Trimming of a ground-source heat-pump system in Saltsjöbaden

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in Sälsjöbaden

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<thead>
<tr>
<th>Approved</th>
<th>Examiner</th>
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<tr>
<td>2014-05-25</td>
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Abstract

The real performance of ground source heat pumps systems are not precisely highlighted in most cases, especially when it comes to installations older than the contractors guarantee period of 5 years. This project analyses measured data, constructs durability diagrams and establishes an energy balance of a whole heating system located in Saltsjöbaden. The system, composed of 3 heat pumps with a total heating power of 270kW and an oil burner, is used to deliver comfort heat through radiators and ventilation as well as tap warm water production. The installation was originally designed with two oil burners now used as an auxiliary heat supplier. Two heat pumps were installed in 1999 and a third unit was added in 2009. However, the oil consumption has been higher than expected. An experiment with controlled oil burner operation confirmed the need of implementing a control strategy. Some weaknesses in the system are pointed out.
## Nomenclature

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<th>Description</th>
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<tbody>
<tr>
<td>GSHP</td>
<td>Ground Source Heat Pump</td>
</tr>
<tr>
<td>VP1</td>
<td>VärmePump 1 (heat pump 1)</td>
</tr>
<tr>
<td>VP2</td>
<td>VärmePump 2 (heat pump 2)</td>
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1. Background

Heating is a critical issue when it comes to designing comfortable housings, especially in Sweden. In spite of district heating solutions being widespread, many homeowners choose individual heating systems such as ground source heat pump (GSHP) systems once they realize the economical advantages. Grouping housings into condominiums allows the design of larger scale heating systems, more efficient and more cost-effective. Thereby a condominium situated in Saltsjöbaden (Syrenparken), has set up a ground source heat pump installation in order to satisfy the heating needs of the residence (Figure 1).

In the current context of global warming, heat pumps have the advantage to only use electricity as energy inputs. No fossil fuels are required, and both their effectiveness and profitability make this eco-friendly heating process attractive (as long as the electricity is produced from a fossil free source). Indeed the electricity consumption is reduced by half compare to basic electrical heating when GHPS are set up. In Sweden more than 1 million heat pumps systems have been installed during the last decade, value which is sky-rocketing. Moreover 51% energy produced in Sweden comes from RES, thanks to district heating, biofuel use and those heat pumps. The popularity of this technology gives incentives to laboratories to explore solutions in order to enhance its effectiveness.

In this project, the condominium’s GSHP performance is not as good as expected and showed by an unwished and significant amount of oil consumed by the back-up heating supply system. Thus this project, carried out in cooperation with local residents, aims at understanding the current system, running and analysis of data acquired from the field in order to optimize the existing GSHP and find explanations as well as recommendations for the system.

This installation has been run for 15 years but modifications are often applied to it. An explanation of the way the system is working was asked by the client and more especially a study of the oil burner behaviour was necessary. The objectives of the project were then to reply to these questioning as well as showing the way to deal with the system in the future.
2. Objectives

The objectives are the following:

1) Complete understanding of the current installation, the available measurement sensors and data acquisition system
2) Analysis of the data and evaluation of the performances of the system by constructing graph and durability diagrams:
   • How is the energy produced and used in the installation?
   • What is the impact of the oil burner on the system?
3) Emit suggestions to improve the system and provide a way to follow up later on.
3. Theoretical background

3.1. Ground Source Heat pumps (GSHP)

3.1.1. Heat pumps

In case of cooling or heating needs in a building, a heat pump system can replace a more conventional electrical/gas/oil heating or cooling system. Indeed space heating as well as hot water can be provided by a heat pump which is economically friendly. Moreover the renewable heat incentives provided in some countries and the reduction of CO\textsubscript{2} emission when this system is used makes the heat pumps a really common energy system all over Europe.

Basically a heat pump is using heat energy from a heat source and some electricity in order to provide heat energy at a higher temperature. A heat pump is composed of 2 heat exchangers (one evaporator and one condenser) separated by a compressor in one way and an expansion valve for the other one creating a cycle.

The refrigerant is the main actor in this cycle taking heat from the heat source and evaporating as a consequence in the evaporator. This cycle can be seen in the Figure 2 Heat pumps cycle. The pressure and the temperature of the refrigerant (saturated vapour) are then raised in the compressor part so as to have a superheated state and a higher temperature which can be used after in the condenser. The condenser is the place where the refrigerant releases heat to warm up water or air or whatever needed, here is the energy provided by the heat pump provided water or air at high temperature. To finish the cycle the refrigerant is then lead to an expansion valve where its pressure drops down reducing the temperature and making the refrigerant returning to its liquid form. The cycle is now completed.
Many different technologies are currently used as a heat source for the heat pump. Thus heat pumps using air, ground or water are the most used. More especially the air one is quite common in the ventilation system for its easy way of installation, its low cost and the possibility to use it for cooling as well as heating. The Figure 4 illustrates this point as heat is rejected at the condenser level (heating) and heat is removed at the evaporator level (cooling). The different technologies differ mainly in price and efficiency link to the COP of the installation which can be read below.

Concerning the efficiency a COP, also called coefficient of performance is introduced. The heat delivered by a heat pump is theoretically the heat provided by the heat source (ground, air....) and the electricity used to run the cycle. The performances of a heat pump are evaluated by using a COP. COP is defined as the ratio between the heat provided by the heat pump and the electricity used to run the cycle (compressor). This coefficient value depends on many factors as the refrigerant, the heat pump technology, the temperature used, the outdoor temperature, etc.

The refrigerant is an important factor in the installation. Chosen regarding its thermal properties it has to be adapted to the temperatures and pressures present in the heat pump. Indeed the refrigerant is the fluid which will be subjected to the cycle (Figure 4).

3.1.2. Geothermal heat pumps

GSHP also known as geothermal heat pumps is one of the best ways to produce heat considering and enviroronic point of view. The energy present in the earth comes initially from the sun. The main point here is to take into account the fact that the ground temperature remains almost the same during the year when it is considered some meters under the ground floor level.

GSHPs exchange heat with the ground by using buried pipes (Figure 5). A calorific fluid is then used to extract the heat. The heat can subsequently be used together with radiators, underfloor, ventilation, hot domestic water, etc. Such as other heat pumps do.
Concerning the properties of the fluid, it can be water or water with a percentage of ethanol. The efficiency of GSHPs is usually better than the other kind of heat pumps partly due to the fact that underground temperature is more stable and less sensitive to the seasons. The payback time of such installation is usually between 3 and 10 years, depending on how it is designed.

3.2. Durability diagram

This diagram is used for representing the power load in time. It is done by ordering the required values in either the ascending or the descending order in the vertical axis and with the amount of hours as a horizontal axis. This diagram can be used for representing any kind of demand fluctuating with time and the time scale on the horizontal axis can be chosen as big as wished by the user. This diagram will them represent the load and is a really useful tool for analysing system behaviour.

In this analysis the durability diagram is used for analysing the power load in the system and more especially the power supplied by the heat pumps and the oil burner over a year.
4. The system in Syrenparken

4.1. System: description

The condominium Brf Syrenparken, located in Saltsjöbaden (20 km from Stockholm) consists of 150 apartments, representing a total heated area of 14000 m² and around 120000 m³ tap hot water every year. A map of the different buildings and a view of the outside are given in Figure 6 Map of Syrenparken and Figure 7 View of some apartments at Syrenparken. The system has around 1800 MWh of heating demand every year (space heating, ventilation and tap water).

The heating system endured several transformations since the apartment block opened. Initially two boilers were providing the houses with the necessary heat. The oil consumption represented at this time around 200 m³ of fuel per year.

The condominium decided to implement a ground source heat pumps installation located in the 7th building so as to reduce this consumption. These modifications of the system occurred progressively since 1998 until last April.

In 1998 the system was upgraded to a hybrid one composed of two GSHP for a total heating capacity of 130 kW (65kW each) with a back-up oil fired boiler. The two heat pumps VP1 and VP2, connected respectively to 7 boreholes located in the nearby park, were intended to cover most of the heating demands. VP1 was mainly dedicated to tap water heating purposes while VP2 was connected to the ventilation system. The remaining burner was planned to be used only during peak hours. The oil consumption lessened by half to 100 m³. A second upgrade occurred in 2009 with the drilling of 12 new boreholes and the purchase of a new heat pump VP3 with a heating capacity of 146 kW. The oil consumption decreased to 60 m³. There is no forced recharging of the boreholes and the oil boiler is expected to work mainly during winter (October to March).

Earlier this year in mid-April 2013 some adjustments have been carried out. VP2 is no longer only allocated to ventilation purposes but also to water heating. This means that now the boiler is supposed to be turned on only when all heat pumps are at full capacity, which is not always the case. The fact the burner turns on at unwilling times is one aspect to tackle during the project and will be studied in the part concerning the oil burner experiment.
The localization of the boreholes can be seen on the Figure 8. Part of them has been implemented in 1998 close to each other while the digging in 2009 proposes boreholes more distant from each other. A east view of these apartment can be seen Figure 7. The impact on the boreholes field and the efficiency of it had been studied by a college Marc Derouet. As an example of documentation, a map giving the locations of set of boreholes drilled in 2009 is given in the Figure 8.
4.2. System: heat pumps and oil burner

The center of the installation is located in the building number 7 (Figure 9) where are present the different parts of the system. Thus the oil burner and the 3 heat pumps can be found directly in the basement of this building. The boreholes are implemented in 2 main areas and bring all the heat to the 3 heat pumps. The most recent heat pump VP3 is linked to 12 boreholes while VP2 and VP1 are linked to 14 other boreholes. An oil burner is turned on in October so as to provide the extra heat need during the winter. The installation is run by a control software built into the heat pumps, except for the oil burner. The oil consumption needs to be taken manually on oil tank gauge comparing the level of oil from one day to another.

![Figure 9 technical center](image)
Heat pumps

The activation of the heat pumps depends on the temperature differences between the temperature wished by the system and measured by the sensor on the hot side.

These sensors will be described later on and rule the whole activation of the system. Moreover these heat pump and especially VP3 can be deactivated when input temperature on the hot side is too hot. Figure 11 and Figure 10 Heat pump VP3 show respectively VP1 VP2 and VP3.

The order the heat pumps are turned on is not really defined and in general VP1 and VP2 will turn on faster than VP3 as it can be seen during the analysis (cf analysis of measure data).
**Oil burner**

The temperature wished by the system is calculated proportionally to the outside temperature. When the temperature measured is still lower than the temperature wished by the system the oil burner is turned on instantly without any waiting period. It is important to mention this point because this instant reaction of the system will cause some problems (cf the oil burner experiment).

The power provided by the burner (Figure 13) is usually around 200 kW. This step resulted in some perturbations for the heat pumps and a valve had been installed at the burner exit.

This valve is regulating the amount of water going through the oil burner in percentage of the total mass flow out of the heat pumps and can be seen in Figure 12 Oil burner Valve. But the issues linked to the oil burner are not totally solved and are discussed in the part concerning the oil experiment.
4.3. System: Tap water and water tanks

This part is composed of 2 heat exchangers, 5 hot water tanks and the output of the tap water. The heat exchanger, in the middle of the Figure 15, is close to VP1 which provides most of the heat for the tap water. This first heat exchanger warm the water from 10-20°C to a temperature around 40-45°C. The second heat exchanger on the bottom right is link to the superheated gas. The temperature of this gas is high (around 100°C) and permit the system to provide a 55°C tap water. The superheated gas is provided by the 3 heat pumps and is representing about 5% of the total power of the heat pumps.

Figure 14 Water tanks in series

The water is stocked in tanks connected in series (Figure 14 Water tanks in serie) except one. These tanks are usually at 40°C and the superheated gas is used for reaching 55°C which is the temperature choose by the condominium for tap water.

A valve is used so that the system could provide hot tap water in case of problem on VP1 or just if VP1 is not providing enough power. This valve can be seen in the Figure 15 Tap water valve regulation.

Figure 15 Tap water valve regulation
4.4. System: software and control panel

In 2009, a data acquisition and control system had been installed next to VP3 so as to monitor the installation and give some useful information to the technician in the installation. The software can be accessed by internet or directly on the screen at the installation site. A lot of different sensors (temperature, flow, etc.) can be found all over the network and are globally summed up in the software. This software is the interface used for collecting the data during the entire project.

4.4.1. Starting screen

The main page of the software shows the overall installation and gives information concerning the implementation of the different components of the system. The starting screen can be seen in Figure 16. The menu on the left can give access to the control panel, the flow, temperature and the energy data of the system. Some specific parts like the common areas (the restaurant and the garage) can also be directly seen in this menu giving the system organization in these specifics parts and measurement in real time.
Figure 17 Energy producers and users shows the different parts of the system. The energy outputs are the ventilation, the radiator and the tap water (on the right side) with the Input temperature and output temperature shown for each of them and the wished temperature from the system. The three heat pumps are linked to the system but are not in series nor in parallel on the hot side but a mix in between. Finally the oil burner is on the top left where information such as temperature in the burner and outside temperature can be read.
4.4.2. Valve and regulation system

The system is also used for showing the regulation of the different valves of the system. Indeed the different sources of heating power are linked to the same heating line which is then led to the 3 heating consumption outputs of the system and regulated by using valves. This can be seen in.

Thus we have:

1. Valve VS2-SV2 for ventilation
2. Valve VS1-SV1 for radiator
3. Valve OP-SV2 for tap water

These valves are linked to the temperature difference between the temperature wished by the system (in purple for the radiator and the ventilation) and the temperature measured just below each of them. These wished temperatures are proportionally linked to the outside temperature.

Figure 18 Valve regulation system
4.4.3. Sensor and data available

The sensors available are mainly thermometers and flow meters. The flow meters are only used for giving the volume of water per day in VP1 and VP2. The thermometers are present all over the system (see Figure 19 Sensors in the system). Some of them are directly linked to the regulation of the system (green ones at the bottom of the Figure 19).

![Figure 19 Sensors in the system](image)

Thermometer with wished temperature

Thermometer

Flowmeter
5. Analysis of measured data at Syrenparken

This analysis part is essential in the comprehension of the system so as to later conclude on its behaviour and to emphasize the eventual weaknesses as well as possible improvements. It is also replying to the mission given by the condominium to understand why the system is consuming more oil than expected.

5.1. Methodology

The following methodology had been applied so as to fulfil the objectives fixed by the condominium and KTH lab. Many of the steps have been performed in collaboration with Marc Derouet, another Master thesis student who was working on the behaviour of the borehole field at the installation.

This project can be separated into 2 periods for a total of 6 month, from October 2013 to March 2014. Indeed from October to December the project was carried on at the same time that my own master courses at KTH, meaning that only half of my time was spent on the project. This strategy is interesting because it allowed us to work during a period of 6 months which is relevant when we consider that the major modifications on the installation occurred in April 2013 and to follow up the whole winter season. From January to March 2014 the master thesis had been performed on full time basis.

The first step was to get in touch with the system and this understanding of the system followed me all over the master thesis work. Documentations from the heat pumps installers and the oil burner basic data were provided and required a long time of comprehension of the system and leading to many visits on site. It is one of the first analyses of such an installation and everything had to be performed, giving interesting info to KTH lab and sponsors as well as the condominium of the installation.

As said before the analysis of the installation, starting by collecting data, was performed at the same time than its understanding. This analysis was necessary to be able to take decisions and assumptions on the system and helping the understanding of the system. Moreover many meetings occurred with the condominium which was an important time to collect information concerning the action which could be done so as to make the analysis going further. The data available were:

- The oil burner given energy every month,
- The heat pumps given energy on daily basis
- The electricity consumption for the heat pumps,
- The power supplied by the heat pumps
- The volume flow per day in two of the heat pumps
- Many temperature sensors
- The time of activation of the compressors
The analysis led to some decisions concerning the way the energy in the system should be considered and finally a COP calculation has been performed leading to relevant tables of energetic data (electricity consumption of the heat pumps, flows in the pumps on the hot side, temperature all over the system, energy used by the radiators, ventilation and tap water, etc.) which now have to be analysed as well. An experimentation of one of the heat pumps has been performed by an external company providing some elements of comparison with our values and a final COP was decided for the 3 heat pumps.

Energy produced, used and energy balance were performed using graphs and durability diagrams so as to point out the different loads in the system and to emphasize the impact of the different heat pumps on the overall production of energy in the system. Thus, comparisons between heat pumps and oil burner heat production are presented. This analysis and some preliminary observations lead to a necessary study of the oil burner impact on the system. Indeed one of the heat pumps seemed to not work properly due to the relatively hot temperature provided by the oil burner.

The oil burner was then studied at the end of the master thesis in February 2014 to confirm first the behaviour of the system when the oil burner cannot be used as a back-up system and then to analyse the impact of when the burner is turned on and off on the heat pumps. The results are showing that one of the heat pumps is mostly impacted as well as some other part of the system and the heat pumps are not enough to provide heat at too low outside temperature. This confirms that the system needs to be improved and especially in its management of the energy. These improvements could permit the heat pumps to cover part of the oil burner energy provided with a better efficiency of the system and then a reduction of the oil consumption.
5.2. Measured data acquisition system

The collected data from the control system were the following:

- Oil volume consumed taken manually every month
- Electricity consumption on daily basis of the 3 heat pumps
- Outdoor temperature every hour
- Power of VP1 and VP2 every hour
- Volume flow in VP1 and VP2 on daily basis

These data were collected via a web interface linked to the system. They were then transferred into the software Microsoft Excel and were manipulated so as to be able to show graphs which can be seen in the analysis results. The table which can be extracted from the software can be seen in the Table 1, written in Swedish, the energy of the different heat pumps are written there on daily basis (for instance).

Table 1: Software: Energy table

<table>
<thead>
<tr>
<th>Uppmätta Energi-förbrukning/produktion Februari</th>
<th>16.02.2014</th>
<th>Diagram</th>
</tr>
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<tbody>
<tr>
<td>Förbrukad Total-energi VP1 VP2 VP3 2014</td>
<td>MWh</td>
<td>MWh</td>
</tr>
<tr>
<td>Producerad Total-energi VP1 VP2 VP3 2014</td>
<td>MWh</td>
<td>MWh</td>
</tr>
<tr>
<td>Förbrukad Vanné energi VP1 VP2 VP3 2014</td>
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<tr>
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<td>MWh</td>
<td>MWh</td>
</tr>
<tr>
<td>Förbrukad Kyl-energi VP1 VP2 VP3 2014</td>
<td>MWh</td>
<td>MWh</td>
</tr>
<tr>
<td>Producerad Kyl-energi VP1 VP2 VP3 2014</td>
<td>MWh</td>
<td>MWh</td>
</tr>
</tbody>
</table>

| 1 | 2.56 | 4.56 | 1.32 | 1.58 | 1.54 | 0.14 | 1.05 | 0.00 | 1.05 |
| 2 | 2.56 | 4.48 | 0.88 | 1.04 | 1.57 | 0.09 | 1.59 | 0.00 | 1.58 |
| 3 | 2.54 | 3.07 | 0.87 | 1.02 | 1.53 | 0.09 | 1.57 | 0.00 | 1.57 |
| 4 | 2.23 | 4.23 | 1.29 | 1.51 | 1.91 | 0.13 | 1.18 | 0.00 | 1.18 |
| 5 | 2.27 | 3.98 | 0.97 | 1.04 | 1.03 | 0.09 | 1.02 | 0.00 | 1.02 |
| 6 | 2.24 | 3.95 | 1.30 | 1.06 | 1.32 | 0.12 | 1.49 | 0.00 | 1.49 |
| 7 | 2.24 | 4.53 | 0.87 | 1.63 | 0.98 | 0.08 | 0.99 | 0.00 | 0.99 |
| 8 | 2.23 | 3.67 | 0.86 | 1.60 | 1.44 | 0.08 | 1.00 | 0.00 | 1.00 |
| 9 | 2.24 | 4.24 | 1.30 | 1.61 | 0.98 | 0.13 | 1.49 | 0.00 | 1.49 |
| 10 | 2.29 | 3.61 | 0.86 | 1.60 | 1.45 | 0.09 | 0.99 | 0.00 | 0.99 |
| 11 | 2.18 | 4.05 | 1.29 | 1.58 | 0.91 | 0.13 | 1.42 | 0.00 | 1.42 |
| 12 | 2.21 | 4.06 | 0.86 | 1.63 | 1.36 | 0.08 | 0.98 | 0.00 | 0.98 |
| 13 | 2.20 | 4.09 | 0.86 | 1.70 | 1.97 | 0.08 | 0.97 | 0.00 | 0.97 |
| 14 | 2.19 | 3.54 | 1.29 | 1.61 | 0.96 | 0.13 | 1.44 | 0.00 | 1.44 |
| 15 | 2.19 | 3.05 | 0.85 | 1.58 | 1.33 | 0.08 | 0.97 | 0.00 | 0.97 |
| 16 | 2.21 | 3.79 | 1.30 | 1.62 | 1.00 | 0.12 | 1.46 | 0.00 | 1.46 |
| 17 | 1.97 | 4.31 | 1.00 | 1.34 | 1.51 | 0.11 | 1.17 | 0.00 | 1.17 |
| 18 | 2.29 | 4.02 | 0.86 | 1.08 | 1.07 | 0.09 | 1.04 | 0.00 | 1.04 |
| 19 | 2.30 | 3.66 | 1.25 | 1.68 | 1.43 | 0.13 | 1.41 | 0.00 | 1.41 |
| 20 | 2.17 | 4.21 | 0.85 | 1.59 | 0.87 | 0.09 | 0.94 | 0.00 | 0.94 |
| 21 | 2.22 | 3.98 | 0.86 | 1.03 | 1.59 | 0.09 | 0.98 | 0.00 | 0.98 |
| 22 | 2.08 | 3.40 | 1.28 | 1.62 | 0.06 | 0.13 | 1.33 | 0.00 | 1.33 |
| 23 | 2.17 | 3.45 | 0.84 | 1.05 | 1.39 | 0.09 | 0.79 | 0.00 | 0.79 |
| 24 | 2.13 | 3.31 | 1.27 | 1.57 | 0.80 | 0.13 | 1.24 | 0.00 | 1.24 |
| 25 | 2.20 | 4.19 | 0.85 | 1.60 | 0.97 | 0.09 | 0.97 | 0.00 | 0.97 |
| 26 | 2.19 | 3.99 | 0.85 | 1.57 | 1.36 | 0.08 | 0.97 | 0.00 | 0.97 |
| 27 | 2.21 | 3.74 | 1.29 | 1.61 | 1.01 | 0.13 | 1.45 | 0.00 | 1.45 |
| 28 | 2.01 | 4.26 | 0.78 | 1.01 | 1.29 | 0.07 | 0.85 | 0.00 | 0.85 |
| Total | 62.55 | 111.53 | 28.99 | 40.21 | 34.63 | 3.00 | 32.06 | 0.00 | 32.06 |
5.3. Calculation method

5.3.1. COP of VP1 & VP2

Some major modifications occurred in April 2013 changing the way VP2 is used. Indeed now VP2 is not linked to the ventilation anymore but all the system can provide heat to this specific output due to a modification in the pipes. The analysis showed that the power given by the software before mid-April 2013 were abnormally high and the COP resulting was too high as well (around 5-6). For calculating the COP of VP1 and VP2 together we took the power from mid-April 2013 to mid-March 2014 and approximated the month remaining so as to have one year COP represented in the Figure 20 COP of VP1, VP2 and VP3.

5.3.2. COP of VP3

Concerning VP3, the software does not give access to the power supplied so the Carnot efficiency was first applied:

\[
COP_{\text{carnot}} = \frac{T_1}{T_1 - T_2}
\]

Then a constant coefficient \( \eta \) is calculated so as to represent the real system:

\[
COP_{VP1\&VP2} = \eta * \frac{T_1}{T_1 - T_2}
\]

This coefficient has been calculated using the measurement performed by the company ETM on VP3 finding a coefficient:

\[
\eta = 0.4548
\]

This value is quite low and result in a COP around 2.5 instead of 3 as it is written in the heat pump datasheet of the company providing it. We applied the COP equation to the domain we knew the values of T1 and T2 which is from November 2013 to March 2014. We then had a look to the trend line linking the temperature in the boreholes and the COP so as to deduce the COP from September till November 2013. We assume a symmetric behavior of the curve and also use the behavior of the COP of VP1 and VP2 so as to deduce a trend line for the COP of VP3 in 2013 which will is then consider the same every year. This results in the Figure 20 COP of VP1, VP2 and VP3.
5.3.3. Results

![Figure 20 COP of VP1, VP2 and VP3](image)

For both of them, the curves are low during winter and summer and getting their maximum in the two other seasons. This seems reasonable considering the low load in summer and will now on been considered for all the period before April 2013. The data after April 2013 will be taken directly in the energy production of the software as they are considered accurate since this last major modification of the system.

This model has some limitations. Indeed this COP depends on the day of the year and the outside temperature but doesn’t take into account the load of the heat pumps. Thus this COP is a bit overestimated at high loads because the electricity consumption is higher than on the constructor data. This models shows higher power calculated for VP1 and VP2 when these later are at full load.
5.4. Energy production

The energy production logically comes just after the COP determination. By using the electricity consumption of the heat pump, which is considered accurate, the COP factor is applied resulting in the energy production for each heat pump. The equation below is used for VP1, VP2 and VP3 for every value before April 2013. This part of the analysis is performed with an assumption on VP2. Indeed for 2013 the data from the website are taken as energy production every day and before April a calculation is performed for having the real energy production of VP2.

\[ Q_{heating} = COP_{heating} * Q_{elec} \]

The oil burner has been added so as to compare it to the energy produced by the heat pumps (Figure 21 Energy monthly produced in 2013 by the 3 heat pumps and the oil burner). The consumption for the oil burner are collected on monthly basis and can be seen in the Table 2. The data from the oil burner has been collected from the documentation of the condominium and the following equation has been taken into account:

\[ P_{oil\ burner} = \rho_{oil} * LHV_{oil} * \dot{m}_{oil} * \eta_{burner} \]

In this equation:
- \( \rho_{oil} \) = 0.89kg/L density of the oil
- \( LHV_{oil} \) = 44MJ/Kg is the low heating value of the oil
- \( \dot{m}_{oil} \) = volume flow of the oil taken manually
- \( \eta_{burner} \) = 0.95

The efficiency of the oil burner had been calculated considering the data from the company providing the oil burner. This efficiency was then considered to be 95%.

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<td>oct-13</td>
<td>3</td>
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<tr>
<td>nov-13</td>
<td>4,8</td>
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</tbody>
</table>

Table 2 Oil burner consumption every month in 2013
The results for the years 2013 are shown monthly in the Figure 21 Energy monthly produced in 2013 by the 3 heat pumps and the oil burner. The heat pumps VP1 and VP2, both of them having a heating capacity of 65 kW, are showing similar result when VP3 (heating capacity of 146 kW) produced twice more energy than the first heat pumps. The first observation underlines the fact that VP3 is producing energy in a logical scale (twice more at least than VP1) when the load in the system is high enough, i.e. during winter time.

It can be seen that the oil burner is used more than it should be, and it represents 450 MWh per year for a total consumption of 1750 MWh. Thus the oil burner is providing 25% of the total energy per year. This phenomenon is really present at winter time and can be seen in the Figure 22 Energy monthly produced in 2013 by the heat pumps and the oil burner. Indeed the oil burner is providing almost 40% of the energy on January 2013 which represent a huge consumption of oil at this time.

It can also be noticed that the oil burner is used in months like April, May, June, September and October while the heat pumps should be enough for providing the heat required by the installation of the condominium. This is potentially linked to the too fast activation of the oil burner explained before and which will be described later on.
5.5. Energy balance of the system

As said before the output going to radiators, tap water and ventilation are regulated by a valve system. No sensors are installed on this side of the system except for a thermometer, so the energy production has been used for the system as energy consumption following the equation below:

\[
E_{VP1} + E_{VP2} + E_{VP3} + E_{oil} = E_{domesticwater} + E_{radiator} + E_{ventilation}
\]

- \(E_{VPX}\) is the energy provided by the heat pump \(X\) in MWh
- \(E_{oil}\) is the energy provided by the oil burner in MWh
- \(E_{domesticwater}\) is the energy used for warming tap water in MWh
- \(E_{radiator}\) is the energy used for space heating via the radiators in MWh
- \(E_{ventilation}\) is the energy used in the ventilation system in MWh

The valve and Delta T present on the radiator and ventilation side allow us to do some assumptions concerning each of their impact on the energy consumption. The system has been considered to use the same quantity of energy all year concerning the tap water. Using summer time it had been deduced that
the tap water consumption is around 21kW. All these assumptions result in the Figure 23 Energy monthly used in 2013 per domain.

The tap water remains constant and the ventilation is not using a lot of energy due to the modifications in April 2013. It logically results in the fact that most of the energy is used for space heating via the radiators system.

![Energy balance 2013](image)

**Figure 23 Energy monthly used in 2013 per domain**

In 2013 the radiator represents 1300 MWh, i.e. around 75% of the heat consumption in a year. On the other hand the ventilation represents 200 MWh and impact lightly the consumption. It appears that the improvements should be focused on the radiators system because of its huge impact on the energy consumption and could result in major modifications in the behavior of the system.
The Figure 24 Energy monthly produced and used in 2013 shows how energy is distributed in the system. Once again most of the consumption is used by the radiators (75%) and, as it can be seen in this same figure, the heat pumps seem not enough for providing heat during the winter even just for the radiator.

All these energies are summed up in the Figure 25 Energy produced and used per sector in 2013 showing the different heat pumps and the oil burner but also the energy used.
These results give a good overview of the system behavior and the energy distribution in the system but the peak load are not present. An analysis showing these peak loads had to be performed resulting in the utilization of durability diagrams for the heat pumps and the oil burner.
5.6. Durability diagram

Durability diagrams based on the data taken from the energy production every day have been built. The step of each data is then 24 hours for the heat pumps since the data are collected on a daily basis. However, the results are showing slightly lower curves than it should be for the oil burner. The peak loads are shown properly because during the day with the highest load the heat pumps are working almost 24h a day but the curves do not become totally accurate when it comes to lower loads in the system.

Concerning the oil burner, a two-step behavior had been considered following the information given by the condominium. A linear approximation had been applied so as to give an aspect of the curve closer to reality. The oil burner had to be considered more as energy produced than as peak load. Indeed the peak loads are not really well represented because of the data available. The consumption on monthly basis is not showing the peak loads. But one peak of consumption had been recorded during 16h gives a good idea of the behavior of the oil burner when it is at the maximum power. Moreover the valve is changing the way the oil burner energy has to be considered. Finally the oil burner curve has to be taken as an area representing the energy used by the burner.

These curves can be seen independently below in the Figure 26 Durability diagram for the heat pumps and the oil burner in 2013, the outdoor temperature had been added so as to perform an analysis of the system behavior versus the outdoor temperature.
The results for VP1 and VP2 are:

- The maximum load of 180kW is impossible and these high values concern the first 700 hours of the year which is linked to the limitation of the COP model.
- The total running time can be considered as all year because VP1 is linked to the tap water production and is used all year.
- The total energy produced in a year is 670 MWh for the year 2013 (dropping to 650 MWh if the power over 130 kW are cut to 130 kW representing a variation of 3%)

The results for VP3 are:

- The maximum load is around 160 kW slightly higher than 146 kW but acceptable this time.
- The total running time is a bit higher than 6000 hours a year confirming that VP3 is almost not used for tap water so not working at summer time.
- The total energy produced is 590 MWh in 2013 which is lower than VP1 + VP2 but due to the fact that VP3 is more used at high loads.

The results for the oil burner are:

- Total running time of around 3500 hours per year which is high for a backup system
- The total energy produced is 455 MWh per year

It can be seen on the graph that the activation of the oil burner (3500 hours) matched with and outside temperature of around 4°C. This temperature is the outside temperature which causes the activation of the oil burner. If the outside temperature is below than 4°C the heat pumps seems not enough for providing heat to the system. This 4°C can actually be seen in the appendix 2.

![Durability diagram power production](image.png)

**Figure 27 Area durability diagram of heat pumps and oil burner in 2013**
The durability diagram can also be used by adding the curves and showing the area matching with the different actors. In Figure 27 Area durability diagram of heat pumps and oil burner in 2013 the energy producers are added and give a relevant view of the system. The different areas represent the energy provided by the different components and the results of this graph are:

- The maximum heat load in this installation is around 550 kW which is possible but probably lower than reality due to the model of the oil burner behavior.
- The heat pumps heating capacity is 276 kW
- The oil burner behavior is not the one wished by the system due to the model but also due to the too fast reply of the system.

Most of the energy is used in the radiator system (74%) as it can be seen in Figure 28 Energy used per domain in 2013. The ventilation and the tap water represent 12% and 14% of the energy used in the buildings, respectively. Indeed, the high loads impact the system by imposing a high delta T between the input and the output of the radiators. This high delta T cannot be reached by the actual configuration of the heat pumps. Moreover this system had been originally designed for oil burner with high delta T which is not fitting with the use of heat pumps as it will be seen in the next section (oil burner experiment part).
6. Oil experiment

This experiment occurred because of the obvious influence of the oil burner on the energy balance. One of the first observations was the oil burner impacts the compressors behavior of VP3 leading to an average of 1h/day off for VP3 during the winter. The experiment was run in February 2014 with low outside temperature (lower than the 4°C seen before).

6.1. Objectives

The objectives were the following:

1) Observe the system behaviour with and without the oil burner
2) Identify the impacts of the oil burner on the system
3) Analyse the result so as to find information linked to the high consumption of the oil burner

6.2. Methodology and conditions

The experiment had been performed in February 2014. This month had really cold outside temperature in a range from -2°C to 8°C and the heat pump system is not able to provide the full heating need for an outside temperature below 4°C. The conditions for this experiment are then perfect for analysing the impact of the deactivation of the oil burner on the system behaviour. The oil burner had been turned off and on following the schedule:

- OFF from the 5th of February at 7:00 until the 10th of February at 15:00
- ON for legionella reason from the 10th of February at 15:00 until the 11th of February at 7:00
- OFF from the 11th of February at 7:00 until the 17th of February at 15:00
- ON for legionella reason from the 17th of February at 15:00 until the 18th of February at 7:00
- OFF from the 18th of February at 7:00 until the 21st of February at 6:30
- ON the 21st of February at 6:30 replying to a need from the community
- OFF from the 24th of February at 20:00 until the end of February

Only the oil burner had been turned off, no further modifications concerning the valves system had been done. The weekly activation of the oil burner is necessary because the system had to be heated until an extra high temperature (for legionella reasons, i.e. not reachable only with the heat pumps). The last OFF period is interesting because it is following a slightly longer ON period and is really reflecting the behaviour of the system when the oil burner is suddenly not working anymore.
6.3. Input data: data used

This experiment had been run in February under the lead of the condominium and the technician of the installation. The oil burner was already a cause of malfunctions in the system and the valve installed at its output was not enough to tackle the entire issue. The data extracted from the system were the following:

- On and Off of the compressors for VP1, VP2 and VP3
- Temperature inlet and outlet on the hot side for the three heat pump
- Mass flow on the hot side for VP1 and VP2 on daily basis
- Temperature set point and measured for the inlet of the ventilation and the radiator (appendix 4 Temperatures collected from the ventilation system)
- Temperature measured for the outlet of the ventilation and the radiator
- Outside temperature
- Temperature set point and measured for the outlet of the heat exchanger for the tap water (appendix 1)
- Temperature in the water tank
- On and Off of the second step of the oil burner

These data had been extracted during February 2014 and treated on Microsoft Excel. One of the part of a table can be seen in table 3. The step chosen was half an hour for giving a precise view of every moment of the system.

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</table>
6.4. Results and analysis

6.4.1. Energy used

As said in the analysis above, the heat pumps alone are not supposed to be able to provide enough heat for an outside temperature under 4°C which was the case most of the time in February.

6.4.1.1. Radiator

Figure 30 Temperature data of the radiators system in February 2014 shows the impact of the oil burner turned off and on during February 2014. The data had been collected at the input and output of the radiator side and can be seen in the appendix 3. The outside temperature is also taken from the system and can be seen in appendix 4. Moreover the on and off period of the burner can be seen on top of the graphic for a better visibility.

The first thing which can be noticed is the instant drop of temperatures measured on the inlet of the radiator. The temperatures measured and desired are supposed to be the same if the system is run properly. This instant drop is illustrated by a delta T of around 5°C between the wished and the measured temperature. The 3 heat pumps seem to not be enough to provide all the required heat in such conditions.

The outside temperature is slightly lower than 4°C in the two first “OFF periods” but it can be seen that the delta T between desired and measured temperature is getting low when the outside temperature is rising. This can be seen on the day 10 and 25 where the delta T is falling to 1°C at night time. Another
aspect is the apparition of temperature oscillations corresponding to the day and night time for the measured temperature. The temperature wished by the system is not reached but the delta T is getting lower at night time due to the low consumption of tap water and the reduction of air movement cooling the system by opening doors for instance.

6.4.1.2. Tap water

Figure 31 Temperature data of the tap water system in February 2014 presents the impact of the oil burner on the tap water side. The temperatures are taken at the output of the heat exchanger between the tap water system and VP1 and the rest of the heating system and can be seen in the appendix 1. The tank temperature is also taken in order to check the proper functioning of the water tank system.

![Temperature data of the tap water system in February 2014](image)

This time, the set point and measured temperature remains really close to each other. This is due to the fact that the tap water system is the first to receive heat. Hence the tap water is considered as a priority of the system, providing then 55°C tap water to the users in every condition. Moreover the tap water system only represents 21 kW and VP1 is mostly linked to it. Thus with 65 kW heating capacity it seems logic that the tap hot water system is not having so much problem with the deactivation of the oil burner.

However the temperature in the tank is dropping a lot from 40°C to 8°C during day time and is refilled at night time. The system is not filling the tank with hot water after the water is used in the morning. This massive drop of 32°C is too high for such a system and the temperature in the tank should not be under 20-25°C. Once again this behaviour can only be noticed when the oil burner is off and is not existing when this later is turned on.
6.4.1.3. **Ventilation**

In the Figure 32 Temperature data of the ventilation system in 2013 is shown the reply from the ventilation side to the activation and deactivation of the oil burner. The outside temperature is present again and this graph can be compared to the radiator one.

The delta T between measured and desired temperatures exists at the same periods than for the radiator but, this time the delta T is lower and around 2 to 4°C. Moreover the outdoor temperature around 4°C allows the system to reach sometimes the desired temperature contrary to the radiator case. Thus during the days 9, 10 and 25 when the oil burner is off the heat pumps system can provide enough heat during short periods.

These graphs confirm the fact that the heat pumps are totally overwhelmed by the heat loads when the outside temperature is under 4°C.

6.4.2. **Energy produced**

The first observation was the impact of the oil burner on the heat pumps system creating problem of too high inlet temperature and drop of heat production. This part presents the impact of the oil burner on VP1, VP2 and VP3.
Figure 33 heating Power of the three heat pumps in February 2014 illustrates the heating power of the three heat pumps in February 2014. The heating powers are calculated with the COP presented above and the electricity consumption for VP3, and are directly taken from the software data for VP1 and VP2.

Concerning VP3 the drop of power is obvious on the 4th of February and the power is falling from 150 kW to 120 representing a drop of 20%. This huge drop is actually a drop in electricity consumption from 60 kW to 55 kW approximately when the nominal electricity consumption of the pump should be 50 kW (nominal value from the datasheet). This variation is more a variation in electricity consumption and the temperatures on the hot side of VP3 dropped from 44 °C to 35 °C. The heat pump is working in new and different conditions and the value cannot be totally trusted. However, this drop remains a point which should be studied further by installing accurate sensor on site. Moreover the power fluctuations seen for the period the oil burner is on are due to the deactivation of some compressors of VP3 and are studied further in the compressors behaviours part.

The drop can also be seen for VP2 falling from 80 kW to 50 kW. This phenomenon shows a problem in the installation. It shows that the way the installation is run has a noxious impact on the heat pumps. The results for VP1 are not really clear but will be studied by using the volume flow.

The volume is measured in the inlet of VP1 and VP2 on daily basis but the full activation of these later as it will be seen in the compressors part provides a relevant curve as it can see in the Figure 34 Water flow on daily basis of VP1 and VP2 in February 2014.
The results are showing a clear drop of the flow when the oil burner is off. This drop results from the opening of all the valve of the system and especially the one leading to the radiator (VS1-SV1), the ventilation (VS2-SV1) and the tap water (OP-SV2). This data will be then used with the temperatures on the inlet and outlet of both heat pumps so as to represent the power supplied by each of them. The following equation is then used:

\[ P = \dot{m} \cdot C_p \cdot \Delta T \]

- \( P \)  Power in kW
- \( \dot{m} \)  Mass flow in kg/s
- \( C_p = 4.2 \text{ kJ/kgK} \) specific heat of water
- \( \Delta T \)  Temperature difference between the outlet and the inlet

The delta T of VP1 can be seen in the Figure 35 Delta T and mean power of VP1 in February 2014 and the mean powers are also presented.
The delta T is rising when the oil burner is turned off which balances the drop in mass flow seen above. Indeed the power supplied is higher when the oil burner is off but the results are not flagrant because the link between the heat pump and the tap water system is making the curve less relevant.

The similar graphs for VP2 are presented in Figure 36 Delta T and mean power of VP2 in February 2014.

The delta T is fluctuating more but gets lower in average, emphasizing even more the drop of power in VP2. The drops are obvious when the oil burner is turned on and come back to the initial value when the oil burner is on again for a time long enough as it can be seen on the 25th. This result confirms the one seen in Figure 33 heating Power of the three heat pumps in February 2014, showing again the abnormal impact of the oil burner on the heat pumps system.
6.4.3. Compressors behaviour

One point which was manifesting the wrong utilisation of the system is the possibility to have the oil burner running even if the compressors of the heat pumps are not all working. This phenomenon had been observed many times and is particularly impacting VP3 as it can be seen in appendix 5. Here one of the compressors of VP3 is not working even if the set and measured temperatures are not the same and the oil burner is still providing heat to the system.

The data had been taken directly on the software on each of the compressor independently. The appendix 6 illustrates how the data are extracted from the software. The data extracted were then computed on Microsoft excel so as to give the following relevant data:

- Time of inactivity of the compressors during the off period of the oil burner
- Time of inactivity of the compressors during the on period of the oil burner
- Forecast of the activations of the compressors

A part of the table resulting of this can be seen below in the table 4 Part of the table of the 1st compressor data of VP3. Here the off time is representing the quantity of time the first compressor is off between 2 activations of this later.

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The common hours and off time forecast are used to analyse all the compressors together on a same scale and the results for the 4 compressors of VP3 are shown in Figure 37 Compressors of VP3 activated
during February 2014. The negative values on the horizontal axis are due to the fact the data begins in January.

This graph underlines the obvious impact of the oil burner on VP3 and confirms the first remarks. Indeed many fluctuations in the activation can be seen when the oil burner is on and are especially apparent on the 10th and 17th of February day of the legionella activation. This phenomenon represents an average of 1 hour per day lost because the compressors are turned off. But the deactivation of these compressors means that the inlet temperature of VP3 is too high and VP3 is then not used in its nominal condition.

On the other hand the four compressors are constantly at full power during the two first long OFF period of the oil burner. This is particularly noticeable as this full activation for such a long time never happened before. The oil burner is making the compressors of VP3 turning off. But the oil burner is not impacting the other heat pumps in such a significant way.

The data of the compressors of VP1 and VP2 are giving totally different results. Indeed VP2 compressors had been activated since the 9th of January without any interruptions in February. The consequence of the oil burner on the compressors of VP2 is not visible and can be consider as negligible. This is a huge contrast with the behaviour of VP3’s compressors.

Finally the compressors of VP1 are turned off during 20 minutes per day in average and this value remains the same whatever the oil burner is turned on or not. VP1 seems totally independent from the oil burner impact on the system. This is due to the link between VP1 and the tap water system said above which remains the priority when the overall heat loads are not reached by the heat pumps.
7. Conclusion

The recent modifications of the system had made the radiator the main energy usage representing 74% of the total energy demand in a year. The ventilation had been changed in April 2013 which makes the radiators system one of the main concern for the condominium. Moreover the radiators are using a high delta T originally designed for oil burner which can explain the current problems on the installation.

The oil burner is more used than it should be, representing 450 MWh (25% of the year energy production). This phenomenon is really present at winter time. Indeed the oil burner is providing almost 40% of the energy on January 2013 which represent a huge consumption of oil at this time. But the oil burner is used in months like April, May, June, September and October. The heat pumps are supposed to provide enough heat to deal with the installation needs during these month and point out the too fast activation of the oil burner.

The heat pumps remain not enough for dealing with the heating demands in the system with a cold outside temperature. This fact is demonstrated with the durability diagram but also with the results of the oil burner experiment. The oil burner experiment emphasizes a massive drop of temperature in the water tank during the morning which is rising again only at night time. The system without the oil burner is not filling the tank with hot water after the water is used in the morning. Finally the heating capacity of 276 kW of the three heat pumps is slightly higher than 50% of the total heating capacity which is low.

Some problems in the management of the energy in the system were observed. The oil burner is impacting the heat pump VP3 and VP2. Thus VP3 has a lower power during the activation of the oil burner and can even be partly turned off during the activation of this later. VP2 sees its power dropping when the oil burner is on, a phenomenon which should not occur.

This master thesis ended with discussions between KTH lab, industrial and the condominium leading to interesting propositions of optimization of the current system. The final discussion was especially captivating all the different actors present which make the project really pleasant to perform. Further analysis will be achieved on this installation in collaboration with KTH Lab.
8. Suggestions of improvements

The temperature level on the radiator side can be reduced by using a higher mass flow or increasing the efficiency of the system by modifying directly the radiators.

The impact of the oil burner on VP3 and VP2 had been limited by the valve OP-SV3 but another solution should be added. The oil burner is reacting too fast and a delay of activation could be put in the system. A modification preventing the burner from working when the 4 compressors of VP3 are not on could solve this problem.

The sensors system could also be considerably improved. The data are only taken from the energy produced. Sensors measuring the energy used in the radiators, ventilation and tap water would give a valuable improvement in the monitoring of this installation.
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CLIMAPAC LCW-P.Z Värmepump Vatten/vatten 40-300 kW R407C, info@climapac.com

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