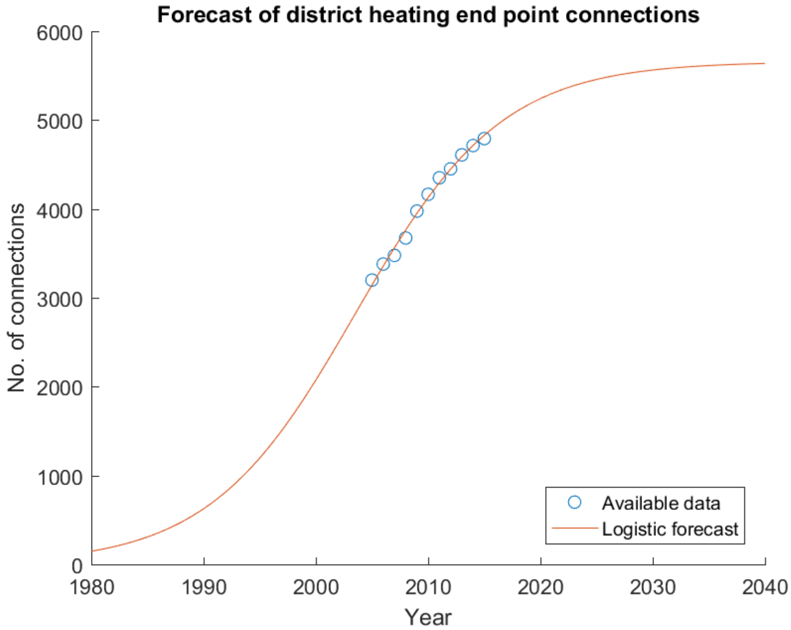

Figure 19: FORECAST OF DISTRICT HEATING END POINT CONNECTIONS

Continuing with the use of non-renewable energy, Figure 20 shows the benefits of using a component logistic model; looking at only the total end use of non-renewable energy (Figure 13), it appears to be decreasing (indeed, making a forecast using only data for the total non-renewable energy use shows a decreasing demand). However, forecasting each sector individually, we see that while the use of non-renewable energy is decreasing for all but two or three of the sectors (the data in the 'Others' category shows no clear trend), for the transport sector the use of non-renewable energy is increasing and if nothing is done to reverse this trend, the total use of non-renewable energy will start increasing again somewhere around the year 2020.

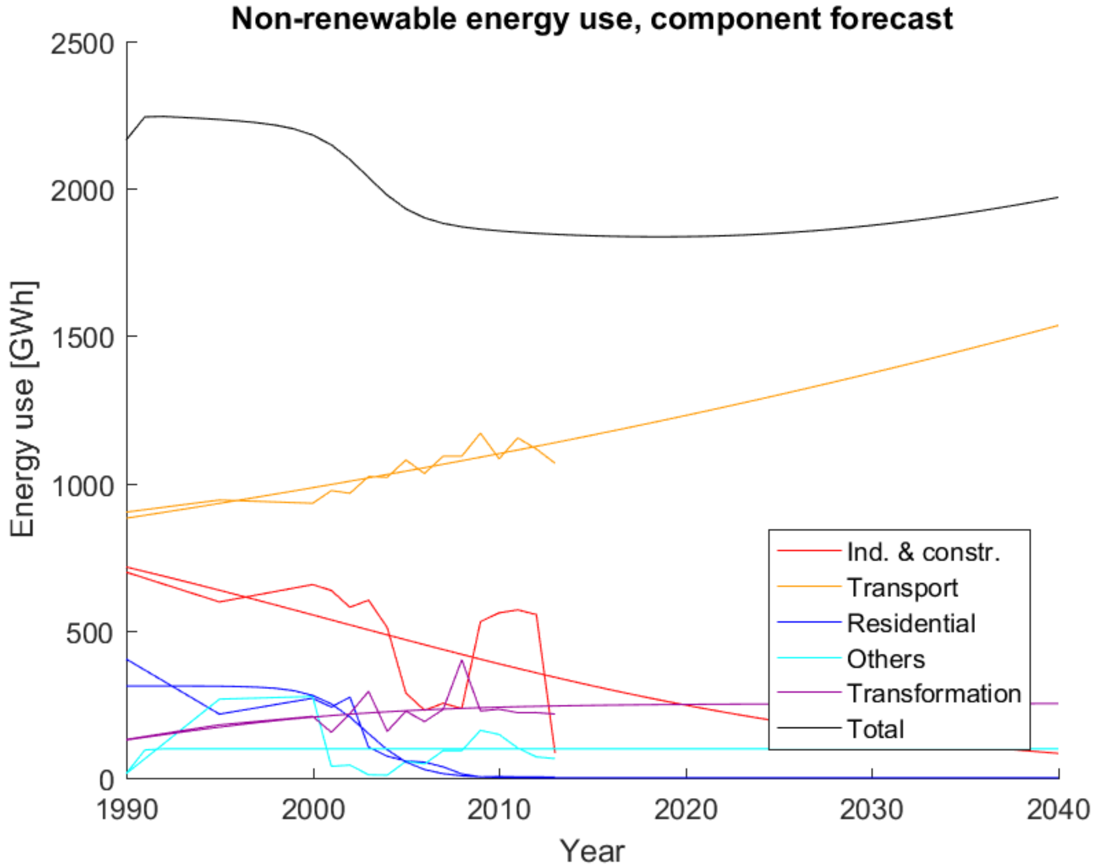

Figure 20: NON-RENEWABLE ENERGY USE, COMPONENT FORECAST. The graph shows the available data (jagged lines) and forecasts (smooth curves) of the total end use of non-renewable energy for the different sectors (including the energy inserted for transformation), as well as the sum of all sectors' forecasted values. The plots for *agriculture* and *public sector* have been omitted from the graph due to very small values for these categories, but are included in the calculation of the total energy use. The *unknown* category introduced in Section 4.3.2.3 is here included as non-renewable energy for the industry & construction sector.

Figure 21 shows the forecast of the end use of biofuels (including the renewable portion of incinerated waste). Here the majority of the energy is inserted into one of the municipality's power plants for transformation into other energy carriers (electricity and hot water), denoted by the 'transformation' category. This category is projected to near its maximum around the year 2030, at around 700 GWh. The total demand is projected to continue to grow beyond 2040 however, as the demand of the residential sector continues to increase.

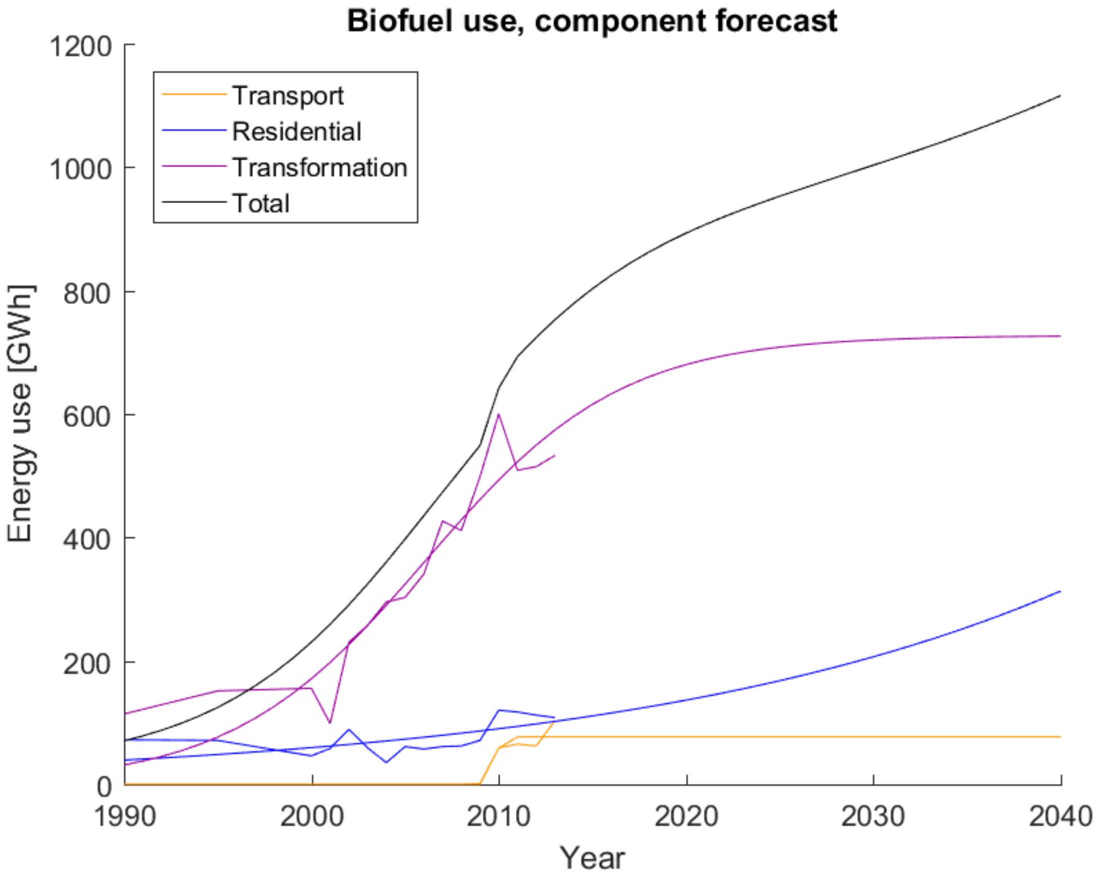

Figure 21: BIOFUEL USE, COMPONENT FORECAST

As the availability of biofuels is limited, one way to check the feasibility of this forecast is to compare it with the maximum potential for obtaining biofuels for the region. A Swedish study attempting to judge the future potential of biofuel production in Sweden (Börjesson, Gustavsson, Christersson, & Linder, 1997) gives the capacity as 230 TWh per year, but also cites earlier studies with lower figures of 15 – 135 TWh per year. Assuming a future capacity of 50 – 230 TWh per year for the whole country, Halmstad's share of that resource can be very roughly approximated as follows: Assuming no import or export of biofuels, and that each municipality has a claim or purchasing power on a certain amount of biofuels based on their population, the biofuel available to Halmstad can similarly be calculated as the total production potential of Sweden multiplied by the population of Halmstad divided by the population of Sweden. In symbols,

$$B_H = B_S \frac{P_H}{P_S} \qquad \text{Equation 15}$$

where B_H is the biofuel available for use in Halmstad, B_S is the biofuel production potential for Sweden, P_H is the population of Halmstad municipality, and P_S is the population of Sweden.

This rough approximation gives a maximum potential availability of 494 – 2 274 GWh per year for Halmstad municipality. Comparing these values to Figure 21, we can see that the demand already exceeds the lower limit calculated, and that the upper limit provides no restriction on the forecast within the timeframe used.

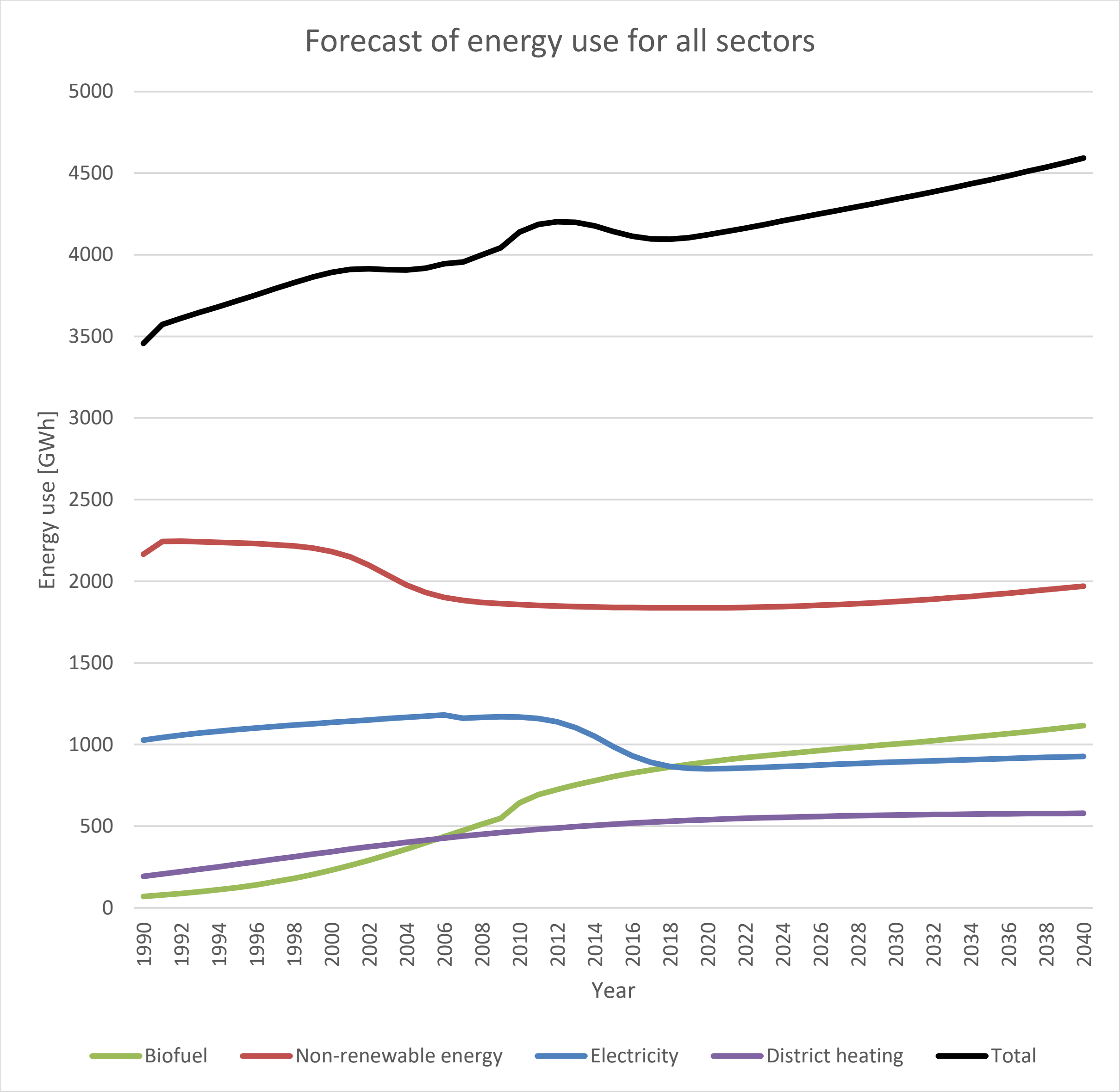

Figure 22: FORECAST OF ENERGY USE FOR ALL SECTORS

In Figure 22, the forecasts of the total end use of electricity, district heating, non-renewable energy and biofuel are presented in a single graph, along with the sum of these four forecasts. As can be seen, the total energy use is projected to increase over the forecasted period, with most of the growth being covered by biofuels. However, non-renewable energy is projected to remain as the main energy carrier; at the end of the forecast still covering almost half of the energy use.

6 EMERGING TECHNOLOGIES: WIND AND SOLAR

After the forecasting of the previous chapter, the following two chapters will analyse further some of the mechanisms that shape the development of the energy system. This chapter will look at two important emerging renewable technologies for electricity production, wind and solar power, and discuss their development in Halmstad municipality.

6.1 WIND ENERGY

Wind power produced 6% of the total energy in Sweden in 2013, and is growing quickly (Statistics Sweden, 2016). One of the areas that has proved suitable for wind power is the Swedish west coast: In 2014 Laholm municipality, which neighbours Halmstad to the south, had 133 wind turbines with a total installed capacity of 160 MW, producing 353 GWh of electricity. This gave Laholm the ranking as the municipality with the 3rd most installed wind power capacity in Sweden. Neighbour to the north, Falkenberg, had 75 wind turbines with a total of 136 MW installed power, producing 297 GWh and giving Falkenberg the rank of having the 8th most installed capacity in Sweden.

Thus, it would seem that also Halmstad municipality should have good geographical opportunities for investing in large-scale wind power, but as was seen in Table 5 (page 22), a relatively small amount of wind power has been built (25 MW in 2014). One major reason for this, cited by both Bernhardsen (2015) and Kindstedt (2009), is the large presence of military installations and training areas in Halmstad municipality, and conflicts between the use of these and wind power installations. Figure 23 shows a map of existing and planned wind power plants in Halmstad municipality and the surrounding regions, along with military exercise areas. As can be seen, these areas cover a significant portion of Halmstad municipality (most critically a large portion of the coastline, where the conditions for wind power are the most favourable). On this map can also be seen the difference in the amount of installed wind power in Halmstad municipality and the surrounding areas.

The areas marked by a purple border are described by the military as having a ‘special need for a lack of obstructions’ (Försvarsmakten, 2015), which in practice means that obtaining permission for building wind power plants (especially larger, more efficient ones) in these areas would prove very hard. Wind power plants also disturb the use of radar and radio communications (Försvarsmakten, 2015).

Thus, the relatively low amount of wind power in Halmstad municipality is not mainly due to technical or economic reasons, but rather due to a conflict of interests; in this case regarding the airspace above the municipality.

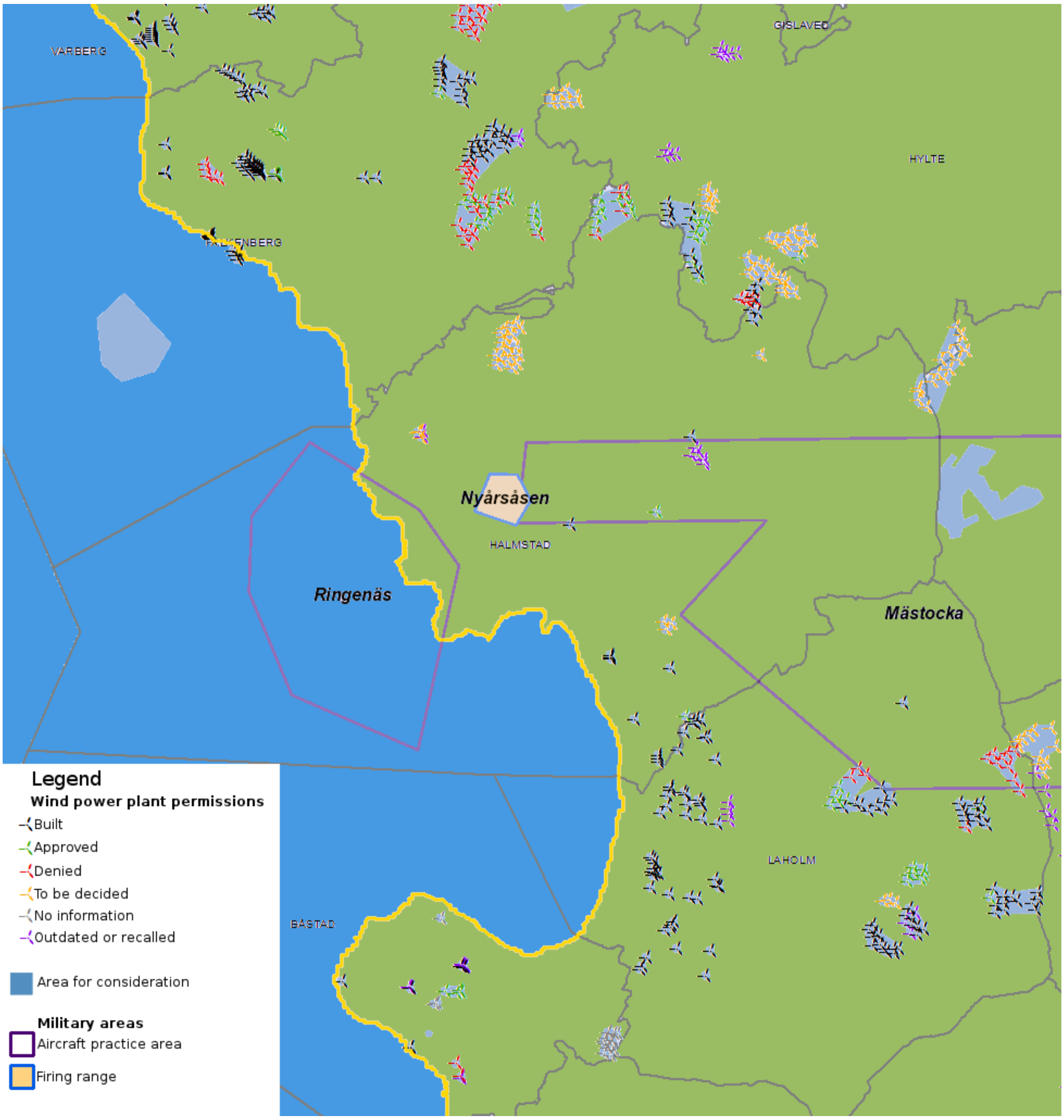

Figure 23: MAP OF BUILT AND PLANNED WIND POWER PLANTS IN HALMSTAD MUNICIPALITY AND SURROUNDING AREAS. The map shows constructed wind power plants (black symbols), as well as planned plants which have been approved (green), denied (red), are waiting approval (yellow) and where the plans are outdated or recalled (purple). In addition, the map shows the two military aircraft practice areas *Ringenäs* and *Mästocka*, and the firing range *Nyårsåsen*. The map is not complete, but shows the difference between the ammount of wind power built in Halmstad compared to the neighbouring municipalities. Source: Vindbrukskollen, *www.vindlov.se*

6.2 SOLAR ENERGY

Partly due to the aforementioned difficulties facing wind power in the municipality, Halmstad municipality has instead aimed to become a leading municipality in the solar energy field, and has made relatively large investments in solar energy, both via HEM and the department of real estate (*Fastighetskontoret*).

6.2.1 CURRENT INSTALLATIONS AND FUTURE PLANS

For HEM, the idea began in 2008 – 2009 with an offer from a customer to take care of excess energy from a planned solar thermal plant. However, since it was already necessary to run the waste incineration plant (*Kristinehedsverket*) at high capacity also during the summers in order to incinerate waste, there was already excess heat within the district heating network during the summer (when the solar thermal plant would produce the majority of its heat). Therefore, the customer was convinced to invest in electricity-producing solar technology instead, and HEM was inspired to do the same. A pilot project was initiated at a school in Halmstad (*Kattegattgymnasiet*), and the plan was to cooperate with the school's education for car mechanics and electricians, offering hands-on experience with grid-connected solar cells and electric cars. Unfortunately, this cooperation never took place, but the planned solar photovoltaic (solar PV) panels were installed anyway. (Bernhardsen, 2015)

In 2014, a full-scale solar PV plant was built on *Skedalahed*, a former landfill. The plant is estimated to generate 500 MWh of electricity per year, and the plan is for the electricity generated to be used for charging electric vehicles (EVs) through a programme ('*Solen i tanken*') where EV owners report their total distance travelled, and HEM guarantees a production of solar electricity matching the electricity consumed by the EVs. However, there are not yet enough EVs in Halmstad municipality to demand 500 MWh per year. As a part of this programme, a number of EV charging points were also built. (Halmstad energi och miljö, 2015), (Bernhardsen, 2015)

The municipality has also made a number of installations of solar panels on municipality-owned buildings via the department of real estate. These investments began in 2009 – 2010 as part of a larger project to reduce energy use within the municipality[21]. In 2010, the department of real estate was granted a yearly sum of 2 million SEK to install 'solar energy solutions', and in 2016 this grant was increased to 2.5 million SEK. Current plans are to install 'at least four new installations' and also test systems for battery storage. (Halmstad municipal department of real estate, 2016)

One reason cited for using battery storage is the low compensation paid for the excess electricity that is delivered to the grid. The municipality is selling the excess electricity to the grid at the spot price, minus a 'smaller fee'. They report an average price of 0.26 SEK per kWh for 2014, but due to a lower electricity price in 2015, the compensation for that year fell to 0.18 SEK per kWh. This can be compared to the average cost of 0.94 SEK per kWh to produce the electricity. During 2015 the total energy produced was 532 MWh, and 68 MWh (13%) of this energy was sold to the grid. (Halmstad municipal department of real estate, 2016) Using battery storage would enable a larger share of the electricity to be used by the department themselves, since energy then could be stored from peak-production hours during the middle of the day to hours where production is low or non-existent, but demand is still high (e.g. evenings).

A list of all solar PV installations made by Halmstad municipality (either through HEM or the department of real estate) can be found in Table 8.

Figure 24 shows the size of each installation and the accumulated total in graph form. In Figure 25, this data is used for a logistic forecasting of future installed capacity. As can be seen, the forecast suggests an installed capacity of 2 MW around the year 2020. Assuming that the forecast represents an approximate future path (the installed capacity levelling out at a relatively low level within the coming

[21] Although installing solar panels on a building does not save energy per se, it reduces the building's consumption of energy from the grid.

Table 8: LIST OF SOLAR PV INSTALLATIONS MADE BY HALMSTAD MUNICIPALITY. Data from Halmstad municipal department of real estate (2016)

Address/Name of installation	Finished	Total cost* [thousands of SEK]	Subsidy [percent]	Area [m²]	Peak output power [kW]	Calc. energy production [MWh/year]	Cost per peak output power [SEK/W]	Cost of energy produced***	Utilisation factor
Unit	-	SEK	-	m²	kW	MWh /yr	SEK /W	SEK /kWh	-
Sannarpsgymnasiet	2010-12-22	3 079	55%	460	56.7	56	54	3.16	0.11
Stenstorpshallen	2011-12-20	858	45%	245	33.2	29	26	1.71	0.10
Frösakullsskolan	2012-04-04	685	0%	218	33.0	26	21	1.52	0.09
Getingeskolan	2012-09-01	899	45%	415	50.8	48	18	1.08	0.11
Kattegattgymnasiet	2012-10-13	407	45%	136	17.6	18	23	1.29	0.12
Vallås Högstadieskola	2012-11-06	898	0%	383	50.0	48	18	1.00	0.11
Söndrumsskolan	2013-06-24	1 003	35%	451	61.7	58	16	0.99	0.11
Gården Ön	2013-08-30	159	35%	51	7.3	7	22	1.30	0.11
Mjellby Konstmuseum	2013-08-30	177	35%	59	8.3	8	22	1.28	0.10
Halmstad Arena	2014-02-01	1 767	35%	902	131.1	123	13	0.82	0.11
Andersbergs Idrottshall	2014-06-04	720	0%	251	35.2	43	20	0.97	0.14
Västra stranden LBVA	2014-06-04	974	0%	401	53.5	62	18	0.91	0.13
Eldsbergahallen	2014-07-02	349	0%	98	15.3	12	23	1.61	0.09
Skedalahed	2014-07-15	11 000	0%	3 240	500**	500	22		0.11
Gathenhielmsvägen 19	2014-09-15	290	0%	128	15.6	17	19	0.96	0.13
Lundsgårds fsk	2014-09-24	171	0%	115	15.6	16	11	0.63	0.11
Hoppets väg 26	2014-12-22	180	0%	113	17.6	17	10	0.61	0.11
Nymansgatan 23	2015-05-15	550	0%	191	25.0	32	22	0.98	0.15
Ringenäs Strandtoalett	2015-09-01	70	0%	3					
	Sum of total costs:	24 236							

**Including installation costs and cost of inverter etc.*
***Calculated by the author from reported projected energy production and average utilisation factor*
****Excluding subsidies*

decade), this seems like a rather disappointing result – although 2 MW of solar PV installations could contribute with learning by doing-effects with regards to local installation costs (more on this in Section

7.2), the overall effect on the energy system would be rather small. However, this curve only represents the ‘first wave’ of solar PV installations which are funded by the municipality, and there is reason to believe that a ‘second wave’ of installations, where private homeowners and companies play a larger role, is forthcoming (see Section 7.2). As this second wave gains momentum, some arguments exist as to why the rate of new installations made by the municipality will slow down and possibly stop altogether. Perhaps the strongest argument for a (relatively low) limit of the installed solar PV capacity made by the municipality is the limited number of municipality-owned buildings which can support the solar panels (and consume the electricity produced by them). Of course, the municipality could continue to invest in panels mounted on other buildings or on the ground, but this brings us to the second argument: as solar power becomes more commonplace, the role of the institutions installing additional solar capacity will shift from '(local) pioneers of a new technology' towards being simply 'electricity producers' – a role which is arguably outside the domain of the municipal department of real estate. The municipality could continue its investments in solar power through HEM, but apart from the *Skedalahed* solar plant, HEM has traditionally focused on the production of heat, and has for example not made any major investments in wind power.

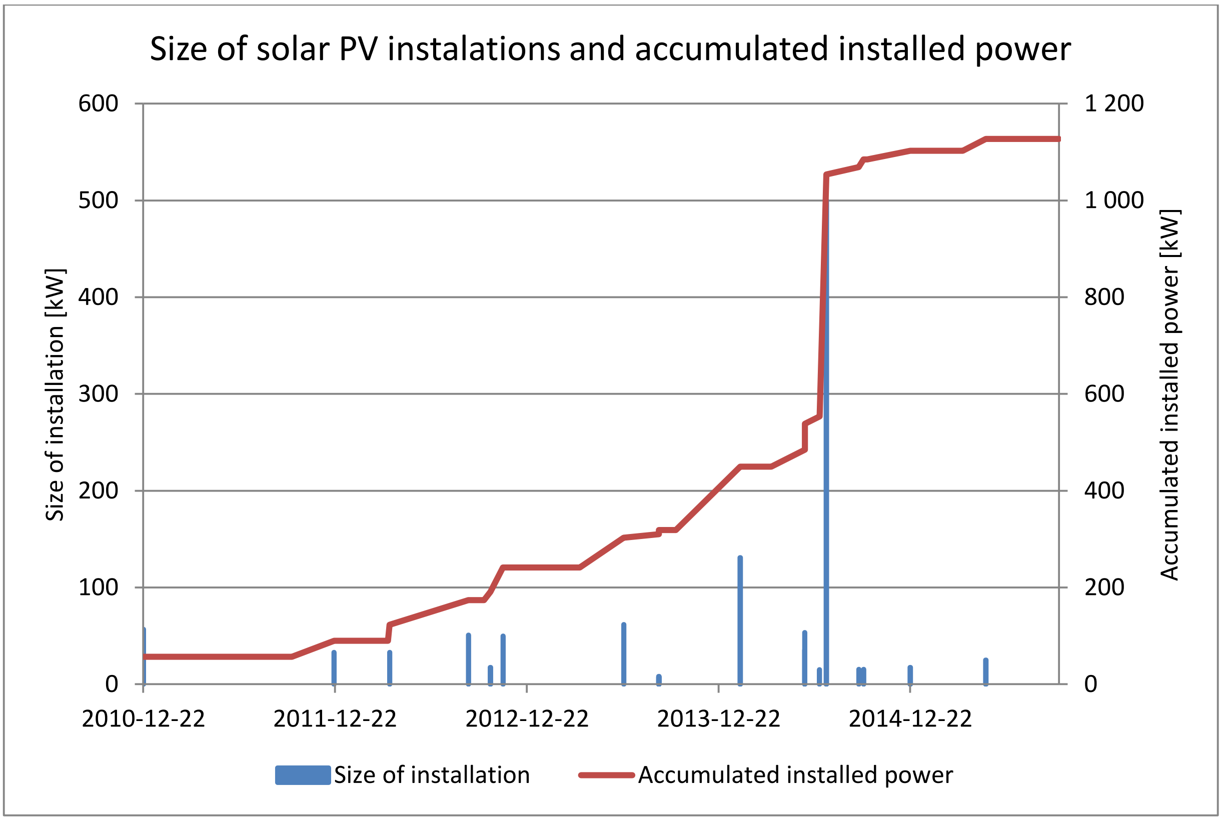

Figure 24: SIZE OF SOLAR PV INSTALLATIONS AND ACCUMULATED INSTALLED POWER

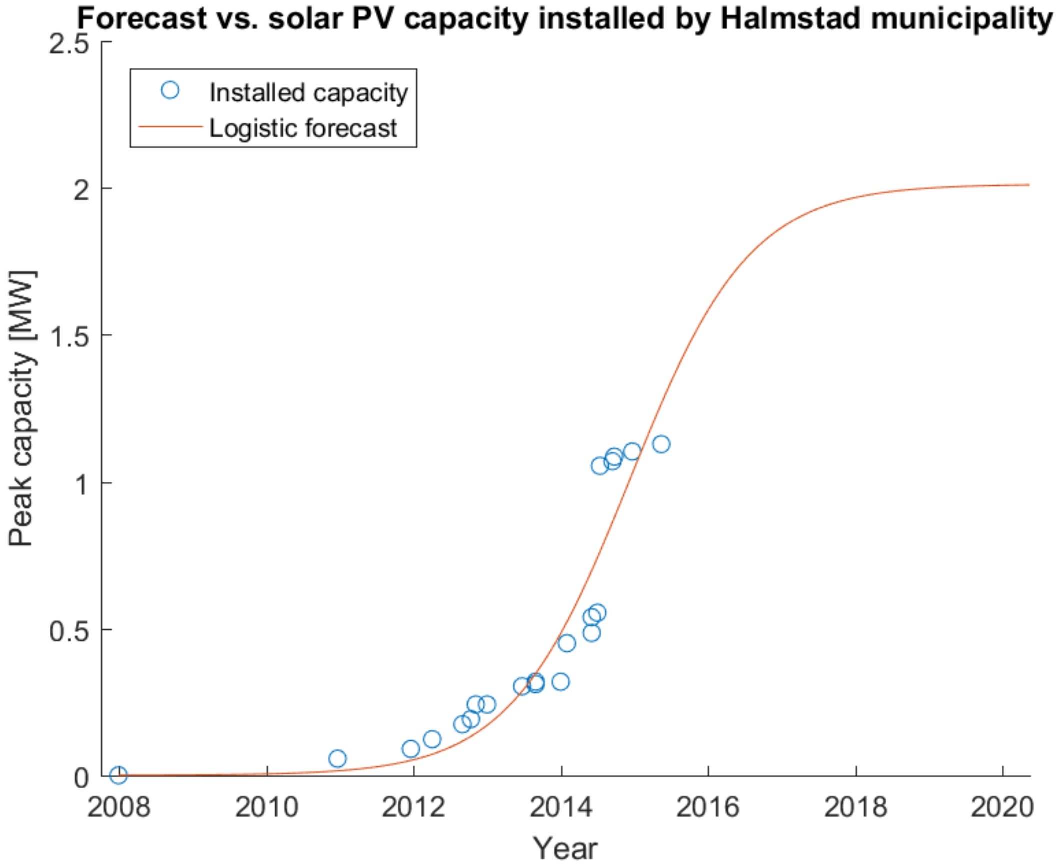

Figure 25: FORECAST VS. SOLAR PV CAPACITY INSTALLED BY HALMSTAD MUNICIPALITY

6.2.2 THE COST OF SOLAR ENERGY IN HALMSTAD MUNICIPALITY

Looking at the total cost (including installation costs, as well as inverters etc.) of installed solar PVs per max output power (Figure 26) we see a dramatic decline in cost from the time of the first investments in late 2010 until mid/late 2012, where the price per kW of maximum output had dropped from 54 000 SEK/kW to around 20 000 SEK/kW. From there, the cost remained fairly stable until mid/late 2014, where it dropped to around 10 000 SEK/kW for two installations which were made as part of the construction of new buildings. In mid-2015, the cost rose back to 22 000 SEK/kW; however, this time for a retrofit on an older building. Looking at the average costs for post 2012 installs on new buildings vs. retrofits, the cost of installing PVs as part of a new building is noticeably cheaper at 15 770 SEK/kW on average, compared to 19 605 SEK/kW on average for retrofits.

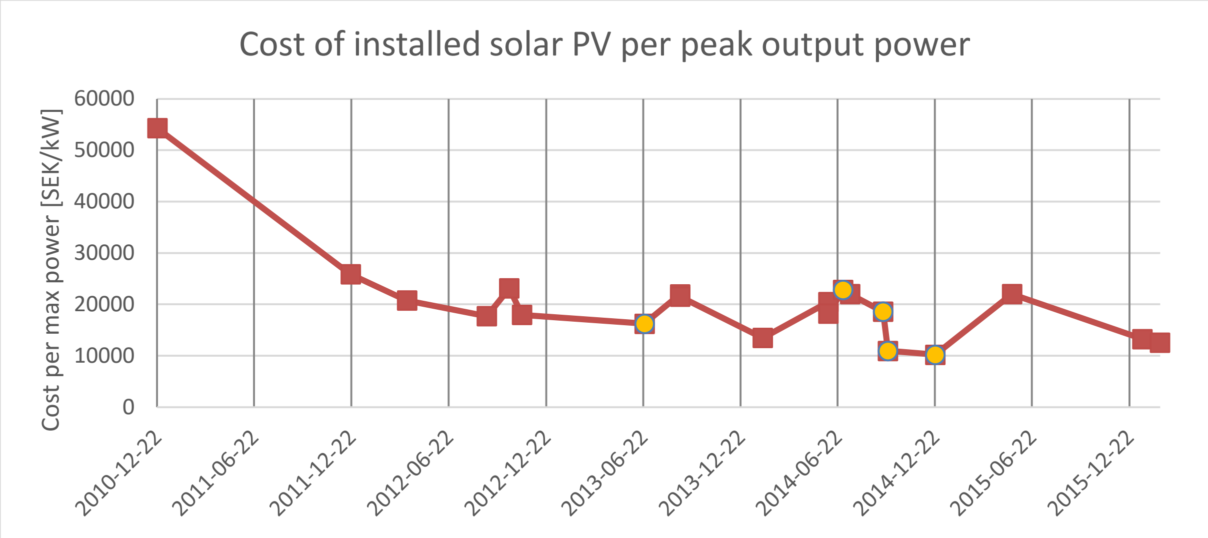

Figure 26: COST OF INSTALLED SOLAR PV PER MAX OUTPUT POWER. The yellow dots represent solar PVs installed during the construction of a new building, while the rest are retrofits on older buildings.

Looking at the cost of the electricity produced (Figure 27) the same drop in cost as in Figure 26 can be seen. We can also note that the unsubsidised installations built in 2014 and 2015 produce electricity at the same cost as (or even cheaper than) the subsidised installations of 2010 to 2013.

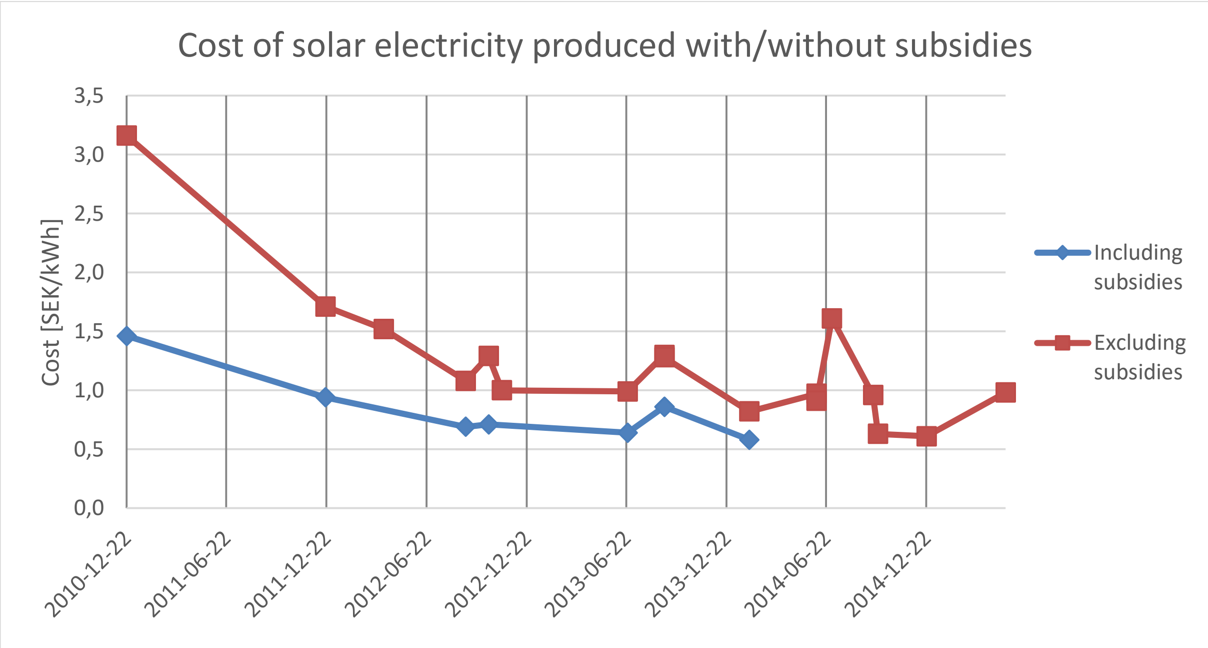

Figure 27: COST OF SOLAR ELECTRICITY PRODUCED WITH/WITHOUT SUBSIDIES

Figure 28 and Figure 29 compares the cost of the electricity produced by the installed solar cells to the average price paid by customers when buying electricity from the grid. The price data is taken from Statistics Sweden and shows the six-month average price paid by eleven different user categories, dependent on the users' yearly consumption of electricity[22]. The categories are presented in Table 9.

[22] This data represents the average for all of Sweden, but since Halmstad municipality is located in the southernmost electricity price district (*elområde 4*) where the electricity prices are generally the highest, the prices in the diagram should be slightly lower than the actual prices paid by a customer in Halmstad.

Table 9: PRICE CATEGORIES FOR DIFFERENT ELECTRICITY USERS

	User category	Yearly consumption
Domestic	DA	< 1000 kWh
	DB	1 000 - < 2 500 kWh
	DC	2 500 - < 5 000 kWh
	DD	5 000 - < 15 000 kWh
	DE	≥ 15 000 kWh
Industrial	IA	< 20 MWh
	IB	20 - < 500 MWh
	IC	500 - < 2 000 MWh
	ID	2 000 - < 20 000 MWh
	IE	20 000 - < 70 000 MWh
	IF	70 000 - < 150 000 MWh

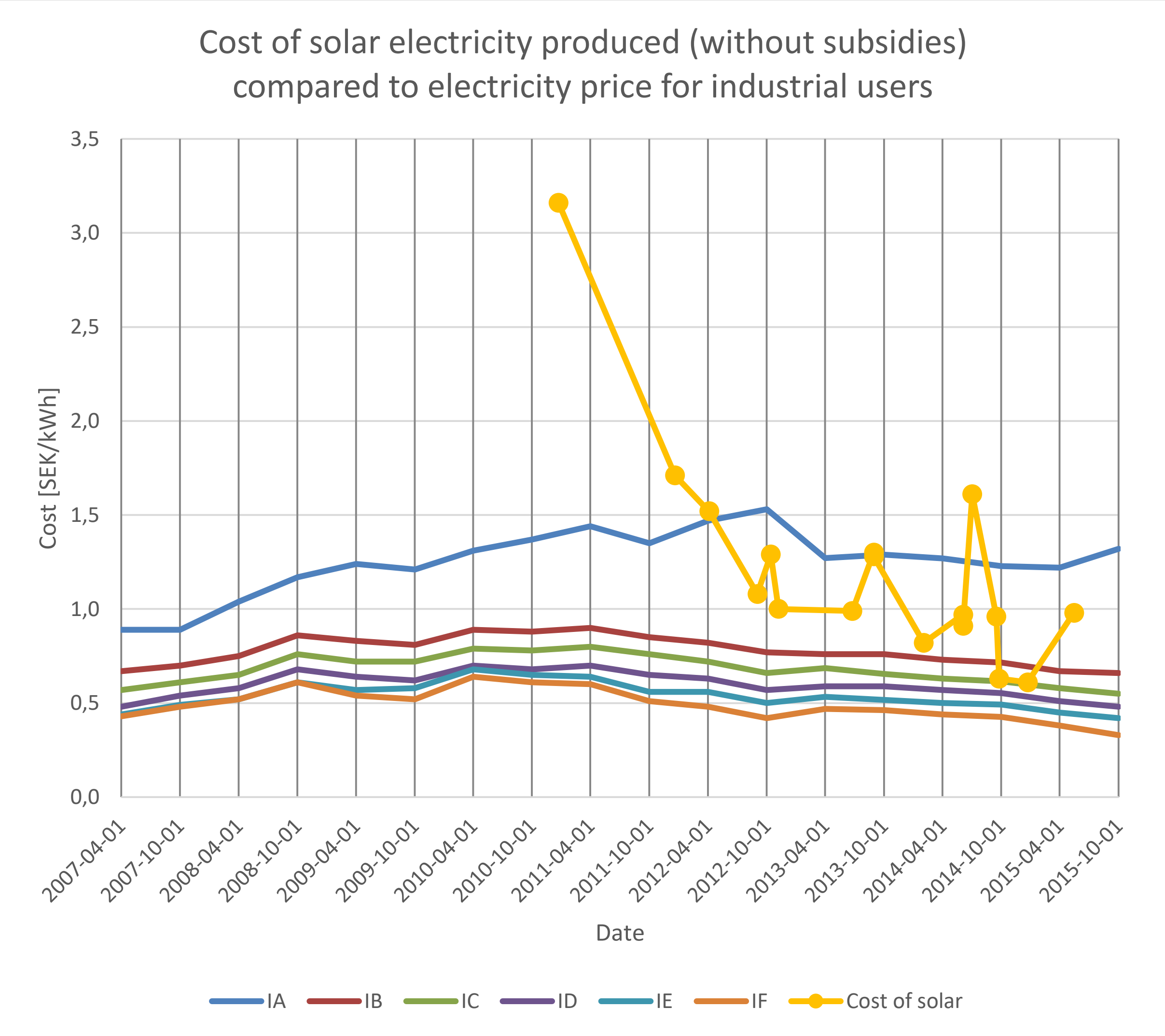

Figure 28: COST OF SOLAR ELECTRICITY PRODUCED (WITHOUT SUBSIDIES) COMPARED TO GRID ELECTRICITY PRICE PAID BY INDUSTRIAL USERS

As can be seen in Figure 28, almost all of the installations made after mid-2012 produce electricity at a lower cost than the electricity price paid by the *IA* category (see Table 9). We also see that two of the installations, made in late 2014, produce electricity that is cost-competitive to the *IB* or even *IC* category. It is also interesting to note how sensitive the competitiveness of the solar panels is to the variations in the electricity price; had the cost of electricity remained as high as in early 2011, the cheapest solar panels would be competitive to even the lowest electricity prices (0.61 SEK/kWh for the cheapest solar energy compared to 0.60 SEK/kWh for the lowest electricity price) [23].

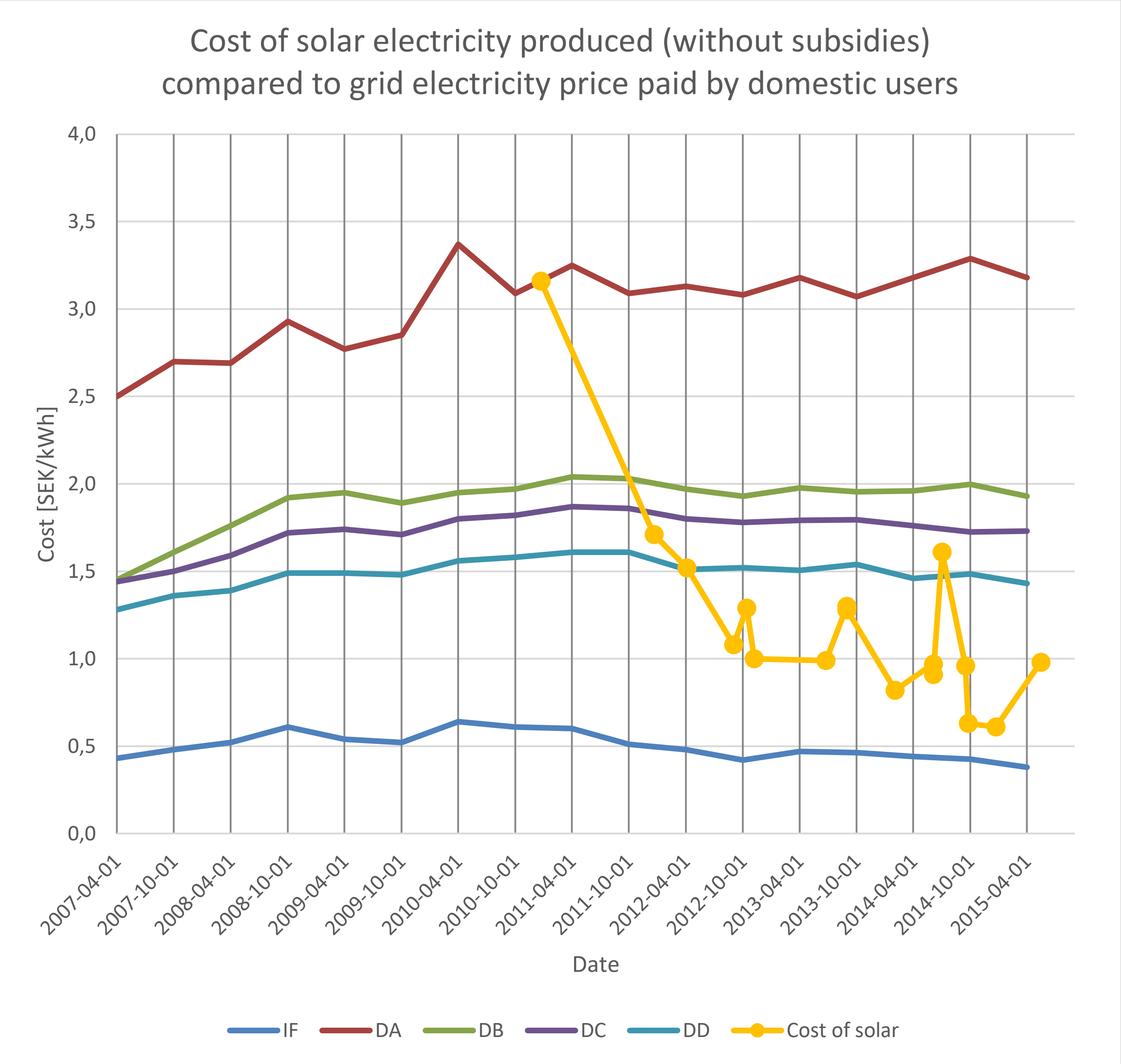

Figure 29: COST OF SOLAR ELECTRICITY PRODUCED (WITHOUT SUBSIDIES) COMPARED TO GRID ELECTRICITY PRICE PAID BY DOMESTIC USERS

Looking instead at the prices paid by domestic consumers found in Figure 29 (which are significantly higher than the prices paid by industrial customers) we see that most of the installations made after mid-2012 produce electricity at a lower cost than the electricity prices of all the domestic user categories. This suggests that installing solar panels is an economically sound investment for domestic and smaller

[23] One could hypothesise, however, that the reduction of the electricity price in the later years is at least partly due to an increase of renewable, near-zero-variable cost energy types like solar and wind power, so that as the price of solar and wind decreases, so will the electricity price; but this is a topic for another paper.

industrial electricity users. To provide a form of reference, most of the installations made by Halmstad municipality are projected to produce between 5 000 and 60 000 kWh per year, which corresponds to consumptions in the range of *DD* to *IB*.

The above sections show that solar PV is economically viable for a customer paying e.g. a monthly bill with a fixed kWh price, but how cost competitive is solar on an hourly basis? Imagining a scenario with a relatively high market penetration of solar power, the electricity price would be lowest on sunny summer days when the solar panels produce near their maximum capacity, and highest on cloudy winter days, when the solar panels would produce little or no electricity. Thus, the solar electricity would mainly compete with already low-cost electricity, limiting their economic potential from this perspective. On the other hand at least two of the three other local electricity-producing technologies currently employed in Halmstad municipality, wind power and CHP co-production, produce more electricity during the winter than during the summer, suggesting that at least a moderate amount of solar power could be useful for producing electricity during summer days with little wind and low production of electricity from the CHP plants due to a low demand of heat.

7 MECHANISMS SHAPING THE ENERGY SYSTEM: OVERALL FACTORS AND TWO IMPORTANT EXAMPLES

In this chapter we will first discuss some overall factors shaping the energy system, and then focus on two specific mechanisms: one an important driving force for new developments within a sociotechnical system, the other an effective barricade, shielding the old and well established technologies against competition from the new. In a way, *learning by doing* (e.g. Hogan (2014)) and *lock-in* (e.g. Unruh (2002)) are two sides of the same coin; in essence the same mechanism, but the former helping a new technology in its developing stage, while the later helps an old technology to keep on thriving when it should be ready to, from a technical, economic and/or environmental standpoint, be replaced by better alternatives.

7.1 OVERALL FACTORS

Some factors in shaping the development of the Swedish energy system in general are presented in Chapter 3. Likely the spark of the electrification was the availability of hydropower which gave a good potential for producing electricity, but also required the development of an electro-technical industry to develop and construct equipment like generators and power grids. This synergy can be related to Grübler's technology clusters, as described in Section 7.3. Hydropower also played an important role in Halmstad's development of the early electric system as well as the industry, as seen in Figure 6 and Section 3.3.

Independence from using imported energy was also an important factor shaping the energy system in the early 20th century, as well as in the aftermath of the energy crises of the 1970's. Today, Halmstad municipality cites independence and strengthening of the local economy as two reasons for investing in locally produced renewable energy (Halmstad municipality, 2015). The support of powerful institutions – in the case of the electrification of Sweden first the industry and later also the state – proves important, not only financially but also by providing legitimacy to the new and unproven technology. A similar situation can be seen in Halmstad today, with the municipality investing in solar power. In the early 20th century, a drastic decrease in cost both for buying equipment such as electric motors as well as for buying the electricity itself made the use of electricity attractive to a wider market – spreading from the heavy industry to the residential sector and public utilities like railroads. Again, some parallels can be drawn to the present growth of solar energy where the effects of learning by doing (as discussed in Section 7.2) have decreased the costs of solar energy installations, thereby making them attractive to a wider market.

The rise of the district heating system in Halmstad in the 1980's can arguably be linked to the introduction of incineration as a waste handling method, which happened a decade earlier. As a result of using incineration as a waste handling method, substantial amounts of 'free' heat was available. This free heat however came with the requirement of significant investments in infrastructure, in the form of a district heating network. These large investments, together with an organisational restructuring so that the municipal energy company now also was in charge of the waste handling, contributed to the lock-in of the use of district heating with heat supplied mainly by waste incineration, as discussed in Section 7.3.

7.2 THE IMPORTANCE OF DEVELOPMENT: LEARNING BY DOING AND LEARNING BY WAITING

We will start by looking at *learning by doing* (and the related *learning by waiting*). Solar PV technology will be used as an example for several reasons: it is a technology with a huge future potential but which is still in an early stage of commercialisation, Halmstad municipality is among the leading municipalities in Sweden with regards to using this technology, and perhaps most importantly, a substantial set of the useful data could be found. The effects of learning by doing have been documented to act similarly on many technologies, however (e.g. (Grübler, 1998), (Junginger, Lako, Lensink, Sark, & Weiss, 2008)).

A way of presenting the effects of learning by doing is the *learning curve*, which determines the reduction in cost for each doubling of cumulative production. For solar PV technologies, this reduction (also known as the *learning rate*) has been on average 19.6% for the last 34 years (Fraunhofer ISE, 2015). Figure 30 shows the cost of installed solar power in Halmstad municipality (in SEK per peak kW) compared to the accumulated installed peak power in a log-log graph. Plotting and analysing a trend line in this graph shows that the average learning rate (or more appropriately for Halmstad, the 'cost reduction rate') here is 15.3%, i.e. for every doubling of installed capacity, the cost of installing new capacity has dropped by 15.3%.

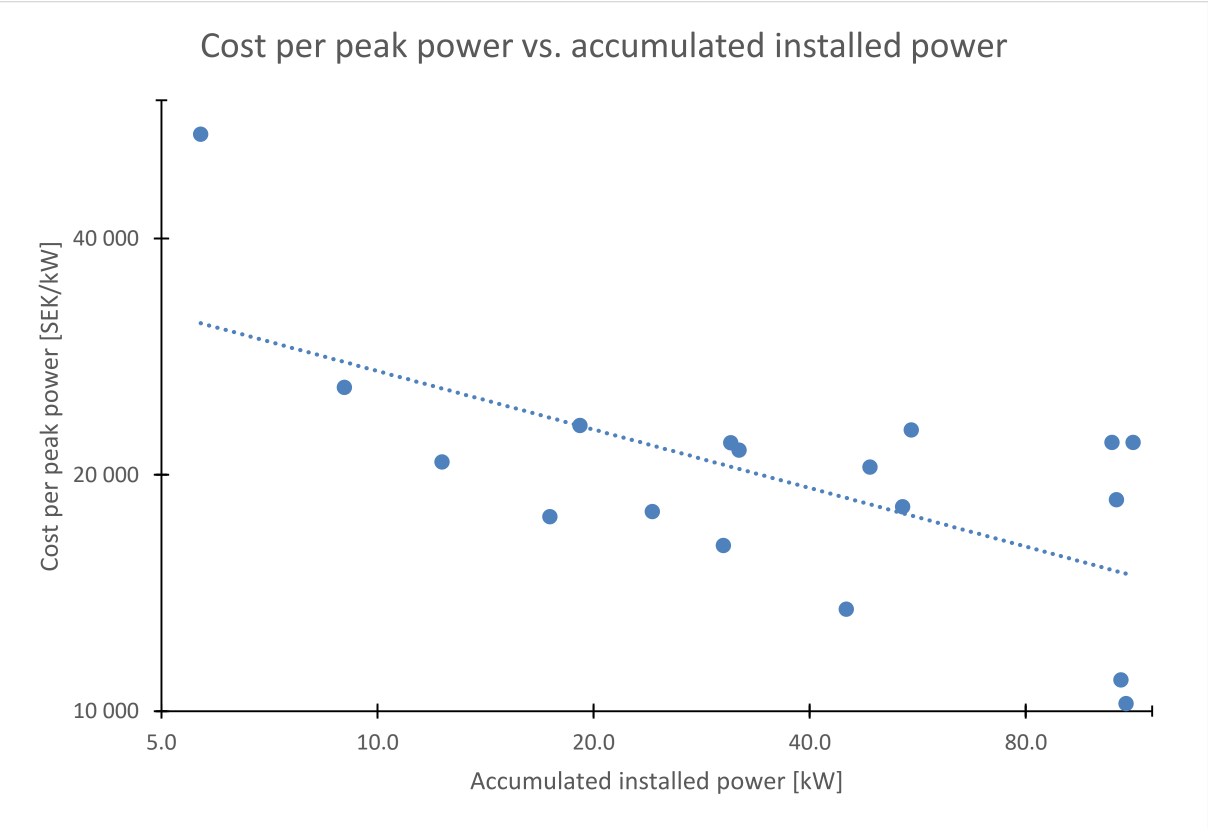

Figure 30: COST PER PEAK POWER VS. ACCUMULATED INSTALLED POWER OF SOLAR PV IN HALMSTAD MUNICIPALITY

Figure 31 shows the cost of installed PV systems in Halmstad municipality compared to the average cost of rooftop PV systems (solar panels plus inverter and additional equipment) in Germany[24]. The

[24] Data for the German market has been used both since reliable data for the Swedish market could not be found and since the German market is larger and more well-developed than the Swedish one, and therefore provides a larger sample size with clearer data.

graph shows the effects of *learning by doing* and *learning by waiting*, as described by e.g. Hogan (2014), Junginger et. al (2008) and Grübler (1998). As can be seen in Figure 31, as time progresses, the costs associated with new installations decrease. However, as we have seen in Figure 30 the factor driving the cost reduction is not the progress of time, but the amount of installed solar PV installations. This is the reason why we cannot, as is sometimes suggested, simply 'wait for new technologies to become cheaper' – if no new investments in the technology are made, the technology will simply be stuck at the same 'development level', indifferent to the passage of time. However, for a smaller actor (or an actor otherwise unsuited for driving the development of a certain technology), simply waiting for development to happen elsewhere can be a viable strategy. This is what is called *learning by waiting*, which is described as '… spillover effects from other industries, technologies or countries (…) The resulting benefits from the innovative technology will appear over time and can be exploited by waiting.' (Hogan, 2014). In other words, this amounts to benefitting from the learning by doing effects created by some other actor's use of the technology.

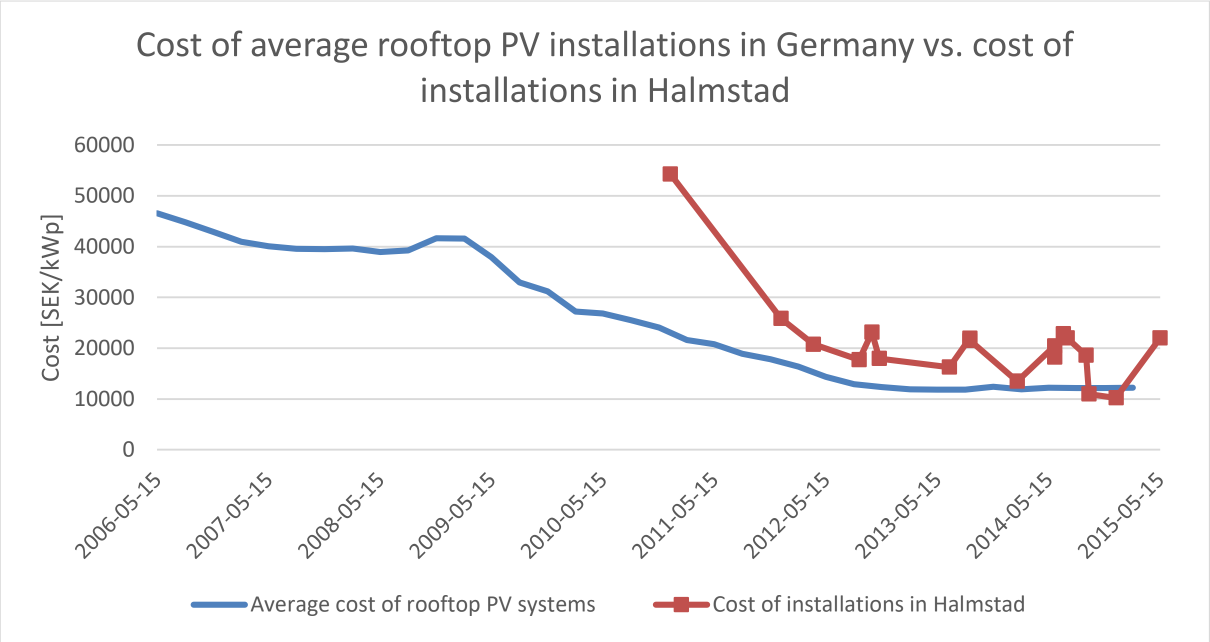

Figure 31: COST OF AVERAGE ROOFTOP PV INSTALLATIONS IN GERMANY VS. COST OF INSTALLATIONS IN HALMSTAD. The German prices have been converted from Euro to SEK via the for each data point corresponding exchange rate, taken from the Swedish National Bank (*Riksbanken*).

Learning by doing is a very important effect – perhaps even the most important – in bringing new technologies from their early R&D stages to a stage of commercialisation and un-subsidised cost-competitiveness with other technologies. However, as Grübler (1998, p. 82) points out, the effect is strongest in the early stages of development and deployment, since each 'unit' of cost reduction requires a doubling in production. Thus, when entering the commercialisation (diffusion) phase, cost reductions will typically be smaller as the market starts to saturate and larger improvements of the technology become harder and harder to come by. Figure 31 hints at this, as the solar PV installation costs for both Halmstad and the German market has stayed at roughly the same level since 2012 – 2013.

Looking again at Figure 31, we can conclude that the reduction of cost of solar PV installations in Halmstad have benefited from learning by waiting; in the years before the first installation in 2011, but also in the years since where cost reductions in (among others) the German market have led to cost reductions also for installations Halmstad municipality. Since 2011, the cost has also most likely been reduced by learning by doing effects: as the accumulated installed capacity has increased, the price of installation in Halmstad has moved closer to (and in some cases even below) that of the German market.

Here we study only the total learning effect, but as Ferioli et al. (2008) points out, a specific technology does not have a single learning curve, but rather an aggregated learning curve made up of learning curves representing all of the components and processes that make up that specific technology. Thus, it is reasonable to assume that learning-by-doing effects seen for solar PV in Halmstad can be divided into two categories, where the first category contains global decreases in e.g. PV module costs (which are not meaningfully effected by local installations in Halmstad), while the second category contains local decreases in e.g. installation costs and building permit handling times (which could be effected also by an increase in global PV capacity, but are likely mostly effected by the amount installed locally).

Lastly, the concept of learning-by-doing provides an important counter-argument to the notion that it would be more cost effective to postpone our attempts to combat greenhouse gas emissions and other environmental concerns until technological improvements have brought down the costs to do so – as Grübler (1998, p. p. 111) points out, ‘There is no such thing as “autonomous” technological learning’, meaning that the costs of new technologies such as solar PV will not lower merely with the passage of time, but only through sufficient investments into the technology.

7.3 LOCK-IN AND TECHNOLOGY CLUSTERS: THE CASE OF WASTE INCINERATION

Turning to the second mechanism, technological *lock-in*, we will use the technology of waste incinerating power plants as an example. This technology represents the established, the tried-and-true; once a big step forward (in Halmstad’s case replacing both landfills and oil-powered heating), but now held in place perhaps more by tradition, institutional culture and societal expectations than actual technological, environmental or economical merit. This phenomenon, where an entire sociotechnical environment premiers one technology over competing ones (even ‘better’ ones), is described by Unruh (2000; 2002) as *lock-in*.

A study analysing the waste incineration system in Göteborg from a lock-in perspective (Corvellec, Campos, & Zapata, 2013) has been used as a base for this chapter, as many similarities between the systems in Göteborg and Halmstad can be identified, e.g. waste incineration in both Halmstad and Göteborg is handled at one large plant, owned by a municipality-owned company which also handles waste collection.

The arguments presented in this chapter assumes that the share of fossil vs. renewable carbon in the incinerated waste remains roughly constant. Should e.g. advancements in bio-plastics shift the balance significantly towards more renewable carbon in the waste, many of the concerns raised would be diminished.

Waste incineration supplies a significant portion of the electricity produced within Halmstad municipality, as well as the majority of the heat supplied to the district heating network. It provides much of the backbone of the energy sector in Halmstad municipality, both energy-wise and investment-wise. The status of waste incineration as the main energy generating technology for the municipality is also evident in the organisational structure, as HEM is a combined energy and waste handling company.

On HEM’s website, waste incineration is presented as an environmentally friendly way of producing energy and handling waste, citing a report comparing the company’s emissions to a baseline scenario (Profu, 2014). However, energy recovery through waste incineration only places as the fourth most desirable way to deal with waste, according to the European Union's 5-step waste hierarchy (European Commission, 2008). According to this hierarchy, energy recovery is more desirable than disposal (i.e. putting the waste in a landfill), but less desirable than recycling, preparing for re-use or preventing the waste altogether. Also the Swedish waste plan (Naturvårdsverket, 2012) describes waste incineration as a less desirable way of handling waste. Therefore, the continued use of and reliance on this system risks hindering the development and implementation of better alternatives.

While the largest issue of a lock-in of waste incineration (or at least the one focused on by Corvellec et al.) lies in the technology blocking development of new waste and resource handling technologies and policies, one can argue that it also blocks development and expansion of alternate energy-producing technologies, especially on a municipal level, where building a waste incineration plant is a very large investment in the energy system. As an example, the construction of a third boiler to double the capacity of Kristinehedsverket in the year 2000 cost 560 million SEK (Halmstad energi och miljö, A). This can be compared to, as an example, the total investment in solar power made by the municipality of 24 million SEK (see Table 8). As the non-renewable part of the waste incinerated makes up the majority of the non-renewable energy inserted for transformation within the municipal energy system (see Section 4.2.3), there exists good reason to replace this technology also from a sustainable energy-point of view.

Related to lock-in are *technology clusters* (Grübler, 1998, pp. 121, 204 - 223). These are groups of technology that together with the institutions that govern them, or depend on them, make up the backbone of the sociotechnical system at a certain point in time, through synergy and mutual interdependency. According to Grübler, we are currently in the fourth overarching cluster of technological development: 'mass production & consumption'[25]. It could be argued that a waste incineration plant is an integral part of this cluster, as it not only enables and helps legitimise mass consumption (and thus a large generation of waste); it is wholly dependent on it. In the example of Göteborg as studied by Corvellec et al., a decision was made in the mid-2000s to add additional capacity to Göteborg's waste incineration plant, in anticipation of an increasing amount of waste produced within the region. When this anticipation failed to realise, the local waste-handling company had to instead import waste from other municipalities, as well as from Norway, to compensate for the local 'shortage' of waste. Thus, in a way, the reduction in waste became a problem, rather than the solution to a problem.

A similar situation appears to exist in Halmstad municipality today, as HEM imports part of the waste incinerated within the municipality from other European countries since the local production of waste is too small. The choice of using waste from outside of Sweden (and thereby increasing the need for transport) is motivated in part by economic reasons; 'With better [waste]sorting and more incineration plants in Sweden it is hard to get paid enough for [incinerating the waste]. Therefore, import is not only good for the environment but also for the wallets of the people of Halmstad' (Halmstad energi och miljö, 2014)[26]. This suggests that a similar overcapacity of waste incineration exists in many other parts of Sweden, as well.

The environmental benefit of the waste import cited by HEM is that, since landfills are the main way of handling waste in many parts of Europe, by importing waste a higher fraction of the total European waste is incinerated instead of being sent to a landfill (thus placing higher on the waste hierarchy). This is true and carries benefits for the current situation, but looking at a longer perspective, viewing waste as a resource rather than as an emission will surely reduce the incentives for moving upwards on the waste hierarchy, both for the exporting and the importing country.

[25] The three previous being 'textiles', 'steam' and 'heavy engineering'.
[26] Quote translated from Swedish by the author.

8 IDENTIFIED CURRENT AND FUTURE SUSTAINABILITY ISSUES OF THE ENERGY SYSTEM

The major issue right now is that in spite of a significant amount of work towards the opposite, almost half of the energy supplied to Halmstad municipality is non-renewable (Figure 7). Even worse, one of the forecasts made in this thesis suggest that the use of non-renewable energy, which currently is decreasing, will start increasing again around the year 2020 (Figure 20). The main culprit is the transport sector, which is both responsible for a large majority of the non-renewable energy use, and is the only sector where no other energy carrier types have any significant presence. Halmstad municipality has made some efforts to increase the share of renewable energy sources in the transport sector, for example the solar electricity-initiative mentioned in Section 6.2.1, but so far the results have been marginal at best.

Current global trends suggest electricity as an increasingly important energy carrier for the future transport sector (with many recent developments in renewable transportation focusing on either battery-electric or hydrogen vehicles, both using electricity for charging). This in turn suggests a substantial increase in the electricity demand, as the transport sector is the largest energy user. A shift towards a large-scale usage of battery electric vehicles and/or a hydrogen economy brings new possibilities of grid energy storage, which will enable the use of intermittent energy sources (such as solar and wind) on a larger scale than before. This storage could take the form of permanent on-grid storage taking advantage of lowered production costs thanks to learning by doing with regards to high-capacity electricity storage within the automotive industry. Another option is the use of vehicle-to-grid schemes (Guille, 2009; Kempton & Tomic, 2004), where the storage capacities of electric vehicles are used for grid balancing whenever the vehicle is parked.

An issue which is not as pressing at the moment, but will likely be pivotal for the long-term transition to a fully renewable society is replacing what Grübler (1998, pp. 121-126) calls the ‘mass production/consumption’-technology cluster with something else. As Grübler (1998, p. 355) writes:

> *‘Environmental objectives will be required to influence the rate and direction of technological change much more in the future than they have done in the past. Incremental improvements will not be enough to significantly reduce potential environmental impacts. What is needed is a technology-led push towards an entirely new “green” technology cluster, characterized especially by dematerialization and decarbonisation.’*

As waste incineration is unlikely to be as prominent in such a cluster as it is today (as discussed e.g. in Section 7.3), this technology will likely have to be at least partly replaced within the not-too-distant future.

A secondary issue is that of biofuels, or rather the allocation of biofuels. With biofuels being a limited resource, priorities must be made to ensure that these fuels are utilised in an optimal way. As biofuels in many technical aspects is the renewable energy carrier that is most similar to fossil fuels, one can argue that these should primarily be used to replace fossil fuels in applications where using other energy carriers (e.g. electricity, hydrogen) proves most difficult, e.g. the long-distance transport sector. However, according to the projections made in the thesis, the use of biofuels is projected to grow mainly for use in producing district heat and electricity, and for use in the residential sector.

9 CONCLUSIONS

Despite some reductions in the use of non-renewable energy in Halmstad municipality during the period studied (1990 – 2013), still in 2013 almost half of the energy supplied to the municipality is non-renewable. The ever-growing transport sector is the major reason for this, using about 75% of the non-renewable energy supplied to the system. This is a well-known issue which is widely regarded as needing an urgent solution (e.g. Miljö- och energidepartementet (2015)), albeit one proving hard to solve. In a way more troubling is the next-largest user, at about 13%: the municipality's waste-incinerating plant, which is in many ways the backbone of the municipality's heating system as well at the waste handling system and therefore very hard to replace. The industry & construction sector, which used to be the second-largest user of non-renewables, has decreased the use drastically in 2013. However, this is mainly the result of companies (most notably sheet-glass manufacturer Pilkington) moving the production elsewhere, rather than reductions of non-renewable energy use in the production itself.

1. How has the energy system developed from 1990 to 2013?

During the 90's and 00's the use of non-renewables in the residential and public sectors has decreased from substantial levels to almost nothing. The non-renewables have been replaced mainly by district heating which itself is not entirely renewable yet (as mentioned above), but has a potential of becoming so. On the electricity side, in spite of a major conflict of interest with military interests in the municipality, the amount of wind power has grown substantially over the last few years. Even more promising for Halmstad's transition to a fully sustainable energy system are the many solar panel installations made on public buildings, as well as the *Skedalahed* solar park. As the electricity produced by these panels is starting to reach lower cost levels than the electricity bought from the grid, it shall be interesting to see what Halmstad can accomplish in this field over the coming years, especially in conjunction with the planned investments in electricity storage and the 'solar power for electric cars'-scheme.

2. What are some main reasons for the energy system to have developed in the direction that it has? Are these driving forces still in effect?

For Sweden in general, a large availability of a relatively easily exploited energy resource: hydropower, started the electrification of the country, and also gave rise to an electro-technical industry which would feature prominently throughout Sweden's industrial history. Also in Halmstad, hydropower played an important role in the development of the early energy system.

Other driving forces identified are energy independence, both for Sweden as a whole and cited by Halmstad today; the support of (powerful) institutions to provide both economical support and legitimacy to new technologies; and other economic factors (which have not been studied in detail in this thesis).

For Halmstad for the past four decades, part of the energy system has been linked to the waste handling system, through waste incineration. Also for at least the past two and a half decades, environmental concerns such as the issue of climate change has had an effect on the development of the energy system.

3. What current and future sustainability issues of the energy system can be identified by analysing the collected data and the forecasting method chosen? How can these issues be tackled?

The main sustainability issue is the continued use of non-renewable energy, representing almost half of the energy supplied to Halmstad municipality. This share is currently decreasing, but the forecasts made in this thesis suggests that it could start increasing again around the year 2020, due to increased demands from the transport sector. The solutions to this issue should therefore be mainly focused on the transport sector, either reducing the amount of road traffic or promoting increased shares of renewable energy carriers for the sector.

A potential future issue is the continued use of waste incineration, which in the thesis is argued to contribute to a lock-in of a less than optimal system for both energy production and waste handling. To break this lock-in would require a reshaping of the waste handling system, as well as a substitution of waste as an energy source.

A second potential future issue is the limited availability of biofuels, and the allocation problems that follow. In Halmstad municipality today, biofuels are chiefly used for stationary energy production (mainly heat), but it can be argued that biofuels are better utilised as replacements for fossil fuels in the transport sector.

To summarise; a lot of good work has been done in the last quarter-century, but there is also much work remaining. The municipality and HEM have the opportunity to push for and legitimise new technology, as they have done with the district heating network, and more recently with solar energy. The municipality also has an important role in the work of changing other parts of the sociotechnical system. A good example is the (suggested, but unfortunately never carried out) co-operation of HEM and one of the municipality's schools, mentioned in Section 6.2.1. In transforming the transport sector, the municipality probably has less overall influence, but initiatives such as installing charging points for electric vehicles and guaranteeing EV owners solar electricity for their vehicles surely helps. A concentrated effort is needed to break the status-quo of waste incineration, and such an effort can realistically only be initiated by the municipality itself, or be forced by decisions made higher up, e.g. in the Swedish or European parliament.

10 REFERENCES

Arnold, D. (2002, February 24). *Fitting a logistic curve to data.* Retrieved September 29, 2015, from https://www.math.hmc.edu/~depillis/PCMI2005WEBSITE/logistic_REDWOODS.pdf

Avfall Sverige. (2012). *Bestämning av andel fossilt kol i avfall som förbränns i Sverige [Determination of the share of fossil carbon in waste incinerated in Sweden].*

Bergek, A. (2002). Shaping and Exploiting Technological Opportunities: The Case of Renewable Energy Technology in Sweden. *Thesis for the degree of doctor of philosophy*. Gothenburg: Department of Industrial Dynamics, Chalmers University of Technology.

Bernhardsen, L. (2011, November 24). *Obefogad och felaktig kritik mot fjärrvärmen*. Retrieved Mars 09, 2016, from https://www.hem.se/om-hem/nyhetsarkiv/obefogad-och-felaktig-kritik-mot-fjarrvarmen

Bernhardsen, L. (2015, May 5). (J. Johannesson, Interviewer)

Boccard, N. (2008). *Capacity factor of wind power realized values vs. estimates.* Elsevier.

Borgquist, W. (1922, March 11). Landsbygdselektrifieringen. *Teknisk tidskrift - elektroteknik*, pp. 19-21.

Borgquist, W. (1923). Sveriges kraftindustri [The Swedish power-industry]. *Elektroteknik*, 101-106.

Börjesson, P., Gustavsson, L., Christersson, L., & Linder, S. (1997). Future production and utilisation of biomass in Sweden: Potentials and CO2 mitigation. *Biomass and Bioenergy, 13*(6), 399-412.

Corvellec, H., Campos, M. J., & Zapata, P. (2013). *Infrastructures, Lock-in, and Sustainable Urban Development – The Case of Waste Incineration in the Göteborg Metropolitan Areas.* Göteborg: School of Public Administration, University of Gothenburg.

Eriksson, B., & Eriksson, K. E. (1980). *Sverige 2020: En framtid för människor [Sweden 2020: A future for humans].* Göteborg: University of Gothenburg - Centrum för tvärvetenskapliga studier av människors vilkor.

European Commission. (2008). Directive 2008/98/EC of the European Parliament and of the Council of 19 November 2008 on waste and repealing certain Directives. *Official Journal of the European Union*.

Ferioli, F., Schoots, K., & van der Zwaan, B. (2008). *Use and limitations of learning curves for energy technology policy: A component-learning hypothesis.* Energy Research Centre of The Netherlands (ECN), Policy Studies Department, Petten/Amsterdam.

Fraunhofer ISE. (2015). *Photovoltaics report.*

Försvarsmakten. (2015). *Redovisning av riksintressen och områden av betydelse för totalförsvarets militära del enligt 3 kap §9 Miljöbalken i Hallands län.*

Grübler, A. (1998). *Technology and global change.* Cambridge: The press syndicate of the University of Cambrige.

Guille, C. (2009). *A conceptual framework for the vehicle-to-grid (V2G) implementation.* Urbana: University of Illinois.

Halmstad energi och miljö. (2014, January 13). *HEM:s historia [The history of HEM]*. Retrieved April 6, 2016, from http://www.hem.se/om-hem/om-hem

Halmstad energi och miljö. (2014, January 23). *Import av avfallsbränsle*. Retrieved 03 15, 2016, from https://www.hem.se/sv/omradesstartsida/import-av-avfallsbransle

Halmstad energi och miljö. (2015, January 27). *Skedalahed solcellsanläggning*. Retrieved February 16, 2016, from https://www.hem.se/om-hem/solitanken/skedalahed-solcellsanlaggning

Halmstad energi och miljö. (A). *Kristinehedsverket - Kraftvärmeverk.* Retrieved November 30, 2015, from www.hem.se/Media/Get/747/Kristinehedsverket,20information

Halmstad energi och miljö. (B). *Oceanen - Kraftvärmeverk.* Retrieved November 30, 2015, from www.hem.se/Media/Get/748/Oceanen,20information

Halmstad municipal department of real estate. (2016, January 22). *Solenergi*. Retrieved February 17, 2016, from Halmstad municipality official web site: http://www.halmstad.se/byggabo/aktuellaprojekt/solenergi.8278.html

Halmstad municipality. (2015, May 26). *Färdigställda lägenheter 1990-2014 [Appartments built 1990-2014]*. Retrieved from http://www.halmstad.se/omkommunen/omhalmstad/statistik/boende/fardigstalldalagenheter.2187.html

Halmstad municipality. (2015). *Handlingsprogram för hållbar energi 2015-2020 [Plan of action for renewable energy 2015-2020]*. Strategy document.

Halmstad municipality. (2015, February 27). *Om Halmstad*. Retrieved November 30, 2015, from Halmstad municipality official web site: http://www.halmstad.se/omkommunen/omhalmstad.143.html

Hogan, W. W. (2014). Clean energy technologies: Learning by doing and learning by waiting.

Hughes, T. P. (1987). The Evolution of Large Technological Systems. In W. E. Bijker, T. P. Hughes, & T. J. Pinch, *The Social Construction of Technological Systems* (pp. 51-82). Cambridge: MIT Press.

IPCC. (2014). *Climate change 2014: Mitigation of climate change.*

IPCC. (2014). *Climate Change 2014; Synthesis report: Summary for policymakers.* IPCC.

Junginger, M., Lako, P., Lensink, S., Sark, W. v., & Weiss, M. (2008). *Technological learning in the energy sector.*

Kaijser, A., Mogren, A., & Steen, P. (1988). *Att ändra riktning: villkor för ny energiteknik.* Stockholm: Allmänna Förlaget.

Kalkuhl, M., Edenhofer, O., & Lessmann, K. (2011). *Learning or Lock-in: Optimal Technology Policies to Support Mitigation.* Potsdam: Potsdam Institute for Climate Impact Research.

Kempton, W., & Tomic, J. (2004). Vehicle-to-grid power implementation: From stabilizing the grid to supporting large-scale renewable energy. *Journal of Power Sources*.

Kindstedt, G. (2009, July 20). *Försvaret stoppar vindkraftprojekt.* Retrieved Mars 1, 2016, from Hallandsposten: http://hallandsposten.se/nyheter/halmstad/1.527395-forsvaret-stoppar-vindkraftprojekt

Kucharavy, D., & De Guio, R. (2011). Logistic substitution model and technological forecasting. *Procedia Engineering, 9*, pp. 402-416.

Kuhlin, L. (2015 A, November 23). *Vattenkraft.info*. Retrieved November 24, 2015, from Vattenkraft.info: http://vattenkraft.info/?page=5

Kuhlin, L. (2015 B, November 23). *Vattenkraft.info*. Retrieved November 24, 2015, from http://vattenkraft.info/?page=4; search for 'Halmstad'

Lund, H., & Mathiesen, B. V. (2007). *Energy System Analysis of 100 Per cent Renewable Energy Systems: The Case of Denmark year 2030 and 2050.* Aalborg: Aalborg University.

Maldonado, G. (1989). *A computer program for fitting a "logistic" growth curve to empirical data.* Göteborg: Chalmers University of Technology.

Maldonado, G. (1991). *Energy systems in the development process: Background.* Göteborg: Chalmers University of Technology.

Miljö- och energidepartementet. (2015). *Fossiloberoende fordonsflotta - ett steg på vägen mot nettonollutsläpp av växthusgaser (Dir. 2012:78).* Retrieved from Regeringskansliet: http://www.regeringen.se/rattsdokument/kommittedirektiv/2012/07/dir.-201278/

Naturvårdsverket. (2012). *Från avfallshantering till resurshushållning: Sveriges avfallsplan 2012-2017 [From waste management to resource management: Sweden's waste plan 2012-2017]*. Naturvårdsverket.

Nyedal solenergi. (n.d.). *Solceller för privatpersoner*. Retrieved Februari 26, 2016, from http://www.nyedalsolenergi.se/egen-el-med-solceller/privatpersoner/

Peterson, A. (1990). Det svenska energisystemets utveckling 1850-1920 - en idé- och teknikhistorisk betraktelse [The development of the Swedish energy system 1850-1920]. *Polhem, 8*, 304-341.

Pilkington. (2014, October 27). *Pilkington Floatglas AB - en del av nordisk glashistoria*. Retrieved from https://www.pilkington.com/sv-se/se/news-insights/latest/013-pilkington-floatglas-ab-en-del-av-nordisk-glashistoria

Profu. (2014). *Klimatbokslut 2013 - Halmstad energi och miljö.*

Rehn, H. (2012). *Kommunal & regional energistatistik 2012 - användarhandledning [Municipal and regional energy statistics 2012 - user guide]*. Statistics Sweden.

Schön, L. (1993, 11). Elektriciteten i svensk industri under hundra år. *Polhem*, pp. 333-354.

Statistics Sweden. (2015). *Kommunal och regional energistatistik [Municipal and regional energy statistics]*. Retrieved 2015, from http://www.scb.se/en0203

Statistics Sweden. (2016, Mars 03). *Tillförsel och användning av el 2001-2014 [Supply and use of energy 2001-2014]*. Retrieved June 08, 2016, from Statistics Sweden: http://www.scb.se/sv_/Hitta-statistik/Statistik-efter-amne/Energi/Tillforsel-och-anvandning-av-energi/Arlig-energistatistik-el-gas-och-fjarrvarme/6314/6321/24270/

Stena. (2014, Mars 6). Stena planerar betydande investeringar i Halmstad [Stena plans substantial investments in Halmstad] (Press Release).

Swedish Energy Agency. (2015, October 20). *Halvårsstatistik 2015, siffror på kommunnivå [Biannual statistics 2015, municipal level]*. Retrieved Mars 21, 2016, from Vindkraft - officiell statistik [Wind power - official statistics]: http://www.energimyndigheten.se/fornybart/vindkraft/marknadsstatistik/officiell-statistik-om-vindkraft/?currentTab=1#mainheading

Unruh, G. C. (2000). *Understanding carbon lock-in.* Madrid.

Unruh, G. C. (2002). *Escaping carbon lock-in.* Madrid: Instituto de Empresa.

Wene, C.-O. (n.d.). *The reference energy system (RES): A snapshot of the energy system.* Göteborg: Chalmers University of Technology.

Wene, C.-O., & Rydén, B. (1988). A comprehensive energy model in the municipal energy planning process. *European Journal of Operational Research 33*, 212-222.

Wikipedia. (2013, January 19). *Halmstads Järnverk.* Retrieved December 9, 2015, from Wikipedia: //sv.wikipedia.org/w/index.php?title=Halmstads_J%C3%A4rnverk&oldid=18916303

Wikipedia. (2015, January 31). *Slottsmöllans tegelbruk,* 29421450. Retrieved December 7, 2015, from Wikipedia: //sv.wikipedia.org/w/index.php?title=Slottsm%C3%B6llans_tegelbruk&oldid=29421450

Vindkraftsnyheter.se. (2014, January 31). *Arise har driftsatt vindkraftpark Bohult*. Retrieved May 24, 2016, from http://www.vindkraftsnyheter.se/2014/01/arise-har-driftsatt-vindkraftpark-bohult

11 APPENDIX: DATA SOURCES

Data	Source
Imported and distributed electricity 1930 – 1965.	Halmstad Municipal Archive [*Kommunarkivet i Halmstad*]
Imported and converted 1990 – 2008; Electricity produced by hydropower 2009 – 2012 and wind power 2012.	Statistics Sweden [*Statistiska centralbyrån*]
End use of energy 1990 – 2013	Statistics Sweden [*Statistiska centralbyrån*]
Electricity and heat produced by combined heat and power and heating plants 2009 – 2013.	Swedish Energy Markets Inspectorate [*Energimarknadsinspektionen*]
Data on solar installations made by Halmstad municipality	Halmstad department of real estate [*Fastighetskontoret i Halmstad*], (Halmstad municipal department of real estate, 2016)
Number of people living in Halmstad municipality 1930 - 2015	Official web site of Halmstad, (Halmstad municipality, 2015)
Apartments built 1990 – 2014	Official web site of Halmstad, (Halmstad municipality, 2015)
Data on district heating connections	Ann-Catrin Hansson, HEM
General information on Halmstad's energy system	Lars Bernhardsen, HEM
Data on waste incineration plant *Kristinehedsverket*	(Halmstad energi och miljö, A)
Data on biofuel/natural gas CHP plant *Oceanen*	(Halmstad energi och miljö, B)
Additional data on hydropower	(Kuhlin, Vattenkraft.info, 2015a), (Kuhlin, Vattenkraft.info, 2015 B)
Data on electricity price 2007-2015	Statistics Sweden [*Statistiska centralbyrån*]