Evaluation of energy conserving measures in buildings connected to a district heating system – case studies in Gävle, Sweden

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This thesis is based on work conducted within the industrial post-graduate school Reesbe – Resource-Efficient Energy Systems in the Built Environment. The projects in Reesbe are aimed at key issues in the interface between the business responsibilities of different actors in order to find common solutions for improving energy efficiency that are resource-efficient in terms of primary energy and low environmental impact.

The research groups that participate are Energy Systems at the University of Gävle, Energy and Environmental Technology at the Mälardalen University, and Energy and Environmental Technology at the Dalarna University. Reesbe is an effort in close co-operation with the industry in the three regions of Gävleborg, Dalarna, and Mälardalen, and is funded by the Knowledge Foundation (KK-stiftelsen).
Abstract

When different energy conserving measures are implemented for reducing energy use in buildings and the buildings are connected to district heating systems, it is important that an overall system analysis is made which takes into account the effects of total change of energy use due to the energy conserving measures.

The method applied in this thesis uses hourly production data for the different production units in the district heating system in Gävle, Sweden. The merit order of the different production units is dependent on the electricity spot market price. To calculate the merit order, hourly data for the electricity price is used. The marginal production unit can then be determined for each hour of the investigated year.

This thesis analyzes five different energy conserving measures in a multi-dwelling building regarding how they affect the marginal production units in the district heating system. For CO₂ emission evaluations, two different combinations of heat and electricity conserving measures are compared to installation of an exhaust air heat pump. This thesis also analyzes how the configuration of the electric meter affects the measured amount of self-consumed and produced excess electricity when a PV system is installed on a single-family house and on two multi-dwelling buildings of different sizes.

The results show that the use of electricity is the most important objective to consider. The increased use of electricity for operation of the heat pump contributes to an increase of global CO₂ emissions and the electricity produced by the solar photovoltaic installation contributes to a decrease of global CO₂ emissions.

The results also show that the configuration of the electric meter is important for the single-family house but negligible for the multi-dwelling buildings. The amount of produced excess electricity is high for all buildings, which means that the economic value of produced excess electricity is important for a profitable installation.

Keywords: Greenhouse gases, simulation, energy conserving measures, solar PV, electric meter, renovation, multi-dwelling building
Sammanfattning

När energieffektiviseringsåtgärder införs i byggnader förändras fastighetens värmelast. Om byggnaden använder fjärrvärme för uppvärmning påverkas inte bara värme-produktionen i fjärrvärmesystemet utan också elproduktionen i eventuella kraftvärmeverk.

Den metod som används i denna avhandling för beräkning av hur fjärrvärmesystemet påverkas vid energieffektivisering i en fastighet, använder produktionsdata från de olika produktionsenheterna i Gävles fjärrvärmesystem med timupplösning. Prioriteringsordningen för de olika produktionsenheterna är beroende av elpriset varför Nordpools el-spotpris används för att beräkna prioriteringsordningen.

Fem olika energieffektiviseringsåtgärder i en flerfamiljsfastighet analyseras med avseende på hur de påverkar de olika produktionsenheterna i fjärrvärmesystemet. För analys av globala koldioxidutsläpp jämförs två olika kombinationer av värme- och eleffektiviseringsåtgärder med en installation av en frånluftsvärmepump. En delstudie analyserar också hur konfigureringen av fastighetens elmätare påverkar den uppmätta andelen egenanvänd och överproducerad el från installerade solceller till elnätet. En enfamiljsfastighet och två flerfamiljsfastigheter i olika storlekar används som referensobjekt.

Resultaten för Gävle visar att minskad elanvändning är den enskilt viktigaste faktorn för att minska koldioxidutsläppen vid energieffektivisering i flerfamiljsfastigheter som använder fjärrvärme för uppvärmning. Den ökade elanvändningen för drift av frånluftsvärmepumpen ger ökade globala koldioxidutsläpp och den producerade elen från solcellsanläggningen ger minskade globala koldioxidutsläpp.

Resultatet visar även att konfigureringen av elmätaren är viktigt för enfamiljsfastigheten men ger försumbara skillnader för flerfamiljsfastigheten. Andelen egenanvänd el från solcellsanläggningar är låg för alla undersökta fastigheter vilket medför att det ekonomiska värdet för överproducerad el är viktigt för att få lönsamma solcellsinstallationer.

Nyckelord: Koldioxidutsläpp, simulering av fastigheter, energieffektivisering, solcellsanläggningar, elmätare, renovering, miljonprogrammet, flerfamiljsfastigheter
Acknowledgements

This research has been carried out under the auspices of the industrial post-graduate school Reesbe where the three participating universities (University of Gävle, University of Dalarna and University of Mälardalen), together with the Knowledge Foundation (KK-stiftelsen) and the 17 participating companies all contributed to making it possible for me to return to the university to fulfill a dream I thought I missed earlier in life.

Various people have helped me along the way and none are forgotten. My research has many influences from my supervisor, Professor Björn Karlsson, and my co-supervisors, Professor Louise Trygg and Docent Mats Rönnelid. Your guidance and knowledge are highly appreciated and necessary for my research results.

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My colleagues at Gävle Energi AB, within Reesbe and at the different universities also deserve a heartfelt thank you.

Many thanks to my wife, who is sharing this journey with me and never complains about early mornings or late evenings of work. My parents and my brother for all the support, now and earlier in life. Last but not least, I want to thank all my friends for making my life more pleasant.
List of papers and Author’s contribution

List of papers
This thesis is based on the following papers, which are referred to in the text by Roman numerals:

Paper I

Paper II
Gustafsson M., Karlsson B., Rönnelid M. 2016. How the electric meter configuration affects the measured amount of self-consumed and produced excess electricity – case study in Sweden. In manuscript.

Author’s contribution

Paper I
Mattias Gustafsson formulated the research question, completed the simulations and calculations required and formulated the results, discussions and conclusions. Mattias Gustafsson did most of the writing for the article with support from all authors.

Paper II
Mattias Gustafsson formulated the research question, completed the measurements and calculations required and formulated the results, discussions and conclusions. Mattias Gustafsson did most of the writing for the article with support from all authors.
# Nomenclature

## Abbreviations

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>CHP</td>
<td>Combined heat and power</td>
</tr>
<tr>
<td>COP</td>
<td>Coefficient of Performance</td>
</tr>
<tr>
<td>DHS</td>
<td>District heating system</td>
</tr>
<tr>
<td>ECMs</td>
<td>Energy conserving measures</td>
</tr>
<tr>
<td>ElCMs</td>
<td>Electricity conserving measures</td>
</tr>
<tr>
<td>IPCC</td>
<td>Intergovernmental Panel on Climate Change</td>
</tr>
<tr>
<td>PV</td>
<td>Solar photovoltaic</td>
</tr>
<tr>
<td>UNFCCC</td>
<td>United Nations Framework Convention on Climate Change</td>
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Introduction

Since the Industrial Revolution started in the mid-18th century, access to energy and infrastructure to exploit the energy in different forms have been the foundation for development. Industrial development has created a high standard of living in parts of the world and large quantities of fossil fuels have been used, and still are. Developing countries aim to progress to the same standard of living, resulting in an estimated increased global energy demand by 37% by 2040 [1].

The increased use of energy, the majority of which is based on fossil fuels [2], leads to increased emission of greenhouse gases, with the resulting need for international activities to reduce emissions to prevent increased global temperature and associated problems. In turn, these international activities result in national as well as local demands and actions that influence the future development of the energy systems on all levels.

In 1988, the Intergovernmental Panel on Climate Change (IPCC) was established as a scientific intergovernmental body under the auspices of the United Nations. The first assessment report from IPCC was the information base in 1992 when the United Nations Framework Convention on Climate Change (UNFCCC) was initiated in Rio. The UNFCCC is an agreement of sustainable development consisting of 27 principles and signed by over 170 countries. The latest climate change conference was held in Paris in 2015. In the resulting Paris agreement, the parties will pursue efforts to limit the temperature increase to 1.5 °C.

The global agreements are followed by other agreements in different countries and continents and the European Union adopted the 20/20/20 strategy to set targets to reduce greenhouse gas emissions by 20% from 1990 levels by 2020, increase the share of renewable energy to 20% in the energy mix, and reduce primary energy use by 20% [3]. The resolution “2030 framework for climate and energy policies” [4], aims to make the European Union’s economy and energy system more competitive, secure and sustainable. The framework sets a target of at least 40% greenhouse gas reduction compared to 1990, but also sets targets of at least 27% renewable energy in the energy mix and 27% energy savings by 2030.

In 1999, the Swedish government decided to adopt a generation goal with 16 environmental quality objectives, which define the direction of the changes in society that need to occur within one generation if the environmental quality objectives are to be achieved in Sweden [5]. The first of the environmental quality objectives is to reduce the climate impact in accordance with the UNFCCC. The national target is then divided into regional
targets and most cities and municipalities have their own agenda on how to contribute to the quality objectives.

To fulfill energy goals and agreements locally as well as globally, a more sustainable use of energy and a transition from use of fossil fuels to use of renewable energy must occur. It is often easy to see the correlation between decreased uses of fossil fuels and decrease in CO₂ emissions. However, if an energy source with low CO₂ emissions is reduced and fossil fuels need to replace parts of the energy demand, a more complicated analysis is necessary.

When different energy conserving measures (ECMs) are implemented for reducing the energy use in buildings and the buildings are connected to district heating systems (DHS), it is important that an overall system analysis is made which takes into account the effects of total change of energy use due to the ECMs. It is common that the heat production units in the DHS produce both heat and power in combined heat and power (CHP) plants. The analysis will be complicated since the local electricity grid is connected to the Nordic and European power network and a change in electricity production locally in the power system can affect power production units in other countries.

Another important aspect in an overall system analysis is the value of saved fuel in the DHS. Can the fuel, in Sweden often biofuels and/or domestic waste, be considered a valuable asset and used in other DHS or industrial processes? If the fuel is a valuable asset, the saved fuel locally in the DHS can be used elsewhere and possibly replace fossil fuels.

Changes in delivered heat in the local DHS can therefore affect the energy systems beyond the DHS itself and an overall system analysis is therefore necessary to perform to avoid sub-optimizations when global CO₂ emissions are studied.
Aim of thesis

The aim of this thesis is to investigate the impact on the DHS in Gävle, Sweden, when different ECMs are implemented in a building connected to the DHS. It is becoming more common to install a solar photovoltaic (PV) installation on the roof when extensive renovations are made in buildings. The owner of the building often sees this as an ECM (reduced need for bought electricity), although the energy use in the building is not affected. This thesis complements common ECMs with a PV installation in a case study of what the impact is for the different heat production units in the DHS. How the global CO₂ emissions are affected when the ECMs and the PV system are implemented is also analyzed.

This thesis also analyzes how the configuration of the buildings’ electric meters affects the measured amount of self-consumed and produced excess electricity. A different electric meter configuration does not affect the produced volume of electricity from the PV installation, but it does affect the economic value of the produced power. Three buildings are analyzed, two multi-dwelling buildings of different sizes and one single-family house.

The main research questions in this thesis are:

- How do different ECMs in buildings connected to the district heating system affect the different heat production units in the DHS in Gävle?
- How does the changed delivered heat from the different production units affect global CO₂ emissions?
- How does the electric meter configuration, for a building with a PV system installed, affect the measured amount of self-consumed and produced excess electricity?
Scope and limitations

All DHS are different depending on local conditions. The DHS in Gävle is characterized by a large share of industrial waste heat, multiple production units affecting the production or use of electricity to produce heat to the DHS and a low share of fossil fuels. Earlier studies on how ECMs affect different production units in DHS were often made on systems with less complexity and/or with a different composition of production units, and the conclusions are not appropriate to use for the DHS in Gävle. This thesis therefore perform a case study of how the DHS in Gävle is affected when different ECMs are implemented in a multi-dwelling building. This thesis also presents a method to make calculations for complex DHS with different production units affecting the production of and use of electricity to produce heat to the DHS.

The method applied in appended Paper I uses real production data for the different production units in the DHS on an hourly basis. The different production units are dependent on the electricity spot market price to calculate the merit order, for which reason hourly data of the electricity price is used. The marginal production unit can then be determined for each hour of the investigated year. When the marginal production unit is known, the change in use of fuel and change in electricity production can be analyzed. The method can be used in other DHS with CHP plants or production units that use electricity to produce heat, e.g. heat pumps or boilers using electricity for heating.

The study of how the electric meter configuration affects the economic value of the produced electricity from the PV installation is largely dependent on the measured amount of self-consumed and produced excess electricity. This is important for countries like Sweden where the number of PV installations are assumed to grow rapidly, but also interesting for countries where old mechanical electric meters are changed to new bi-directional electronic meters.

Both appended papers use limited numbers of buildings as case studies. The results show tendencies but further research needs to be performed to validate the conclusions in the papers for a larger building stock and prevailing conditions other than in Sweden.
Background

Energy use in the world

The energy use in the world increased by 40% between 1990 and 2012 [2]. Fossil fuels are the most common energy sources used and constitute 81% of the energy use in the world. Nuclear power amounts to 5% and renewable energy to 12%. Figure 1 presents a more detailed distribution of energy sources used in the world in 2013 [2].

![Energy Sources](image)

Figure 1: The world use of energy in 2013.

The energy use in the European Union is similar and fossil fuels constituted 76% of the energy used in 2010 [6].

Fossil fuels have some benefits compared to other energy sources: They are easily available all over the world, easily combustible, and contain a high energy density which also entails possibilities to transfer large quantities of energy quickly, e.g. to fill up fuel in vehicles. It is also easy to store fossil fuels and they are available at a fairly low price. Some countries in the world have managed to reduce their use of fossil fuels substantially in some areas but no country is close to being a fossil-free nation.
Energy use in Sweden

The industrial development in Sweden was, like the rest of the world, established by the use of fossil fuels. In the first half of the twentieth century, hydro power plants were built, mostly in the northern part of Sweden. Between 1975 and 1985, four nuclear power plants were commissioned, mostly in the southern part of Sweden. The large share of hydro power and nuclear power contributes to an electric power system almost free from fossil fuels. In the mid-twentieth century, DHS were also built and today, almost all cities in Sweden have an extensive DHS for heating buildings in central areas or where the heat density is high, e.g. shopping centers or industries where heat is required within the temperature range of the DHS.

When the nuclear power plants were built, electricity was a cheap alternative for heating buildings and the use of oil for heating was reduced. Electricity is still a common way to heat single-family houses in Sweden, both for domestic hot water and for space heating. The development of the DHS, different types of heat pumps and boilers which use biofuels have resulted in a heating system almost free from fossil fuels. There is some use of fossil fuels in the industrial sector but most fossil fuels are used in the transport sector in Sweden [2].

The energy use in Sweden differs from the world and European Union average. The energy use in Sweden, 2013, is presented in Figure 2 [2].

![Figure 2: The energy use in Sweden in 2013.](image)

Energy use in buildings in Sweden

Sweden is a country where the summer temperatures reach up to +20 °C or higher during summer and down to -20 °C or lower during winter in most parts of the country. This means that the use of energy is strongly connected to the outdoor temperature. Cooling systems are common in industrial and
commercial buildings, offices, etc., but uncommon in residential buildings (both single-family houses and multi-dwelling buildings).

Buildings contribute almost 40% of the energy use in Sweden [2] and the energy is used for space heating, domestic hot water supply, electricity used by homeowners or tenants and facility electricity for building operation.

Statistics for single-family houses, multi-dwelling buildings and non-residential premises show that DHS is the dominant source for heating. The second largest source is electricity and includes electricity for operation of heat pumps. Electricity is most common in single-family houses where electricity contributes 45% of required heat demand. For multi-dwelling buildings electricity contributed 6% and in non-residential premises 14% of the required heat demand [7]. Figure 3 shows the energy used for heating in single-family houses, multi-dwelling buildings and non-residential premises in Sweden, 2013.

![Figure 3: The energy used for heating in single-family houses, multi-dwelling buildings and non-residential premises in Sweden, 2013.](image)

The building situation in Sweden

There are approximately 1,900,000 single-family houses in Sweden [8] and they constitute approximately 44% of the total building area. About 28% of the total building area is multi-family buildings and the remaining 28% is other buildings such as commercial and public buildings [9].

There are approximately 2,500,000 apartments in multi-dwelling buildings in Sweden [10] and of these 43% were built before 1961, 34% between 1961 and 1975 and finally 23% between 1976 and 2007 [11]. In 1964, the Swedish government implemented a residential reform to decrease the housing shortage and increase the living standard. The reform resulted in more than 1,000,000 dwellings of different types built between 1965 and
Among the buildings built between 1961 and 1975, no major renovation had been completed for 78% of these buildings [11].

**Energy conserving measures in buildings**

When taking actions to fulfill the directives from the European Union and UNFCCC different ECMs will be implemented in buildings. There are many different technologies to use and ways to implement them but there are three common methods to reduce the use of energy in buildings. First is to reduce transmission losses with increased insulation, e.g. on walls or in the attic or to improve existing windows or install new ones. The second is to reduce ventilation losses by recovering heat from the exhaust air, either by using a heat pump or a heat exchanger. The third common way to reduce the use of energy in a building is to reduce the use of electricity, either the facility electricity or the electricity used by owners/tenants.

The distribution of energy used for space heating is high in multi-dwelling buildings in Sweden and 72% of the energy used annually is for space heating and domestic hot water supply. Facility electricity contributes 10% and 18% is electricity used by users/owners of the apartments [12]. The large share of energy used for heating entails that most ECMs implemented affect the use of heat more than the use of electricity. In a comprehensive investigation on energy retrofits in eleven multi-dwelling buildings in Sweden, the dominance of heat reduction measures compared to measures to reduce the use of electricity is confirmed when implementing ECMs [13].

**Solar PV systems as an energy conserving measure**

A PV installation produces electricity inside the building; for a building the building boundary is commonly the electric meter. If the electricity produced is momentarily lower than the use of electricity in the building, it reduces the amount of electricity transferred through the electric meter. If the PV installation momentarily produces more than the internal use of electricity in the building, the measured amount of used electricity is zero and the produced excess electricity is exported to the grid.

A PV installation does not reduce the amount of electricity used inside the building. The building owner, who often is more interested in the costs for used energy than the amount of used energy, often considers a PV installation as an ECM. A PV installation also increases the local available amount of electricity in a national power system and can therefore be considered as an ECM because other production units, within the system, can decrease their production. The accounting methods for CO₂ emissions due to changes in electricity use, used in this thesis, do not take into account whether the electricity produced by a PV system is used as self-consumed or as produced excess electricity, which also supports the reasoning to consider a PV installation as an ECM.
**District heating systems**

DHS are characterized by heat production plants distributing heat in a network of pipes to the customers where water is the most common heat carrier in Europe [14].

The hot water (or steam in some areas) is distributed in pipes to the customers, commonly underground, and when the hot water reaches the building, heat is most commonly transferred through one or more heat exchangers to the space heating and the domestic hot water system or for industrial processes. See Figure 4 for a picture of how a DHS can be built.

One of the main benefits of DHS is the possibility to utilize energy from local sources, such as industrial waste material suitable for combustion (bark, tree tops and branches, recycled waste wood, etc.), domestic waste and waste heat from industrial processes. Another benefit is the possibility to use CHP plants to produce electricity as well as heat.

![Figure 4: A diagram of how a DHS can be built with a CHP plant, industrial waste heat and the customers using heat distributed in an underground network of pipes.](image)

When producing electricity in a thermal power plant according to the principles of the Rankine cycle, there is always heat suitable for heating buildings when the steam has passed through the turbine. The heat available is normally condensed and cooled down in cooling towers or similar. Since thermal power plants are commonly used all over the world, the potential for DHS is large but the market penetration is currently fairly low. To some extent, the local heat demand, the temperature demand required by the users of the heat and possibilities to build the infrastructure limit the potential. A study analyzing 83 European cities concluded that the average heat market share for district heating to heat multi-dwelling buildings was 21% for investigated cities [15]. That can be compared to Sweden, where 92% of required heat to multi-dwelling buildings was delivered by DHS [16].
District heating systems in Sweden

The composition of the fuel mix used in the Swedish DHS in 2014 was 42% from biofuels, 24% from domestic waste, 10% from flue gas condensers, 8% waste heat from industrial processes, 8% from fossil fuels and 5% heat from heat pumps [17].

The production units to cover the base load in a DHS is characterized by a long utilization time and in Sweden, often based on CHP plants that use biofuels or domestic waste as energy source and/or waste heat from local industries [18]. Peak load plants have short utilization time and commonly use fossil fuels [18]. Figure 5 presents an example of a load-duration diagram with base load, intermediate load and peak load.

![Load-duration diagram](image)

Figure 5: An example of a load-duration diagram with base load, intermediate load and peak load.

When ECMs are implemented in buildings connected to the DHS, saved heat is mostly produced by biofuels or domestic waste covering the base load or the intermediate load. The saved biofuels and domestic waste have a value on the market, e.g. Sweden imported 800,000 tons of domestic waste in 2011 [19].

There are studies analyzing if an increased use of industrial waste heat in the DHS will increase greenhouse gas emissions due to a reduced electricity production in the CHP plant. If a broad system perspective is used and the saved biofuel is used to produce electricity in a European power network, depending on different assumptions, there can be both positive and negative global CO₂ emissions [20,21].

District heating system in Gävle

The first part of the DHS in Gävle was built in the late 1960s when heat-only boilers were locally connected together. The system originally used oil as energy source but in 1978 Korsnäs AB, a pulp and paper company, was
connected and the DHS mainly used waste heat from the industry. As the DHS grew a CHP plant named “Johannes” was built by Gävle Energi AB, which uses biofuels only. In 2012, a joint venture between Gävle Energi AB and Billerud Korsnäs AB (formerly Korsnäs AB) built a new CHP plant, Bomhus Energi AB.

There are three oil boilers to cover peak and reserve demands. Two use fossil oil and one uses bio-oil. There are plans to completely eliminate the use of fossil oil in boilers before the end of 2017. Due to the current low electricity price in Sweden, an electric boiler is also used to produce heat when there is a high heat demand and the electricity price is low. There is a local heat storage (accumulator) at Johannes CHP to cover peaks in the morning and in the afternoon. The accumulator is not included in the modulation. Local heat storage with accumulators in buildings is uncommon in the Swedish DHS and is not investigated.

The system is quite complicated due to the development over time and the cooperation with Billerud Korsnäs AB. The production units and their connections to the DHS and the electricity grid are presented in Figure 6. There are possibilities for other connections, e.g. to preheat the water before the electric boiler, but the standard connections are presented.

![Figure 6: The production units in the DHS and its relations to the electricity grid. The arrows show the direction of the energy flow.](image)

The annual heat demand varies between approximately 700 to 850 GWh, mostly depending on the outdoor temperature during the year. The heat load demand varies between approximately 20 MW during summer to 250 MW during peak loads in the winter.

As a part of the pulp process, black liquor is passed through an evaporation process. The evaporation process has two benefits: one is the reduction of the water level in the black liquor to make it usable as fuel in a recovery boiler, and the other is that heat from the process can be used in the DHS. The evaporation process is driven by introducing live steam [22]. In the calculations, 1/3 of heat delivered to the DHS from the evaporator process is assumed to be delivered from the CHP plant.
Heat delivered from the black liquor evaporator and the electric boiler is gathered in the hot water condenser before delivered to the DHS.

The direct condenser is an alternative condenser in parallel to the turbine and the turbine condenser in the Johannes CHP plant. If there is high heat demand and low electricity price, some or all heat can be produced in the direct condenser instead of running the steam through the turbine. This means that the electricity production is decreased when the direct condenser is used.

The maximum heat capacity and the efficiency of the different production units are listed in Table 1. The production units at Billerud Korsnäs AB and Bomhus Energi AB are dependent on the working conditions in the pulp and paper industry and therefore they vary. The other production units including the oil boiler at Billerud Korsnäs AB can vary according to the remaining heat demand in the DHS. The peak capacity of the oil boilers is high due to the fact that they are reserves for all other production units. The heat capacity of the flue gas condensers is dependent on the boiler load.

The Johannes CHP uses a fuel mix (2014) of 50% bark from the pulp and forest industry, 40% wood chips from waste wood from the local recycling system, and 10% wood chips from tree tops and branches from the forest industry. In the calculations, all CO₂ emissions from use of fuels are allocated to the boiler process, therefore no fuels are assumed for the flue gas condensers. In 2014, the heat demand in the DHS was 730 GWh. The use of fossil fuel was limited to 0,3% [17].

Figure 7 is an illustrative figure of produced heat from the different production units during one year. The figure is for illustrative purposes only and the heat demand, electricity spot price and available power from the different production units are simplified. Figure 8 shows the produced heat during the investigated year. Each production unit and the total heat delivered to the DHS are presented.

### Table 1: Data for production units in the Gävle DHS.

<table>
<thead>
<tr>
<th>Production unit</th>
<th>Fuel</th>
<th>Maximum heat capacity</th>
<th>Efficiency</th>
<th>Power to heat ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Waste heat from Billerud Korsnäs AB</td>
<td>-</td>
<td>23 MW</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Flue gas condenser Bomhus Energi AB</td>
<td>-</td>
<td>40 MW</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Black liquor evaporator Billerud Korsnäs AB</td>
<td>-</td>
<td>36 MW</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>CHP Bomhus Energi AB</td>
<td>Bark</td>
<td>150 MW</td>
<td>88%</td>
<td>0,3</td>
</tr>
<tr>
<td>CHP Johannes</td>
<td>Biofuels</td>
<td>77 MW</td>
<td>88%</td>
<td>0,3</td>
</tr>
<tr>
<td>Flue gas condenser Johannes</td>
<td>-</td>
<td>20 MW</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Electricity boiler Billerud Korsnäs AB</td>
<td>-</td>
<td>50 MW</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Peak and reserves Billerud Korsnäs AB</td>
<td>Oil</td>
<td>120 MW</td>
<td>90%</td>
<td>-</td>
</tr>
<tr>
<td>Peak and reserves Gävle Energi AB</td>
<td>Oil</td>
<td>60 MW</td>
<td>90%</td>
<td>-</td>
</tr>
<tr>
<td>Peak and reserves Gävle Energi AB</td>
<td>Bio-oil</td>
<td>74 MW</td>
<td>90%</td>
<td>-</td>
</tr>
</tbody>
</table>
Figure 7: An illustrative figure of the annual heat demand and the different production units in the Gävle DHS.

Figure 8: Produced heat by the different production units and the total production of heat in the Gävle DHS.
Electric power systems and CO\textsubscript{2} emission evaluation

Electricity is distributed at regional and national level by a power transmission network. The local distribution connects buildings to the regional power transmission network. All countries are also connected to each other, directly or indirectly. Sweden has high-voltage connections with Norway, Finland, Denmark, Germany, Poland and Lithuania. Sweden is a part of the Nordic electricity trading market, Nordpool, which comprises Sweden, Norway, Denmark, Finland and Estonia, and the time scale for trading is one hour [23].

The system boundaries for the electricity market are not limited to local or national levels and changes in use of electricity in Sweden can affect the power systems in other countries. Therefore evaluation of the impact on CO\textsubscript{2} emissions from changes in electricity use or production is difficult to evaluate and there are several accounting methods used in different studies [24].

Solar PV technology

Producing electricity with a PV installation on private or commercial buildings is increasing in popularity. The global installed PV capacity was estimated at the end of 2014 to 177 GW\textsubscript{p}, mostly grid-connected systems. PV installations delivered approximately 1% of the global electricity demand in 2014. Germany, which is the country with most installed PV capacity, had 38,2 GW\textsubscript{p} of installed power, which during 2014 produced 35,2 TWh, corresponding to approximately 6% of the national gross power generation for that year [25]. The largest PV markets in the world in 2014 were China, Japan and USA, with UK at fourth place followed by Germany [26]. Those five countries together had 78\% of all installations in the world (2014) [26]. There are studies indicating that PV installations can contribute to 16\% of required electricity demand in the world by 2050 [27].

The PV technology has historically been more expensive than competing technologies to produce electricity. Different market incentives and enablers were therefore introduced in different countries to stimulate the PV market. The market incentives and enablers have been, and still are, dominated by different feed-in tariff schemes [26,28]. A feed-in tariff scheme is characterized by long-term contracts where the price paid for electricity produced from e.g. PV systems reflects the costs to produce the electricity. In 2014, 64\% of the market incentives and enablers were feed-in tariff schemes, 16\% were direct subsidies or tax breaks and 16\% were incentivized self-consumption or net-metering [26]. Besides the dominant markets today, it can be assumed that the PV market will increase rapidly in new countries. Which market incentives and enablers will be used, if any, is still an open question.

Solar PV technology in Sweden

Sweden has a limited PV market. In 2008, the cumulative installed capacity was less than 8 MW\textsubscript{p}. In 2014, 79 MW\textsubscript{p} cumulative PV capacity was
installed [29]. The increase was mostly dependent on a capital subsidy that was introduced in Sweden in 2009. This subsidy has been ongoing except for an interruption in 2012. The subsidy is successful in the sense that there are more applications than available funds (December 2015), and the Swedish government has proposed an increase in capital subsidies in the budget proposal for 2016 [30].

In 2015 a tax deduction scheme for excess electricity produced to the grid was implemented. The tax deduction scheme is similar to a feed-in tariff scheme, but the produced excess electricity is credited with approximately 60 EUR/MWh as a tax refund. The tax deduction scheme has an upper limit of approximately 1900 EUR per year and building owner and is therefore not aimed at large PV installations or building owners with multiple buildings with PV installations.

It is also possible to apply for the electricity certificate scheme. Electricity certificates are a market-based system to financially support the production of electricity from renewable energy sources. During a limited time, up to 15 years, producers of electricity from renewable energy sources receive one certificate for each MWh of produced electricity. The certificate can then be sold to the market and power suppliers and certain power customers are obligated by law to buy electricity certificates corresponding to a proportion of their electricity sales or usage. For normal electricity end users, the cost of the electricity certificates is included in the electricity bill.

When producing electricity into the local grid, losses due to transfer of electricity from other production units to the local grid are reduced and it is therefore also possible to receive financial compensation from the local grid owner for the reduction of these losses. Excess electricity produced by the PV installation is commonly sold to electrical utilities for the electricity market spot price. There are some local electricity and energy companies in Sweden that buy electricity produced by PV installations for a considerably higher price than the spot market, but the most common compensation in Sweden is the electricity spot market price [31].

**The value of electricity produced by a PV installation**

There are two commonly used methods to manage/measure local electricity production: gross metering and net metering arrangement [32]:

- Gross metering arrangement: All electricity produced by the local production unit is directly fed to the grid and measured separately from the use of electricity.
- Net metering arrangement: The net metering arrangement can be made in different ways [33], but the principle is that the electricity from the production unit is fed inside the boundaries of the electric meter (inside the building) and decreases the measured use of electricity. When excess electricity is produced (electrical power used is less than the produced PV power), the
electric meter measures the amount of electricity delivered to the grid. This is not possible in all countries, dependent on whether the owner of the PV system is paid for exported electricity.

If a PV installation is producing electricity in a gross metering arrangement, the value for the produced electricity usually is dependent on a feed-in tariff scheme. If the PV installation is producing electricity in a net metering arrangement, there are usually different economic values for the electricity depending on whether the electricity is used inside the building boundaries (the electric meter) or produced to the grid as excess electricity. The electricity used inside the building boundaries balances purchased electricity and therefore commonly has the same value.

If there is no feed-in tariff scheme or similar constructions the excess electricity usually has the value of the electricity spot market price only. That is under the circumstance that the building owner is allowed to sell the excess electricity to a utility. The difference in value for self-consumed electricity and produced excess electricity varies between countries and sometimes within the country as well. Some countries have a net metering arrangement with a long settlement time, for example a month or even a year. That means that the excess electricity is credited towards electricity used for that period and the value of excess electricity is the same as electricity used. This is often called net metering, which can cause confusion with the electric meter arrangements.

In Sweden, excess electricity is sold to electric utilities and the value for sold electricity usually is the same as the electricity spot market price. With a low electricity spot price the difference can be significant between the electricity spot price and the price for purchased electricity. For a building owner with more than one building it is possible to transfer produced excess electricity from one building within the company to another building and on an hourly basis balance electricity used in the second building for excess electricity produced by the first. In the budget proposal for 2016 from the Swedish government [30] which now is implemented, all transferred electricity is subject to energy tax. If a building owner has an installed PV capacity of more than 255 kWp, counted towards all owned buildings, all electricity produced by the PV installations is subject to energy tax. The energy tax on electricity in Sweden is approximately 32 EUR/MWh.

The total cost of electricity for building owners in Sweden is divided into three parts. These parts are:

- The cost of the electricity, bought from competing electric utility companies.
- The electric grid cost, a fixed and a variable cost for transfer electricity on the electric grid.
- Taxes and additional fees, energy tax and value added tax on both the electricity price and the cost for transfer electricity on the grid. A fee is also included for electricity certificates.
The economic value for self-consumed electricity only affects the variable costs of electricity used and also varies between different customers due to different contracts with electric utilities. An economic value for self-consumed electricity can be assumed to be approximately 100 EUR/MWh [34].
Method and data collection

Both appended papers use existing buildings in Gävle or nearby Gävle as case studies. Paper I uses a five-floor building with 27 apartments, built in 1973 and with 2500 m² heated floor area (Picture 1a). Paper II uses the same reference building as the first but also uses a three-floor building with 87 apartments, also built in 1973 (Picture 1b), and a single-family house in Älvdal, 26 kilometers southeast of Gävle (Picture 1c).

Picture 1: a) the five-floor tower block, b) the three-floor slab block and c) the single-family house investigated in this study.

Production data for the DHS and the marginal production unit

To analyze the impact of the DHS when ECMs are implemented, historical data from 2014 are used. Hourly data on production from the different production units for the DHS are compared with hourly values of the electricity spot price. The merit order for the different production units is dependent on the electricity price and the fuel price. The fuel price is assumed to be constant over the year, due to long contracts with suppliers and possibilities to store fuel, so the merit order is assumed to be dependent on the electricity price only. When the electricity price was known, the marginal production unit was calculated for every hour during the investigated year. The hourly data of the electricity price were obtained from Nordpool [23]. In Figure 9a is the electricity price during 2014 presented. In Figure 9b is the electricity price presented from highest value to lowest. Note that the electricity price varies between approximately 21 EUR/MWh and 42 EUR/MWh (200 SEK/MWh to 400 SEK/MWh) for the majority of the year.
Energy system optimization tools and energy models

There are different optimization tools available for energy system optimizations. The tools often explain the complex relation between different parts of the system mathematically and large amounts of data can be processed [35]. Different input data can often change over time to have different conditions during the year and to forecast future demand, e.g. fuel price, electricity price, etc., to be able to optimize a composition of the system.

The common methods of those tools are to create a model where data for the different production units (maximum capacity, fuel cost, efficiency, etc.), any investment costs for new production units and environmental pollution are included. Models of complex energy systems are by necessity simplified models of the reality. Depending on the aim of the study, the model can have different levels of detail and prioritize cost or environmental optimizations.

Examples of energy system optimization tools are MARKAL and MODEST. MARKAL was originally designed to develop a strategy for research, development and demonstration for the International Energy Agency (IEA) to evaluate energy systems over a period of 40 to 50 years at national, regional or municipal level [36-38]. MODEST (Model for Optimization of Dynamic Energy Systems with Time dependent component and boundary conditions) is an energy system optimization model that optimizes the costs for the energy system. The system boundaries can vary from town districts to national levels. MODEST was developed by Linköping University [35, 39,40].

Simulation of different ECMs

During the residential reform in Sweden, there were many multi-dwelling buildings built between 1965 and 1975. Many of those buildings are in need of renovation and a building with a common style and construction from that period was chosen as a reference in this thesis. The aim of the first appended paper is to see the tendencies of impact on the DHS when ECMs are imple-
mented. Therefore only one building was investigated and not a number of buildings.

When renovating buildings from that period, there are two common ways to proceed. The first is to let the tenants move to a temporary location and only leave the structure of the building intact and more or less construct a new building on the old structure. The other method is to let the tenants stay in the apartment or organize a short-term alternative living when the building changes the insulation on the outside walls and the attic together with new or refurbished windows and a new ventilation system. Many of the buildings from this period had exhaust air ventilation only without heat recovery systems. When changing to a new ventilation system, an exhaust air heat pump or a supply and exhaust air heat exchanger are common technologies to install. The latter often requires that a supply air system is complemented. In this thesis, an exhaust air heat pump is chosen because the electricity for operation is of interest to analyze.

In total, five different ECMs are first analyzed separately:

1. 400 mm extra insulation in the attic.
2. 200 mm extra insulation on the external walls.
3. Improved windows to triple-glazed with a low E-coating.
4. Installation of a 15 kW exhaust air heat pump with COP=3 (assumed to be constant over the year).
5. Electricity conserving measures (ElCMs). The ElCMs are assumed to decrease the facility electricity use by 30%.

**Simulation tool IDA-ICE**

To simulate the changes in energy use when the different ECMs are implemented, a simulation software called IDA-ICE is used [41]. The program can be set to simulate the use of energy in the building with and without the different ECMs on an hourly basis. To be able to simulate the use of energy a weather data file for the simulation period is required. The weather data file contains information about the air temperature, relative humidity, wind direction, wind speed, and direct and diffuse solar radiation. A weather data file was created for 2014 with the program Real-Time Weather Data [42]. All meteorological data are hourly values.

**Simulation of reference building**

The building used as a reference for the simulations was built in 1973 and is a five-floor building with 27 apartments and 2500 m² heated floor area. The required heat for tap water and space heating is delivered by the DHS by a centralized substation on the ground floor. The building uses approximately 300 MWh annually for tap water and space heating (data from building owner) and 20 MWh for facility electricity (electricity to households
and electricity used outdoors, e.g. electricity for engine preheaters are excluded), which corresponds to a specific annual energy use of approximately 120 kWh/m² and a UA value of 2030 W/K. The thermal performance of the building is described in Table 2. The building has an exhaust air ventilation system without heat recovery and the building has not undergone any major renovations.

Table 2: Thermal characteristics of the reference building before and after ECMs.

<table>
<thead>
<tr>
<th>Before energy conserving measures</th>
<th>U-values</th>
<th>Heat recovery ventilation</th>
<th>Air flow ventilation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ground floor</td>
<td>0.3 W/m²K</td>
<td>0.7 W/m²K</td>
<td>none</td>
</tr>
<tr>
<td>External wall</td>
<td>2.9 W/m²K</td>
<td>g-value = 0.8</td>
<td>2030 W/K</td>
</tr>
<tr>
<td>Windows</td>
<td>0.3 W/m²K</td>
<td>0.3 W/m²K</td>
<td>none</td>
</tr>
<tr>
<td>Roof</td>
<td>0.7 W/m²K</td>
<td>0.57 W/m²K</td>
<td>1930 W/K</td>
</tr>
<tr>
<td>UA value</td>
<td>g-value = 0.7</td>
<td>15 W/m²K</td>
<td>Exhaust air HP CDP=3</td>
</tr>
<tr>
<td>Air flow ventilation</td>
<td>0.9 m/s</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>After energy conserving measures</th>
<th>U-values</th>
<th>Heat recovery ventilation</th>
<th>Air flow ventilation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ground floor</td>
<td>0.3 W/m²K</td>
<td>0.2 W/m²K</td>
<td></td>
</tr>
<tr>
<td>External wall</td>
<td>1.5 W/m²K</td>
<td>g-value = 0.7</td>
<td></td>
</tr>
<tr>
<td>Windows</td>
<td>0.3 W/m²K</td>
<td>0.3 W/m²K</td>
<td></td>
</tr>
<tr>
<td>Roof</td>
<td>0.7 W/m²K</td>
<td>0.57 W/m²K</td>
<td></td>
</tr>
<tr>
<td>UA value</td>
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</tr>
<tr>
<td>Air flow ventilation</td>
<td>0.9 m/s</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

CO₂ emission impact of electricity use

In this thesis CO₂ emissions from changes in electricity use are evaluated with three different accounting methods. First is the marginal electricity approach, where all changes in use of electricity are assumed to affect the marginal production. The marginal electricity approach is compared for both the short-term marginal production unit, coal condensing power, and the long-term marginal production unit, natural gas combined cycle condensing power. For purposes of comparison the mean electricity mix of Sweden, Norway, Finland and Denmark is also used [23]. Other common accounting methods are the residual electricity mix of the Nordic countries or the residual electricity mix of the northern European countries.

The residual mix is explained in simplified terms as the produced electricity in one or several countries during a calendar year where the sold electricity with Guaranty of Origin has been removed from the production mix, and the remainder constitutes the residual mix. The project Reliable Disclosure Systems for Europe (RE-DISS) has defined a recommendation for tracking-related policies [43]. The short-term marginal production method is chosen because it is commonly used in Sweden. The long-term marginal production method is chosen because natural gas combined cycle condensing power can be considered as marginal production on an international electricity market in the long run [24]. The short-term marginal method (coal condensing power) and the mean electricity mix of the Nordic countries (low share of fossil fuels) also give the extremes regarding CO₂ emissions, for which reason other common methods should give results between those two methods.

Change in CO₂ emissions due to ECMs

For the evaluation of CO₂ emissions, two different combinations of ECMs are compared to installation of an exhaust air heat pump. The first combined ECM (ECM1) is extra insulation of the external wall and in the attic together
with improved windows. The second combined ECM (ECM2) is identical with the first but also includes EI CMs and local production of electricity, which in this case is a PV installation.

A working group within the Swedish District Heating Association calculates emissions annually from production of heat for the Swedish DHS [44]. They use emission factors for biofuels between 11-37 kg CO₂ eq/MWh with the lowest values from recycled waste wood and secondary biofuels such as bark, tops and branches. Because most fuels used in Bomhus Energi AB and Johannes CHP plants are secondary biofuels, the maximum value in this study is assumed to be 15 kg CO₂ eq/MWh. Since different models for calculating CO₂ emission from biofuels are used, both values are used in the calculations and give a slight dispersion of the result.

The different CO₂ emission factors used for the evaluation of electricity and fuels are displayed in Table 3 [44,45].

The peak and reserve boilers are evaluated with two different scenarios. The first scenario is fossil oil only and second scenario is bio-oil only as fuel. Industrial waste heat from Billerud Korsnäs AB is assumed to have no CO₂ emissions.

<table>
<thead>
<tr>
<th>CO₂ eq(kg/MWh)</th>
<th>Electricity mix Sweden, Norway Denmark, Finland</th>
<th>Natural gas combined cycle condensing power</th>
<th>Coal condensing power</th>
<th>Tops and branches</th>
<th>Recycled waste wood</th>
<th>Bark</th>
<th>Oil</th>
<th>Bio-oil</th>
</tr>
</thead>
</table>

### Monitoring of electricity use in buildings and PV production

When combining analyses of PV production and the electricity demands of households, the time step is important. The solar irradiation during a cloudy day can quickly change and the same applies for the electricity use in households [46,47]. When PV production and electricity use are investigated individually, the quick changes might not cause problems, but when investigating the produced excess electricity from a PV system, the changes in both PV production and use of electricity can underestimate the amount of produced excess electricity, therefore a short time-step is recommended [46-48]. In the appended Paper II, a time step of one minute is used.

The electricity use in the multi-dwelling buildings are logged with a TinyTag Energy Logger [49] and the electricity use in the single-family house is monitored with an eGauge data logger [50]. All monitored data are with one minute time step.

The single-family house has a 2.6 kWp PV installation on the roof and the produced electricity is monitored together with the use of electricity on all three phases individually. The multi-dwelling buildings do not have PV systems installed and only the used electricity is monitored on all three phases.
individually. To be able to estimate the electricity produced from different sizes of PV installations, monitored solar irradiation from a nearby village, Bergby, is used. The solar irradiation is monitored with an interval of 30 seconds with an SPN1 pyranometer, manufactured by Delta-T Devices Ltd [51]. The sensor measures both global and diffuse radiation on a horizontal surface.

The PV installations are assumed to be installed in south-facing direction and with a tilt angle of 45 degrees. The monitored radiation data are used to calculate irradiance on the roof, using the Liu and Jordan isotropic sky model [52]. No shading from buildings or other obstacles is assumed. A relatively small PV installation (10 kW$_p$) is compared to a larger PV installation (30 kW$_p$) for the five-floor tower block building (flat roof area of approximately 500 m$^2$). For the larger three-floor slab block building (flat roof area of approximately 1400 m$^2$), the number of apartments as well as the roof area is substantially larger, and PV systems of 20 kW$_p$ and 80 kW$_p$ are compared.
Results

This chapter presents and summarizes the results from both appended papers. This chapter also includes a study on global CO₂ emissions when ECMs are implemented in buildings heated by district heating in Gävle and how the global CO₂ emissions change if the saved biofuel from the different production units is treated as a valuable asset and used to produce electricity within the European electricity power network.

Changes in used energy in the DHS due to ECMs

Different ECMs affect the distribution of energy use in a building in different ways. A heat pump, which in this study is connected to both the space heating and domestic hot water system, will reduce the use of energy during both the space heating season and the summer. ECMs that affect the U-value will only affect the use of energy during the space heating period.

When renovating buildings, different ECMs are often implemented together and both the U-value, the use of electricity and losses in the ventilation system are improved. In appended Paper I, the tendency of impact for the different ECMs is of interest and presented individually or in combination as ECM1 and ECM2. In Figure 10, the use of heat is presented for the investigated building without ECMs, with the combined package of ECMs that affect the U-value (ECM1) and installation of an exhaust air heat pump.

![Figure 10: The use of heat for space heating and domestic hot water supply for the investigated building without ECMs, with the insulation package (ECM1) and with an exhaust air heat pump.](image-url)
The simulated and calculated results on how the different individual ECMs affect the total use of energy and the distribution of energy change are presented in Table 4, where the different production units are categorized in: (1) waste heat from Billerud Korsnäs AB together with the flue gas condensers at Bomhus Energi AB and energy from the black liquor evaporator; (2) the CHP plants at Bomhus Energi AB and Johannes and the flue gas condenser at Johannes, labelled as biofuels; (3) use of electricity in hot water boiler and reduced production of electricity in the direct condenser; and (4) oil for peaks and reserves. The last column presents the change in electricity production and use of electricity for heating in the DHS. It shows the sum of decreased production of electricity in the CHP plants, the decreased use of electricity in the hot water boiler and the increased production of electricity in the turbine when the direct condenser is the marginal production unit.

Table 4: Simulated results of change in energy use for heating in the building, the distribution of energy change in different categories of production units and the total change in production/use of electricity in the DHS.

| Improved windows | -32 | 5% | 73% | 17% | 6% | -1,7 |
| Attic 400mm insulation | -8,0 | 6% | 73% | 16% | 5% | -0,5 |
| External wall 200mm insulation | -35 | 6% | 73% | 16% | 5% | -2,1 |
| Electricity conservation measure (30%) | 1,1 | 9% | 74% | 13% | 4% | 0,2 |
| Exhaust air heat pump | -110 | 19% | 67% | 11% | 3% | -11 |

All five ECMs affect the use of energy for heating in the building. Improved windows, increased insulation on the wall and in the attic and the exhaust air heat pump reduce the use of heat. ECMs reduce the use of electricity and therefore increase the use of heat for space heating due to lower internal heat gain. The distribution of energy change is similar for improved windows and increased insulation on the wall and in the attic. The exhaust air heat pump affects the used energy delivered by waste heat and the flue gas condenser more than other ECMs due to the reduced use of heat during the summer. The distribution of energy change for electricity in the hot water boiler and the use of oil are lower for the heat pump compared to the ECMs affecting the U-value. This depends on a lower decrease in energy use during the coldest periods and the decreased use of energy during the summer.

When the two combinations of ECMs, ECM1 and ECM2, are compared to the exhaust air heat pump, there are apparent differences. The exhaust air heat pump has the largest decrease in the total production/use of electricity and together with the electricity used for operation of the heat pump, 48 MWh of electricity needs to be produced within the electric power network to balance the net increase of electricity use due to the ECM. On the other hand, for the second combined ECM, ECM2, the net decrease of electricity
is 22.9 MWh and the electric power network can decrease the production to balance the increased amount of electricity available due to the ECMs. In Table 5, the reduced amount of energy used for heating due to ECM1, ECM2 and the exhaust air heat pump is presented together with how the decrease in energy use is allocated to the different production units and the change in electricity use locally. The change in electricity use locally is presented both for the total change in production/use of electricity in the DHS due to ECMs but also the change in use of electricity due to EICMs together with the PV installation and the use of electricity due to operation of the heat pump.

Table 5: The reduced amount of energy delivered by the DHS used for heating in the building and how the decrease is allocated between the different energy production units. The change in electricity use/production is also presented together with the change in use of electricity due to EICMs, the PV installation and the operation of the exhaust air heat pump.

<table>
<thead>
<tr>
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<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Combined ECM 1</td>
<td>76</td>
<td>13</td>
<td>64</td>
<td>4.8</td>
<td>17</td>
<td>-4.3</td>
<td>0</td>
</tr>
<tr>
<td>Combined ECM 2</td>
<td>75</td>
<td>12</td>
<td>63</td>
<td>4.7</td>
<td>17</td>
<td>-4.1</td>
<td>-77</td>
</tr>
<tr>
<td>Exhaust air heat pump</td>
<td>110</td>
<td>12</td>
<td>86</td>
<td>4.2</td>
<td>23</td>
<td>-11</td>
<td>37</td>
</tr>
</tbody>
</table>

**CO₂ emission evaluation due to ECMs in the DHS**

In Gävle, most of the base load in the DHS is covered with waste heat from Billerud Korsnäs AB. Therefore, the reduced use of heat during summer (as for the exhaust air heat pump) has a minor effect on the global CO₂ emissions due to low CO₂ emissions from industrial waste heat (assumed to be zero in this thesis).

The accounting method used for calculating the emissions from the change in electricity use locally dominates the results and the interval for CO₂ emissions for biofuels only affects the results marginally. Figure 11 presents the change in CO₂ emissions for ECM1, ECM2 and the exhaust air heat pump for the case when fossil oil is used in the peak and reserve boilers. The difference for the different emission factors for biofuels is difficult to observe but is approximately 0.5 ton/year for the compared ECMs and accounting methods.
Figure 11: The change in global CO$_2$ emissions due to the different ECMs when fossil oil is used in the peak and reserve boilers. A minus sign is a decrease in CO$_2$ emissions.

If bio-oil is used instead of fossil oil, the changes in CO$_2$ emissions due to the compared ECMs are slightly lower. The results are presented in Figure 12 and the difference because of the emission factors for biofuels is approximately 0.5 ton/year for the compared ECMs and accounting methods.

Figure 12: The change in global CO$_2$ emissions due to the different ECMs when bio-oil is used in the peak and reserve boilers. A minus sign is a decrease in CO$_2$ emissions.
Biofuels as a valuable asset

When ECMs are implemented in DHS, as in this case study, the reduced amount of heat is mainly produced by biofuels, as presented in Table 4. If the saved biofuels have a value on the open market and saved biofuel is sold to other energy producers or other commercial businesses, the global CO$_2$ emissions from the different ECMs decrease substantially and are presented in Figure 13. An assumption is made that the saved biofuel produces electricity in a power plant with the same efficiencies as Johannes CHP and the electricity produced replaces electricity within the power system produced by power units using coal or natural gas.

![Figure 13: The change in global CO$_2$ emissions due to the different ECMs when fossil oil is used in the peak and reserve boilers and the reduced biofuels are used to produce electricity in a power plant. A minus sign is a decrease in CO$_2$ emissions.](image)

How the electric meter configuration affects the measured amount of self-consumed and produced excess electricity

The electricity use on each phase and the electricity production from the PV installation was monitored with an interval of one minute for 12 months for the single-family house. In Figure 14, the monitored use of electricity and the PV production are presented for July 1, 2015. There is a low electricity demand during daytime when the production from the PV installation is high. There is a periodic load on phase 2 which is caused by an immersion heater for the domestic hot water system.
The intermittent solar irradiation during a partially cloudy day is noticeable in Figure 14 but also the quick changes in electricity use and the difference in electricity use between the phases.

In Table 6, the amount of self-consumed and produced excess electricity is compared for the PV installation when connected by a single-phase inverter to any of the phases or by a three-phase inverter for the two different electric meter configurations. The use and production of electricity was measured from November 1, 2014 to October 31, 2015. It is assumed that the produced electricity with the three-phase inverter is equally distributed between the three phases, independent of how much electricity actually is used on each phase.

The first four rows in Table 6 show self-consumed and produced excess electricity when the electric meter configuration measures each phase individually and row five when the electric meter configuration measures the sum of the phases.

Table 6: The amount of self-consumed and produced excess electricity for a PV installation on a single-family house when connected by a single-phase inverter connected to all three phases individually or a three-phase inverter for two different electric meter configurations. The measured period is one year.

<table>
<thead>
<tr>
<th></th>
<th>Production PV installation</th>
<th>Produced excess electricity</th>
<th>Self-consumption</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 phase inverter, electric meter configuration per phase, phase 1</td>
<td>1990 kWh</td>
<td>1430 kWh</td>
<td>560 kWh (28%)</td>
</tr>
<tr>
<td>1 phase inverter, electric meter configuration per phase, phase 2</td>
<td>1990 kWh</td>
<td>1520 kWh</td>
<td>470 kWh (24%)</td>
</tr>
<tr>
<td>1 phase inverter, electric meter configuration per phase, phase 3</td>
<td>1990 kWh</td>
<td>1460 kWh</td>
<td>530 kWh (27%)</td>
</tr>
<tr>
<td>3 phase inverter, electric meter configuration per phase</td>
<td>1990 kWh</td>
<td>1040 kWh</td>
<td>950 kWh (48%)</td>
</tr>
<tr>
<td>1 or 3 phase inverter, electric meter configuration sum of phases</td>
<td>1990 kWh</td>
<td>900 kWh</td>
<td>1090 kWh (55%)</td>
</tr>
</tbody>
</table>
The electricity use for the two multi-dwelling buildings was monitored during two summer months, July 1 to August 31, 2014. The PV production from two different sizes of PV installations was calculated for both buildings. The PV system sizes on the five-floor tower block were 10 kW\textsubscript{p} and 30 kW\textsubscript{p}. On the three-floor slab block, the PV system sizes were 30 kW\textsubscript{p} and 80 kW\textsubscript{p}. The PV installations are assumed to use three-phase inverters evenly distributed between the phases.

The electricity use and PV production on July 1, 2014 for the five-floor tower block is presented in Figure 15 and for the three-floor slab block in Figure 16.

Figure 15: The electricity use per phase and the PV production from a 10 kW\textsubscript{p} and a 30 kW\textsubscript{p} PV installation on the five-floor tower block on July 1, 2014.

Figure 16: The electricity use on each phase and the production from a 20 kW\textsubscript{p} and an 80 kW\textsubscript{p} PV installation on the three-floor slab block on July 1, 2014.
For the smaller five-floor tower block, the electricity use changes comprehensively during the day. It is the common laundry room used by tenants that affects the use of electricity most. It is also seen that the use of electricity is low when the laundry room is not in use and that there is a dispersion between the electricity use on the different phases. The PV production is higher than the internal load during the day and excess electricity is produced.

In the larger three-floor slab block, the electricity use for the tenants is included in the facility electricity. Therefore the base load is significantly higher and the peak loads are not as prominent as for the five-floor tower block. There is still a difference in use of electricity between the phases. The calculated PV system sizes are larger than for the five-floor tower block due to larger available roof area and for the larger PV installation, a substantial part of the produced electricity is produced as excess electricity to the grid.

In Table 7, the produced electricity for the two different PV installations, 10 kWp and 30 kWp is compared with the two different electric meter configurations for the five-floor tower block. The amount of self-consumed and produced excess electricity is calculated between July 1 and August 31, 2014. The inverters are assumed to be three phase units.

Table 7: The produced electricity in the five-floor tower block for a 10 kWp and a 30 kWp PV system compared with the different electric meter configurations and the amount of produced excess electricity and self-consumption between July 1 and August 31, 2014.

<table>
<thead>
<tr>
<th>PV Installation</th>
<th>Production excess electricity</th>
<th>Self-consumption</th>
</tr>
</thead>
<tbody>
<tr>
<td>10 kWp PV installation, electric meter configuration per phase</td>
<td>3230 kWh</td>
<td>1190 kWh</td>
</tr>
<tr>
<td>10 kWp PV installation, electric meter configuration sum of phases</td>
<td>3230 kWh</td>
<td>1160 kWh</td>
</tr>
<tr>
<td>30 kWp PV installation, electric meter configuration per phase</td>
<td>9680 kWh</td>
<td>5970 kWh</td>
</tr>
<tr>
<td>30 kWp PV installation, electric meter configuration sum of phases</td>
<td>9680 kWh</td>
<td>5950 kWh</td>
</tr>
</tbody>
</table>

In Table 8 the produced electricity for the two different PV installations, 20 kWp and 80 kWp is compared with the two different electric meter configurations. The amount of excess electricity produced and self-consumption is calculated between July 1 and August 31, 2014.

Table 8: The produced electricity in the three-floor slab block for a 20 kWp and an 80 kWp PV system compared with the different electric meter configurations and the amount of produced excess electricity and self-consumption between July 1 and August 31, 2014.

<table>
<thead>
<tr>
<th>PV Installation</th>
<th>Production excess electricity</th>
<th>Self-consumption</th>
</tr>
</thead>
<tbody>
<tr>
<td>20 kWp PV installation, electric meter configuration per phase</td>
<td>6450 kWh</td>
<td>560 kWh</td>
</tr>
<tr>
<td>20 kWp PV installation, electric meter configuration sum of phases</td>
<td>6450 kWh</td>
<td>450 kWh</td>
</tr>
<tr>
<td>80 kWp PV installation, electric meter configuration per phase</td>
<td>25810 kWh</td>
<td>15000 kWh</td>
</tr>
<tr>
<td>80 kWp PV installation, electric meter configuration sum of phases</td>
<td>25810 kWh</td>
<td>14930 kWh</td>
</tr>
</tbody>
</table>
The self-consumed electricity produced on the five-floor tower block is 63% and 64% for the small PV installation (10 kW_{p}) and 38% for the larger (30 kW_{p}). For the three-floor slab block, the self-consumed electricity is 91% and 93% for the small PV installation (20 kW_{p}) and 42% for the larger (80 kW_{p}). The difference due to the electric meter configuration is almost negligible for both multi-dwelling buildings.
Discussion

The method used in this thesis to analyze the changed amount of delivered heat from different marginal production units and how it affects the electricity production uses real production data from all production units in the DHS in Gävle for the investigated year. All data are on an hourly basis and the electricity spot market price is used to calculate the optimized merit order of the different production units. Since the simulations of the different ECMs in IDA-ICE use a climate file, created by the program Real-Time Weather Data in this thesis for the investigated year, the climate conditions are similar in the simulations to the actual conditions during the investigated year. It is therefore assumed that this gives a small difference compared to if local climate data was monitored and used in the simulations.

The common method to build a model of an existing energy system and run it in an optimization program always contains errors due to limitations in the model. The method used here avoids this problem since real data are used. If the aim of the study is to predict how implemented ECMs will affect the energy system in the future, the method used is not appropriate and an optimization tool is necessary.

When the two packages of energy conserving measures, ECM1 and ECM2, are compared with the exhaust air heat pump, the latter affects the production of electricity and use of electricity to produce heat in the DHS more than ECM1 and ECM2. Together with the electricity for operation of the exhaust air heat pump, the need of electricity in the vicinity of Gävle is increased when an exhaust air heat pump is used and the power system is affected since more electricity must be produced to balance the change. ECM1, which only reduces the transmission heat losses in the building, slightly decreases the available amount of electricity locally, but when ECM1 is combined with electricity conserving measures and a PV installation, as in ECM2, the available electricity locally is increased. This entails that the amount of electricity produced in the European or Nordic power system can be reduced.

The electricity produced in the CHP plants in Gävle is based on biofuels. If the available amount of electricity changes locally, other production units of electricity within the Nordic or European power system change their production. Since the DHS in Gävle uses biofuels in the CHP plants, industrial waste heat and only a small share of oil and electricity for heating, a change in available local amount of electricity affects the global CO₂ emissions substantially when electricity production in the European power system, with a large share of fossil fuels, is changed to balance the local change in
Gävle. The alternative with fossil oil or bio-oil in peak and reserve boilers in Gävle affects the evaluation to a minor extent.

The exhaust air heat pump, which increases the use of electricity locally, has a negative impact on global CO₂ emissions for all accounting methods. ECM2, which increases the available amount of electricity locally, has a positive impact on global CO₂ emissions for all accounting methods. For ECM1, which only affects the use of heat, the impact on global CO₂ emissions is positive or negative depending on the accounting method used.

This result is based on the assumption that saved biofuels due to different energy conservation measures have no alternative use as an energy source. However, if it is assumed that the saved biofuel can be used somewhere else, e.g. replacing fossil fuel in a power plant within the European power network, the results change. Assuming coal or natural gas as the marginal production units will change the values of the CO₂ emissions substantially, but not the overall tendencies.

Building owners often see installation of a PV system as an ECM even though the system does not affect the energy used in the buildings. Combining ECMs in buildings connected to the Gävle DHS with PV installations has a positive effect on global CO₂ emissions and contributes to fulfilling energy goals and agreements locally as well as globally. If the PV technology is to become a common technology for building owners the installations need to be economically profitable.

Electricity produced by a PV installation on a building can either be used instantaneously inside the building boundaries (electric meter) or delivered to the grid to be used by others. The economic value of self-consumed electricity in Sweden is the same as bought electricity for most building owners. In Sweden, the value of produced excess electricity, without the tax deduction, is most commonly the electricity spot price together with a small economic compensation for reduced losses in the transmission network and possibly some compensation for produced electricity within the electricity certificate scheme.

If there is a low electricity price, the difference between self-consumed electricity and produced excess electricity can be significant. The electric meter configuration affects the measured amount of self-consumed and produced excess electricity for single-family buildings with bi-directional meters connected with a three-phase connection to the grid. The connection to the grid varies around the world and smaller buildings can be connected to only one phase or two phases. In Sweden, almost all buildings are connected to all three phases.

The tax deduction scheme, introduced in Sweden in 2015, where produced excess electricity is entitled to a tax deduction of approximately 60 EUR/MWh, decreases the economic differences between bought electricity and produced excess electricity. The tax deduction scheme also minimizes the economic difference due to the electric meter configurations and the mismatch between use of electricity in buildings and produced electricity by
PV installations because the economic value of produced excess electricity becomes close to bought electricity.

The tax deduction scheme is an ongoing scheme without guarantees to last over the life span of the PV installations. The uncertainty of the future value of produced excess electricity, which as presented can be a large proportion of the produced amount of electricity, will act as a barrier for a future market development. Another barrier is the concern about the energy tax that is currently undergoing a change. Owners of multiple multi-dwelling buildings with PV systems can be obligated to pay energy tax for all electricity produced by the PV systems. Together with a possible high share of produced excess electricity, the economic profitability of PV systems can be uncertain.
Conclusion

The method used in the first appended paper can be used in other DHS with production units where the merit order between the production units is related to the electricity spot price. The method gives a detailed description of how the production units are affected based on historical data of produced heat. When the tendency of impact on the DHS, due to implementation of different ECMs is studied, the method can be preferable compared to different system optimization tools. The method has limitations in predicting how different ECMs affect the heat produced in DHS in the future and an energy model-based optimization program is then preferred. In this thesis, where the tendency of impact on the different production units in the DHS is investigated, the method gives a detailed description of saved fuel and changes in electricity production/use for the different production units.

The work performed shows that saving electricity, as well as locally producing electricity (e.g. by PV systems) in the buildings, reduces the global CO₂ emissions while increasing the electricity use increases the global CO₂ emissions. This is also the case if the electricity used is increased by installing an exhaust air heat pump, although the heat demand then is reduced. Only saving heat by reducing the transmission heat losses for the building has a small effect on the global CO₂ emissions. These results are general and independent of the accounting methods for how the electricity is produced on the margin in the European or Nordic power system. However, there will be different results if the saved biofuel is assumed to have an alternative use in other heat or power production units, although the general conclusions are still valid.

PV installations together with ELCMs give the largest reduction of global CO₂ emissions in this study, regardless of which accounting method is used. The Swedish government has an aim to increase the PV market further but there are some barriers to overcome for a future prosperous market. For single-family houses, the electric meter configuration is an important factor to consider when planning the system. The tax deduction scheme is ongoing, and if the scheme ends before the end of the expected life time of the system, the economic profitability is jeopardized.

For multi-dwelling buildings in Sweden the energy tax is a barrier for future development of PV systems. If the building owner has a total solar PV installed peak power of 255 kW or more, all produced electricity is subject to energy tax. Some building owners own large areas of buildings, e.g. municipally owned building companies, and only a few of the buildings can install PV installations before all electricity produced by the PV installations is sub-
ject to energy tax. This means that together with the limitations to transfer excess electricity between buildings, large building owners have difficulties in fully adopting the PV technology if the systems should be economically profitable. In the future work regarding energy tax and the PV technology, the Swedish government should consider:

- To decide how the electric meters should be configured to create a fair market.
- That the tax deduction scheme should be contracted over a certain time and not be an ongoing scheme.
- Clarifying the rules for the energy tax and consider how to structure the energy tax to create a fair market for both building owners with one or a few buildings and large building owners with many buildings.

Many of the multi-dwelling buildings built between 1961 and 1975 in Sweden have substantial need for renovation where the use of energy can be assumed to have high priority. Besides reduced heat demand due to better insulation and heat recovery ventilation systems, PV installations should be a technology to consider due to their positive environmental impact. Only a limited share of building owners will probably consider the technology if the tax deduction scheme and the regulations for energy tax are uncertain.
Further research

Further research will follow the theme in the research school Reesbe, Resource-Efficient Energy System in the Built Environment, and will deal with effects in the DHS when ECMs or PV installations are implemented. Some research areas of interest are as follows.

Electricity storage in buildings

Different storage solutions for local storage of electricity in buildings have been introduced to the market where batteries are the most common technology. Battery storage systems decrease the share of produced excess electricity because stored electricity can be used as self-consumed electricity. When self-consumed electricity has a higher value than produced excess electricity, battery storage systems can be profitable. Battery storage systems will probably be a common solution in the future, but the technology is still too expensive to be a realistic alternative for most PV owners [26,53].

Another storage technology that has been introduced for both single-family houses and multi-family buildings is to store excess electricity as heat to be used for space heating or domestic hot water [53,54]. There are studies indicating that excess electricity stored as heat is more profitable than battery systems [53,55].

A potential research question is what the economic assumptions are today and in the near future for different storage solutions and how the different technologies affect the DHS.

Biofuels as a valuable asset

As discussed and shown in this thesis, biofuels can be considered a valuable asset, and how the saved fuel is used affects the CO$_2$ emission evaluations. A potential research question is therefore to further investigate how saved fuel in Gävle or nearby cities can be considered in a CO$_2$ emission evaluation.

Can the distribution of district heat be affected when ECMs are implemented?

The distribution network of district heat is designed to transport energy with a medium (water) temperature between approximately 65 °C to 120 °C. The possible delivered heat power is dependent on the flow and temperature difference in the district heating medium. The district heating network is designed
for current heat loads, and if ECMs are widely implemented, the change in heat load, especially during the summer, can cause distribution difficulties. A potential research question is therefore to evaluate how different ECMs can affect the distribution system if implemented in different areas of the DHS.
References


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Papers

Associated papers have been removed in the electronic version of this thesis.

For more details about the papers see:
http://urn.kb.se/resolve?urn=urn:nbn:se:hig:diva-21398
Evaluation of energy conserving measures in buildings connected to a district heating system – case studies in Gävle, Sweden

When different energy conserving measures are implemented for reducing energy use in buildings, it is important that an overall system analysis is made. This thesis analyzes five different energy conserving measures in a multi-dwelling building regarding how they affect the district heating system. For CO₂ emission evaluations, two different combinations of heat and electricity conserving measures are compared to installation of an exhaust air heat pump.

This thesis also analyzes how the configuration of the electric meter affects the measured amount of self-consumed and produced excess electricity when a solar photovoltaic (PV) system is installed. The results show that the use of electricity is the most important objective to consider. The increased use of electricity for operation of the heat pump contributes to an increase of global CO₂ emissions and the electricity produced by the solar photovoltaic installation contributes to a decrease of global CO₂ emissions.

The results also show that the configuration of the electric meter is important for a single-family house but negligible for multi-dwelling buildings. The amount of produced excess electricity from a solar PV installation is high for all buildings, which means that the economic value of produced excess electricity is important for a profitable installation.

Mattias Gustafsson