Internship Report

Zero Net Energy Project

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Internship Report

Internship Details

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Location: Deventer, Netherlands   Internship Duration: 11/09/2017 – 08/12/2017

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Summary

The purpose of this report is to present all the tasks I carried out and activities I was involved in during my internship with Bosch in Deventer. Bosch is working towards introducing a cutting-edge product, also known as the Energy Bar, for consumers to be in line with a goal of the Paris Agreement, stating that all residential buildings should be energy neutral by 2050. That means that all houses, in 2050, must be able to locally produce all the energy they consume within the course of a year, in order to gradually become eco-friendlier and less dependent on the grid's energy supply. Other companies, much like Bosch, view this as a great opportunity to acquire a piece of a new market that is expected to grow within the next years. My role was to provide all-around help to the team that was in charge of this project and speed up the process of introducing the Energy Bar to the market. The report basically describes all my learning experiences which ranged from conducting research to running simulations/tests as part of Bosch's Zero Net Energy Project. However, since supply of the product to the market is yet to be underway, and because some areas of the product are still under development, limited information about Bosch's Energy Bar will be disclosed due to a confidentiality agreement signed between the company and myself. As a result, some data and results, although mentioned throughout the report, might not be presented in detail.

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Nomenclature

α	Correction factor for convection and inaccuracy in implementation	P	Pressure
η	Efficiency	PHE	Plate heat exchanger
		Q	Power Factor
λ	Heat conductivity coefficient	Q_{HP}	Heat output
ϱ	Density	Rc	Heat resistance value
φ	Volumetric flowrate	Rm	Heat resistance of the separate layers
CH	Central heating	Rse	Heat transfer resistance surface exterior
COP	Coefficient of performance	Rsi	Heat transfer resistance surface interior
dB	Decibel	r	Distance from source
d	Thickness	SPF	Seasonal performance factor
DCW	Domestic cold water	T	Temperature
DHW	Domestic hot water	W_{HP}	Power drawn
L_P	Sound pressure level	$W_{HP(annual)}$	Total electricity consumed by a heating system in a year.
L_{PAeq}	Sound pressure level **EQ**		
L_W	Sound power level		
L_{WAeq}	Sound power level **EQ**		

Introduction

In the year 2050, all households of countries following the Paris Agreement must be climate neutral, meaning that the existing housing stock must be modified to accommodate systems that generate on site all the amount of energy consumed by the building and its users on an annual basis. Hence the concept of 'Zero Net Energy (ZNE) Buildings' which describes houses that have undergone changes to be able to abide by the aforementioned law. Steps of a ZNE renovation usually consist of adding extra insulation to reduce heat losses, installing PV panels for electricity production and implementing energy efficient devices for DHW, CH and ventilation. Bosch envisions a single cohesive system that will be able to embody those steps whilst creating a comfortable setting for the residents.

Bosch's Energy Bar is an integrated and innovative construct which is assembled by combining solutions tested by Bosch. Consequently, my work initially focused on learning everything about the individual components that form the Energy Bar and the factors that influence its operation. In addition, because products like the Energy Bar have to undergo a number of tests, to guarantee they meet certain standards set by numerous entities, I ended up working on concepts such determining the minimum heat resistance required from a wall layer to accommodate the Energy Bar and testing the noise produced by the system during full operation. In any case, I feel that Bosch really gave me a chance to have an active contribution in one of their upcoming products and helped me gain invaluable experience. The following sections hopefully provide an adequate level of information to support my claim.

Essence/Activities

Heat Pump Theory

Before arriving at Bosch my knowledge surrounding heat pump systems was very basic. But, because heat pumps are of the most important constituents of the Energy Bar, and significant products of the Bosch brand, I went from knowing that 'heat pumps use the temperature gradient between two sides to transfer heat to a desirable area' to learning about the heat pump refrigerant cycle, the heat pump's main compartments and all the factors that affect a heat pump's operation.

Heat pumps, those providing CH and DHW services, operate on the vapor compression cycle. That means they make use of one or more refrigerants with useful thermodynamic properties. A simplified air-to-water domestic heat pump system is shown by Figure 1.

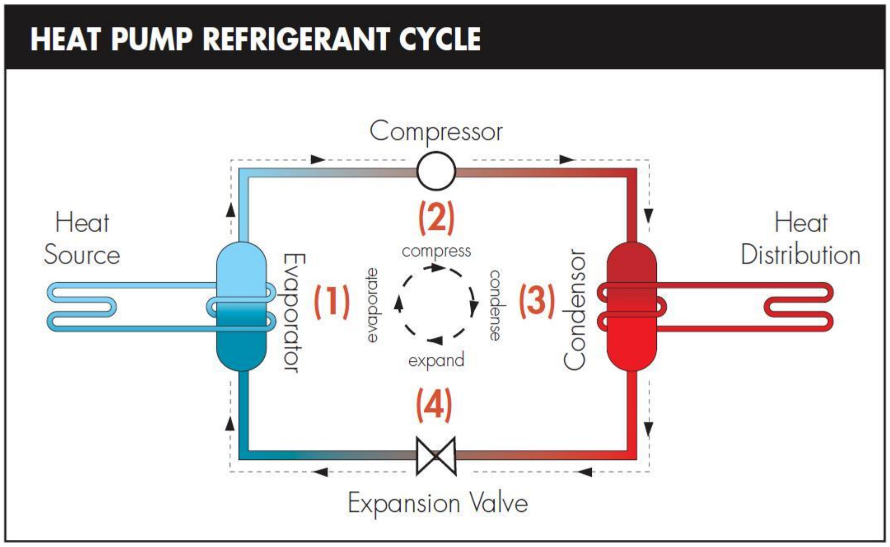


Figure 1: Idealized (reverse Carnot cycle) heat pump cycle

Suppose an air-water heat pump like the Nefit VentiLine VA/W 1.4C model is installed in a house. Air from inside the house would be directed to the evaporator through a fan. A portion of the refrigerant flowing evaporates and moves in the compressor where the refrigerant fluid's temperature and pressure increases. The outlet hot fluid then moves to the condenser and it transfers heat to the water that, depending on the system configuration, is used for CH and/or DHW. The now cooled down refrigerant liquid passes through an expansion valve, or a similar instrument, that decreases its pressure. Finally, the refrigerant moves through the evaporator where the cycle can start over again.

Lastly, an important aspect of heat pumps I learned about was their performance. Heat pump performance, or rather heat pump efficiency, is expressed using the COP, SPF and the system efficiency parameters. COP is the most common method of evaluating instantaneous heat pump efficiency;

$$COP = \frac{Q_{HP}}{W_{HP}} \quad (1)$$

The difference between COP and SPF is that the second focuses on the efficiency of the system for a defined period of time. So for a system like the Energy Bar, that aims to provide energy neutrality within the course of a year, SPF would be calculated after reaching a year of operation.

$$SFP = \frac{Q_{HP(annual)}}{W_{HP}(annual)} \ (2)$$

● Heat Pump Training

Knowing the theory surrounding heat pumps, although indispensable, is not enough to fully comprehend and work around a heat pump. Bosch realizes that, and that is why I received 'heat pump training' to learn heat pumps inside out, literally. In general, the operating principles of heat pumps are the same. The only things that may change are the heating source used and the structure of the system. There are three types of heat pumps: air-to-air, air-water, and ground source (geothermal). In terms of structure, heat pumps can be classified into split and mono(bloc). In the former, the main components of the heat pump, mentioned in the section above, are split into two subsystems, usually known as the outdoor and indoor unit; In this case, the outdoor unit usually contains the evaporator, the compressor and the expansion valve whilst the indoor unit contains just the condenser. The latter accommodates all the components under one large casing.

Figure 2: Nefit VentiLine VA/W 1.4C

As part of my training session I interacted with a number of different models like the Nefit VentiLine and the Nefit EnviLine Spit. I got the chance to understand why each version is unique, in terms of their hydraulic design and operation principles, and appreciate how small modifications make systems differ from each other.

● Boiler Theory

The Hybrid Version of the Energy Bar uses a combi boiler to do the 'heavy lifting' and supplement the heat pump whenever there is a large heating demand. This might render the Hybrid Version less eco-friendly than the All-Electric Version, since with every gas fired appliance come CO_2 emissions, however is it emphasized that the boiler is activated only to cover the extra demand of CH and DHW. Moreover, because the gas consumption and the resulting CO2 emission are compensated by the extra supply of solar electrical energy to the grid, the overall CO2 balance will be neutral over the year, assumption that the power plant will reduce its yearly supply of electrical energy.Since the average user has associated the process of heating with a domestic gas fired appliance, the boiler feature offers the consumer a sense of familiarity to the Energy Bar whilst enabling the building to achieve

Figure 3: HRC 24 CW 4

energy neutrality within the course of a year. Be that as it may, acquiring some knowledge about boilers in general helped me better understand the Energy Bar's operation and made the simulation of such systems a lot easier.

Focusing on the Nefit Proline NxT HRC 24/CW4 (Figure 2) model I found out the term 'combi' refers to boilers that are water heaters fueled by natural gas or oil and are able to contribute to both the CH and the DHW. I also learned that the depicted boiler of Figure 2 is a condensing boiler and its' main constituents include; a burner, a primary heat exchanger and a secondary (condensing) heat exchanger. Condensing boilers in general tend to achieve efficiencies(η) as high as 95% (H_s) by condensing water vapor in the exhaust gases, and thus recovering its latent heat of vaporization, which would otherwise be wasted.

Perhaps everyone can attest to what a boiler does. However, only by breaking down the steps of its operation was I able to really appreciate the engineering work behind it. Fuel is burned and the fumes (flue gas) produced pass through a heat exchanger where most of their heat is transferred to water. A pump then pushes the hot water which is used for CH and/or DHW. The difference between a condensing and a non-condensing boiler system lies in the heat exchanger condensate drainage system which exists in the former but not in the latter.

Almost all boilers have modulating burners that are usually controlled by an embedded system with built in logic. Moreover, a common feature among boilers is using aluminum alloys and/or stainless steel to cope with high operating temperatures and the acidic condensate.

● Heat Resistance

The Energy Bar is a system that heavily relies on efficient heat transfer between its components and the interior of the building it operates for. The Energy Bar is also designed to be integrated to the exterior of buildings, by being mounted to the facade, thus making it easier for maintenance and repairs to take place without troubling the life going on in the interior. The Energy Bar's casing is primarily made out of regular steel, which is a good conductor of heat, and forms a thermal bridge (or heat bridge) creating a path for heat transfer. In simple terms, this phenomenon provides an alternative path for heat to be transferred outside the house and thus might lead to significant heat losses.

Estimating the overall surface heat transfer value or Rc-value of the energy bar is very important to determine the minimum heat resistance value that the house layer should have in order to refrain from having significant heat losses because of the Energy Bar. The Rc value was computed using the following equations.

$$Rc = \frac{\sum Rm + Rsi + Rse}{1+\alpha} - Rsi - Rse \quad (3)$$

$$Rm = \frac{\text{d (thickness in meters)}}{\lambda \text{ (heat conductivity coefficient) [W/mK]}} \quad (4)$$

Equation (4) was used to find the heat resistance value of individual layers while equation (3) was used to find the heat resistance of the entire configuration. Rsi and Rse are the heat resistance values of the surface's interior and exterior respectively while a is simply a correction factor applied to make the calculation more accurate. An excel file was made for the calculations, a depiction of which is provided in the appendix of this report (Figure 11). It includes a brief explanation for every parameter shown and a calculated value of Rc based solely on the materials of the Energy Bar casing. The section left empty (yellow) is for the layer of the house's wall. The Rc value, as it is, is really small and thus would be unacceptable for Dutch standards. However, on condition that the empty cells are filled by values representing a good insulator, the Rc value will increase reaching, maybe even surpassing, the acceptable threshold. Because of how important this calculation is, external help had to be sought after from a team that would be able to verify our method and advise us on how to proceed.

● BTSL

BTSL is, as defined by Bosch, a library of dynamic component models in MATLAB/Simulink to build up and simulate the dynamic behavior of building energy systems. It is very popular within the Bosch community as it allows for reproducible field tests to take place without actually coming into contact with any hardware. Familiarizing myself with BTSL gave me the chance to test, evaluate and understand components and systems under different realistic and reproducible boundary conditions. Because of BTSL, not only did I interact with systems I would have otherwise never had the chance to work with, but, I also gained a better understanding around what dictates their performance.

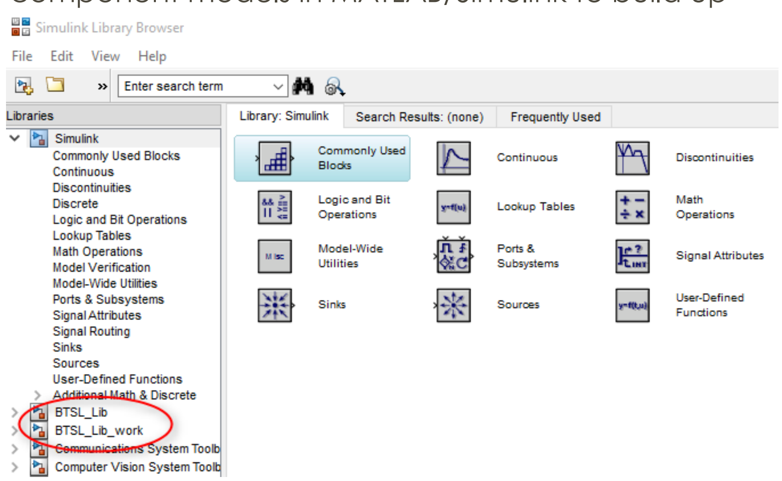


Figure 4: BTSL embedded into Simulink

In fact, I was able to create a model that would calculate the energy needs of a household by incorporating the following; a building(household) block, with dimensions of my choosing, a user (consumer) block, whose energy behaviour I governed, a simulation control block, dictating the time period and duration of the simulation, and an environment block which simulates the climate conditions of various countries/areas. Once a valid energy system was established, and the energy requirements were determined, the stage was set for an appliance to be tested as to the kind of tuning required to be able to meet the energy demand of the model. As part of my BTSL I also had to tune and simulate a combi model which resembles the boiler used in the hybrid version of the Energy Bar. Starting to work with BTSL was key and to this day I have a lot of ground to cover in order to understand the existing models and start making models of my own. BTSL will be the main tool used for my thesis and so becoming better at it is a top priority.

● Vakbeurs Energie Event

Vakbeurs Energie is the largest energy exhibition in the Netherlands and the go-to place for energy professionals and young people aspiring to a career in the energy industry. Joining my project manager and a colleague, I got the chance to interact with numerous company representatives who were present to advertise their companies and make sure their products got the right amount of exposure. I found out about several new energy systems and products that were recently introduced into the market and have the potential to really contribute to a eco-friendlier way of living. In addition, I increased my brand awareness by speaking to the people of the Bosch stand and by observing how third parties viewed the presented Bosch systems. Last but not least, by visiting stands and speaking to executives of competitor companies I was able to view different approaches to issues that are also addressed by Bosch and gather valuable information regarding work similar to our Zero Net Energy project.

● Competitor Report

Sizing up your opponents is very important before entering in any sort of competition. As a result, it is important for Bosch and the Zero-Net Energy Project to know what they are up against, to be able to estimate the size of the market they are entering and predict the market share they will be getting. Therefore, an additional objective of every member of the Zero-Net Energy Project team attending the Vakbeurs Energie was to get information about companies, with similar projects to ours, in order to compile a competitor report that provides some insight to everything we need to know before entering the market. My part of the report focused on OSH and Daikin.

OSH'S product is called the 'Energy Cabinet' and bears a resemblance to one version of the Energy Bar. Specifically, the cabinet consisted of; solar panels, a heat pump that uses 4 compressors to deal with fluctuating heat demand, a PV converter, an expansion vessel and a relatively large buffer tank. The main difference between the cabinet and the Energy Bar, other than the heat pump operation and the size of buffer tank, is that the cabinet must be accommodated by the attic of the residence and cannot be placed anywhere else. Several houses are expected to be equipped with the energy cabinet by the end of January 2018.

As for Daikin, their set-ups have similar features to those seen by both versions of the Energy Bar. However, Daikin has chosen not to integrate solar panels to their designs as of yet, which, as a result, rely solely on energy supplied by the grid to meet their electricity demand.

Sound Testing of the Energy Bar

All energy systems such as; air conditioners, liquid chilling packages, heat pumps and dehumidifiers with electrically driven compressors for space heating and cooling, must have their sound power level calculated in order to determine the amount of airborne noise they produce. Heat pumps (Nefit EnviLine 3kW), and as a result, electrically driven compressors are of the main constituents of the Energy Bar. Hence, Bosch is bound by European law to test the sound power level of its machine before introducing this product to the market to ensure that the dBs of sound emitted do not exceed the set standard. The standard is set to guarantee the convenience of customers and protect bystanders or neighbors affected by the product in question. It is emphasized that this standard only refers to airborne noise.

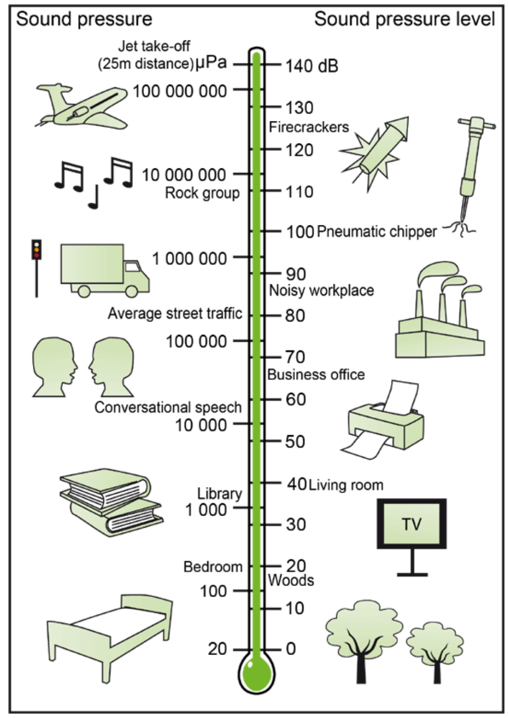


Figure 5: dB Scale

A Bosch associate of mine and myself carried out the sound testing and composed a detailed report presenting the outcomes of this process. Prior to actually measuring the noise produced by the Energy Bar, we had to familiarize ourselves with some concepts provided by Bosch Training Document on Sound. The latter also contained estimated values of the sound pressure level, facing the Energy Bar, at distances 1-15m from the Energy Bar. The goal was to compare our measurements to those calculated values and determine whether the metal casing surrounding the Energy Bar suppresses the emitted sound. We were able to link the sound pressure measured to the decibel scale, see Figure 5, and associate each value to a distinct sound class.

Distinguishing between the **sound power level** and the **sound pressure level** was key. Sound power level (Lw), also known as sound emission, is independent of distance and direction and is sound source specific. It describes the total sound energy of the source and is an important factor to be considered when comparing Bosch's systems to that of competitors.

$$L_w = 10 \log \frac{P}{P_0} \; [dB]$$ → Independent on the distance

$$P_0 = 10^{-12} \, W$$ → Reference power

On the other hand, the sound pressure level is generated when air is vibrating due to a sound and relies on the distance, direction and surrounding of the sound source. Similarly to the sound power level, it is an important parameter as it determines whether a device meets the local legal requirements.

$$L_P = 10 \log \frac{P^2}{{P_0}^2} \quad [\text{dB}]$$ → Distance law: $LP \sim 1 / r$

$$P_0 = 20 * 10^{-6}\ Pa$$ → Sound pressure as reference

My colleague and I used a Bruel & Kjaer 2260 sound level meter to measure the sound pressure at three different angles and two different height levels when facing the Energy Bar. For the first round of sound tests, the system was turned off so that the sound pressure of the surroundings can be measured and thus taken into account when determining the sound pressure level of the system. It is important to mention that the test took place inside the production unit of Bosch and thus, even though nobody worked that day, some minor background noise existed coming from operating power tools and ventilators. Nevertheless, because Bosch's system is aimed for the exterior of households, we assumed the background noise simply compensates for air or traffic noise that exists near every house, making the test conditions quite realistic.

The system (Energy Bar) was in operation for the second test, as recommended by the manufacturer in its installation and operation manual, and the values measured were compared to those of the first test to examine their validity. As expected, the values of the second test exceeded those of the first due to the 'extra' noise generated from the Nefit Enviline 3kW ODU. In fact, the sound pressure levels barely exceeded the 'conversational speech' threshold of the dB scale, even when the microphone was at a very close proximity to the ODU. The values of the measured sound pressure level facing the ODU were lower than those of the calculated sound pressure which proves that some noise is dampened because of the steel casing. Nonetheless, even though we feel that all sound pressure levels were reasonably low, and so should be deemed acceptable, the classification really depends on the standards of each user/bystander and their distance from the Energy Bar.

$$L_{PAeq} = L_{WAeq} + 10 \times log\left(\frac{Q}{4 \times \pi \times r^2}\right)$$

L_{PAeq}	geluidsdrukniveau (SPL) bij ontvanger [dB(A)]
L_{WAeq}	Geluidsvermogen van de bron [dB(A)]
Q	Richtingsfactor rekening houdt met de ruimtelijke afstraling van de geluidsbron, bijvoorbeeld huismuren
r	Afstand tussen ontvanger en bron [m]

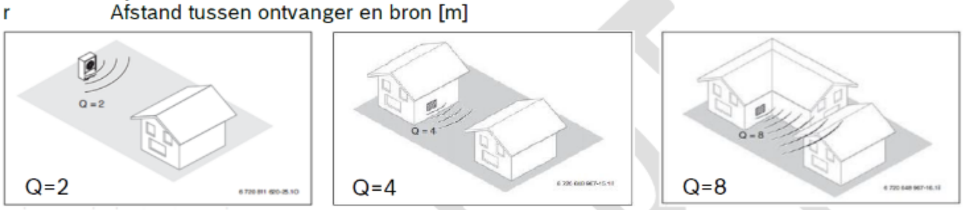


Figure 6: Typical house with Energy Bar layout and sound pressure calculation

● Battery Survey

Part of working on a product like the Energy Bar is finding ways to upgrade the existing model to make sure it adapts to future customer demands and has features that guarantees its market longevity. At the moment, the Energy Bar makes a building '0-Net Energy' within the course of a year, however, it fails to make the building energy independent. Any building equipped with the Energy Bar will still heavily rely on the grid for electricity supply, especially during periods of peak demand and insufficient solar electricity generation. Fortunately, exchanging energy with the grid will makes sense for as long as a user can sell a kWh of energy at the same price of purchase from the grid.

Bosch is already a player in the battery market, through its batteries for electric vehicles (EVs), but wants to look into ways that would make their systems self-preserving by supplementing them with energy storage systems. As a result, I was assigned to conduct a survey about battery systems that focuses on recent research findings of Dutch institutions, the current state of the battery market, residential applications of battery storage for renewable integration and battery products already hitting the shelves of the Dutch market.

After gathering enough information to address the main topics of this survey I came to the conclusion that a comprehensive study about batteries for individual households should be on the works in preparation for the period following the abolishment of the Dutch 'salderingsregeling'. Moreover, it is certain that innovations and development of energy storage technologies will lead to more cost reductions and performance improvements, especially in batteries and power-to-gas technologies. The tracked progress, along with an increased need for various services in the electricity system, will assist the wider implementation of energy storage. The market is growing fast and its environment is susceptible to changes with the increasing deployment of several emerging energy technologies. Figure 7 displays an estimated, yet credible, route of battery storage for the next 5 years in terms of installed capacity in MW and annual revenue in US Dollar ($).

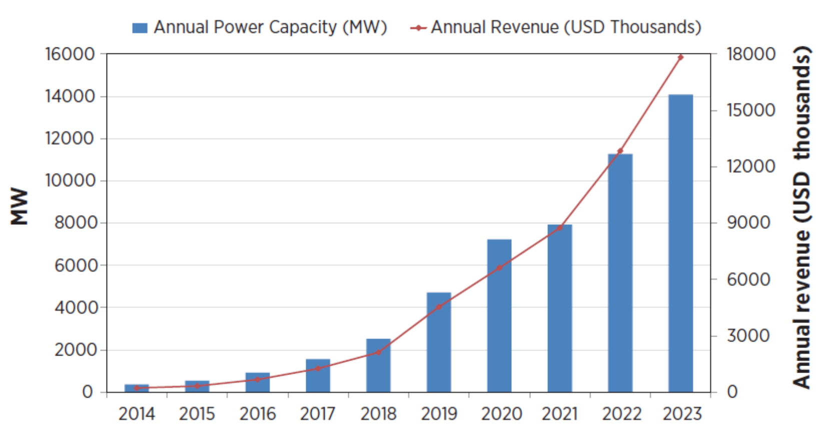


Figure 7: Global forecast of battery storage capacity (MW) and annual revenue (USD) for utility-scale applications

Given Bosch's size and global reputation a potential investment to acquire a bigger share of this fast-growing market could be very profitable. This paper, along with the studies mentioned, shows that batteries will have a tremendous impact on future energy systems. Consequently, I concluded stating that 'Bosch would benefit from adding batteries to its existing and future systems. It would show forward thinking and a desire to be innovative'. Take the Energy Bar for instance; A battery packet system paired with the electrical control management would be a major upgrade if integrated to the Energy Bar. In some cases, it would make the system 'grid independent', if needed, and would fully unlock the potential of the its Solarwatt PV panels. In fact, Bosch should event try to strike a deal with Solarwatt where the latter produce the PVs and the former manufacture batteries that match perfectly the solar panels.

● Field Test Data Monitoring

To this point, the Zero-Net Energy Project has been put to the test through various simulations. Yet, if a field test is not carried out to validate, at certain extent, the results of those simulations the product of the Energy Bar cannot be launched to the market. As part of the upcoming Energy Bar field test, I was assigned to list all the parameters that should be measured to evaluate the performance of the project and find the best sensors/meters to monitor/control those parameters. Specifically, I made a preliminary file that had to be reviewed and approved by the project manager before turned into an actual plan.

For this task, I decided to create an excel file and categorize each parameter with respect to the component they are associated with. Taking the heat pump as a point of reference (Figure 12, Appendix), the most important thing to calculate that reveals how well the system works is the COP. The COP (explained above) would require the energy input, in the form of electricity, and the energy output, in the form of heat supplied to the home. For the former, a regular kWh meter would suffice, although a single unit would probably not be enough to reveal the electricity's source. For the latter, we would require temperature sensors, like the PT-100 which are embedded in the Alpha-Innotec heat pump storage combination, for the temperature of the water entering and exiting the condenser, and a flowmeter to get the mass/volumetric flowrates of the water used for CH and DHW respectively. Similar steps were taken for the rest of the components and the whole process takes quite some time since finding the exact meters (type & model) that best suit our case is not very straightforward. Final step would be deciding the duration of the tests, since the performance of every component depends on the energy demands, which vary with seasonal change, and getting an expert's feedback on our findings.

● FLEXCON 2017

FLEXCON 2017 is a relatively new international conference aiming to bring together parties who are interested in the flexible energy revolution. The conference was held on 20th and 21st of November, at Pakhuis De Zwijger, in Amsterdam. The presentations and exhibited products promoting an eco-friendly transition to energy systems, paving the way for a fully renewable energy future.

As opposed to the Vakbeurs Energie energy exhibition, going to Amsterdam was part of my initiative. I felt that since this took place during my internship period with Bosch, and it helped me learn a lot about the current and future state of the energy industry, it should have a place in my report. Specifically, I learned a great deal about new concepts that will completely modify the way energy is distributed from the grid and allow for easier energy transactions between neighboring homes. I learned more about energy storage and how batteries will be soon a major component of domestic energy systems, which also helped me with my battery survey for Bosch. I was happy to discover that heat pumps, systems that I have been working on since my first day at Bosch, will have a key role to the future of domestic heating. Lastly, I managed to link up with fellow students, graduates and experts of the field whilst coming across great ideas and learning about exciting projects.

● Hydraulic configuration of (domestic) heating systems

Prior to starting my thesis, which revolves around the hydraulic configuration of the Hybrid Version of the Energy Bar, I had to learn more about the layout and operation of heating systems. As a result I used the Energy Bar as the means to find all the pieces that make up a hydraulic structure.

Today, heating systems are characterized depending on how they distribute energy. Therefore, systems are classified as either centralized or decentralized. The former is a type of heating system that generates heat from one "central" point of the building (house). From that single source, heat is supplied to the various rooms and areas of the house in order to reach the desirable temperature setting as indicated by the thermostat. On the other hand, the latter allow individual control of the temperature in different areas of a building, thus ensuring that energy is consumed in a more cost-efficient manner. Decentralized systems, although impractical in many cases, are easier and cheaper to install than centralized ones, whilst their repairs only involve units in the space where the faults occur. Centralized systems are easier to control and yield an even and consistent temperature from room to room.

To simplify matters, heat sources can be empirically categorized into active or passive. Passive sources go hand-in-hand with renewable energy technologies because their output relies on the uncontrollable and unpredictable weather trends. To the contrary, active heat sources include technologies that can have their input, and thus output, adjusted and controlled to achieve the desirable setting. Take a solar collector as an example; no matter how high the demand for energy, unless there is enough sunlight, in most cases, the need for energy will not be met. This however, is not an issue using a combi boiler burning gas (for now) or an air source heat pump.

Active sources can be further subcategorized to *low temperature sources* (LTS) and *high temperature sources* (HTS). In fact, LTS work more efficiently at lower temperatures and, due to their inability to handle high energy demand, are usually paired with a HTS so that the required temperature and power can always be produced.

The exact same principles apply to the Hybrid Version of the Energy Bar where the heat pump (LTS), which gives a higher COP with a lower difference between flow temperature and source temperature, is paired with a standard combi boiler (HTS) to take care of a house’s energy demand which rises in the form of CH and/or DHW (Figure 8).

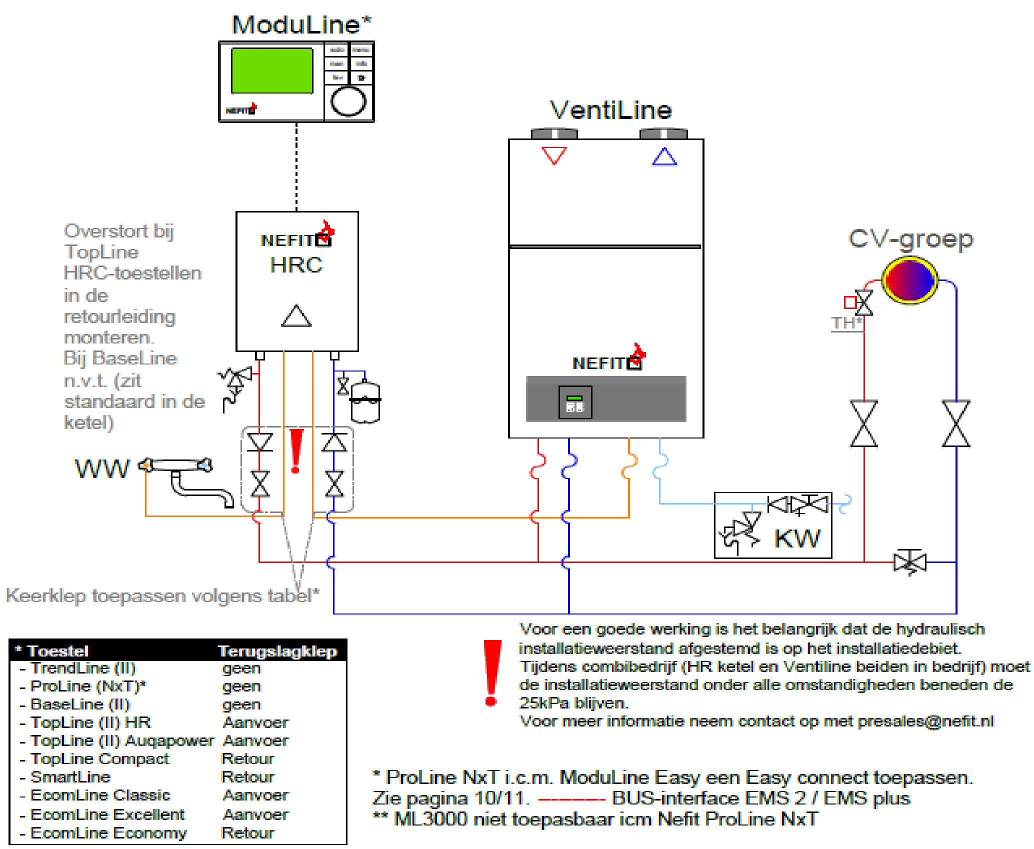


Figure 8: Hydraulic scheme of one possible combi boiler and heat pump pairing

As distinguished from figure 8, both appliances contribute to the CH and DHW. Starting from right to left, cold water streams enter the heat pump (Nefit VentiLine) in the form of grid water and CH used water. The heat pump has a red output stream which contributes directly to the CH and an orange stream line which enters the boiler (Nefit ProLine), i.e. the secondary heat exchanger (see section below), only to be reheated and exit the boiler to respond to the DHW demand. The boiler receives a cold, used water stream coming from the CH system and heats it up using its primary heat exchanger (heat cell) to supply the CH (red output line). The amount of heat required can be governed by the

ModuLine block which is located at the top of the hydraulic scheme. The described case uses water for both the underfloor heating system (CH) and DHW.

● Hydraulic configuration and operation of combi-boiler appliances

This section is more than just an extension of the 'Boiler Theory' segment. The theory, while useful, is not enough to understand how the boiler operates and definitely not enough to be able to carry out accurate simulations. Combi boiler type heating appliances are part of the water heaters' and one of the main products manufactured and sold by Bosch. As defined earlier, the water demanded by the users is commonly known as the DHW, whereas the system water circulating under the floor, or through radiators, is called the CH water.

The Nefit ProLine is the combi boiler that Bosch uses for the hybrid version of the Energy Bar, and its features mirror those of what is known as "standard combi boiler" (figure 9).

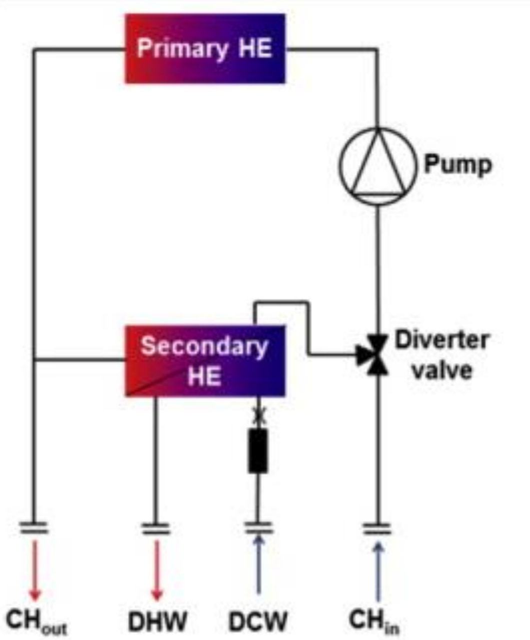


Figure 9: Schematic view of a standard combi boiler

A standard combi boiler has two heat exchangers, a primary and a secondary. Based on the operation shown in Figure 8, the primary heat exchanger (or heat cell) heats up the central heating water using the flue produced when burning natural gas, or a similar fuel source, before channeling it through the underfloor heating circuit for energy to be transferred to the surrounding air through convection and conduction. If a DHW demand comes through, the space heating function pauses, and the diverter valve changes the flow direction of the CH water from underfloor heating to the secondary heat exchanger. The hot CH water passes through the secondary heat exchanger, i.e. the PHE, to heat up the water (DCW at the time) requested by the users.

When it comes to DHW supply function the main working modes of a standard combi boiler are eco and comfort mode. During eco mode both the CH water and DHW are heated up instantaneously. Comfort mode on the other hand, has regular pre-heat periods for increasing CH water temperature in the system to an upper temperature limit in case there is a user-demand; consequently, DHW set temperature is reached rapidly and waiting period to produce DHW from cold tapping water is significantly reduced. Be that as it may, whether there is tapping or not, with these pre-heat phases the CH water is always kept between critical upper and lower temperature limits.
I learned that sometimes systems are supplemented by additional storage tanks for increasing the comfort level of the appliances. These tandem systems are divided into two groups according to the

purpose of the water that is stored, whether it is primarily used for CH water or DHW. An additional storage tank is a must for meeting the requirements of some high standard markets since it helps the appliances obtain high rating scores at the end of the tests.

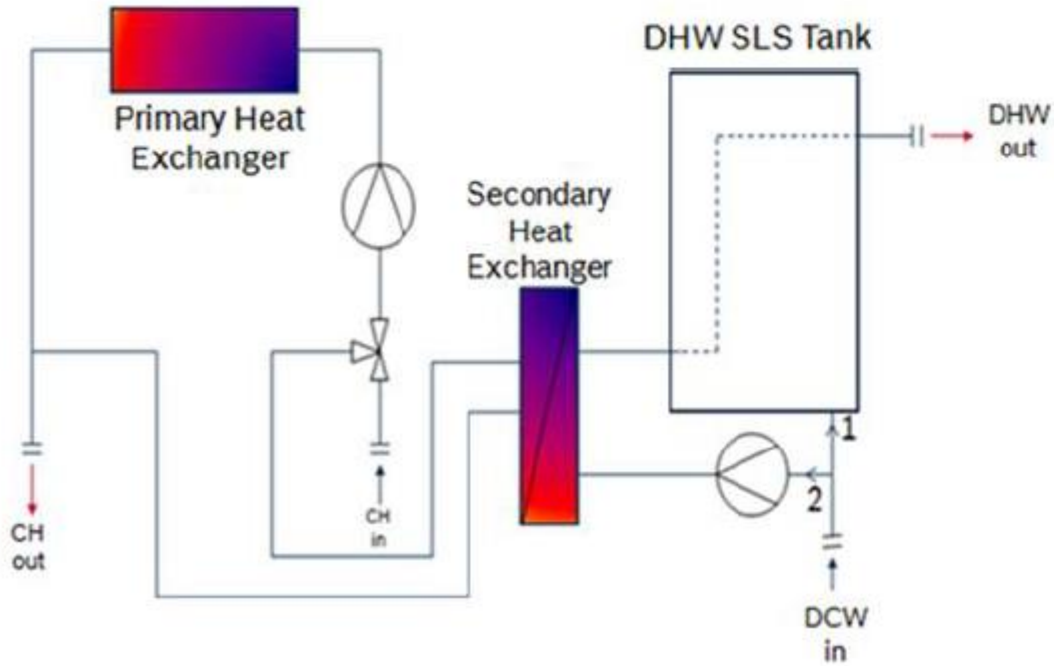


Figure 10: Schematic view of a stratified layer storage (SLS) tank concept

● Mathematical modelling of heat pump

Bosch, as a brand, is not a heat pump manufacturer. However, heat pumps are vital components of the Zero-Net Energy Project. Bosch keeps models of all its appliances for simulation purposes and in order to be able to evaluate the performance of the products they sell. Because heat pump systems are built by partner companies, Bosch's level of knowledge surrounding heat pumps is really small compared to that of boilers or ventilation systems. Subsequently, I started developing a heat pump model[1] that would be able to describe, using simple equations, the heat pump cycle and the movement of hot water to accommodate the CH and DHW demand. The model was designed to calculate more than one COPs to correlate the refrigerant's cycle with the temperatures and flowrate of the water passing through the appliance. The calculations were carried out in an Excel file to "start simple" before been integrated to a more sophisticated software that should be able to carry more complex calculations. The Excel model was paired with a Word file which explained the logic behind every calculation. The model, a detailed summary of which is provided below, was

[1] The equations and descriptions appearing in the files are based on numerous sources, from UT notes, papers (e.g. "G.J.M Smit, A predictive model for smart control of a domestic heat pump") and books (e.g. M. Moran, H. Shapiro, Fundamentals of Engineering Thermodynamics, Wiley, 2000).

divided into sections depending on the presented calculations. The list of abbreviations for part of the heat pump model was too big to be placed in the main body and so it was inserted in the Appendix. However, most variables, especially those in the DHW and CH part, are explained on the go.

Basic Cycle

In practice wet vapor is difficult to compress and expand so the refrigerant is usually dry entering and superheated exiting the compressor. The cooling process may produce anything from the wet vapor to undercooled liquid. The expansion of a liquid in a turbine is impractical and so a throttle valve is used instead.

1-2 Isentropic compression (power delivered by the compressor into a refrigerant)

➔ $P_{in} = \rho_{ref} * \varphi_{ref} * (h_2 - h_1)$

2-3 Constant pressure cooling (energy input of refrigerant into the expansion valve)

➔ $\Phi_{out} = \rho_{ref} * \varphi_{ref} * (h_3 - h_2)$

3-4 Throttle expansion

➔ $P_{out} = \rho_{ref} * \varphi_{ref} * (h_3 = h_4)$

4-1 Constant pressure cooling

➔ $\Phi_{in} = \rho_{ref} * \varphi_{ref} * (h_4 - h_1)$

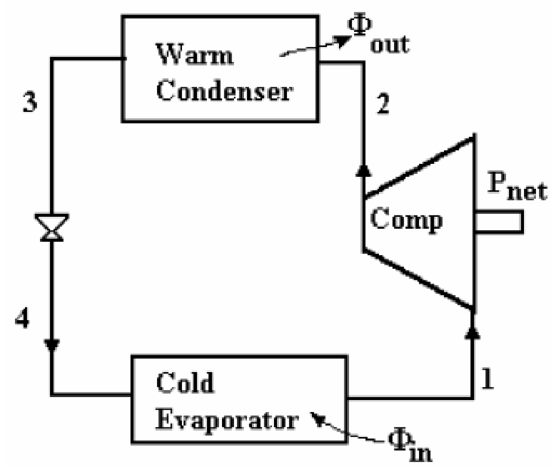


Figure 11: Heat pump using a throttle valve

A throttle valve produces no "useful work". However, it converts the pressure into internal energy. This makes the liquid evaporate and since the saturation temperature goes down it ends up cold. The enthalpy before and after a throttle is the same. The entropy on the other hand increases over a throttle.

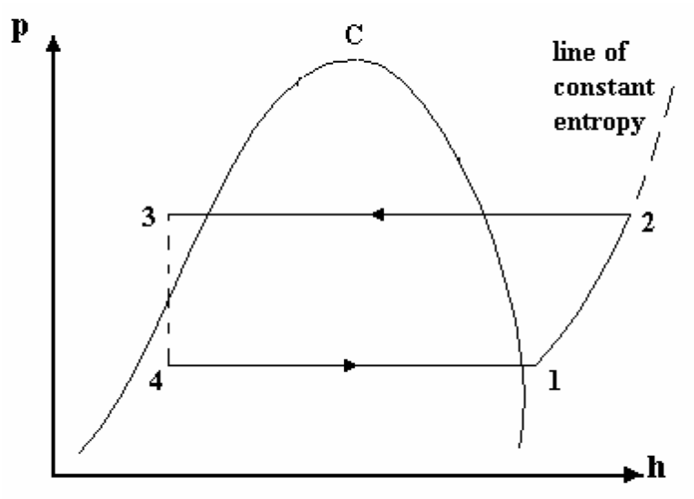


Figure 12: Realistic Pressure (P)-Enthalpy(h) diagram describing the refrigerant cycle

Finally, the heat flow received from the environment through the evaporator can be expressed by:

$$Q_{evap} = \rho_{air} * \varphi_{air} * c_{p,air} * (T_1 - T_2)$$

COP

A heat pump extracts heat from a (cold) reservoir with the temperature T_{cold} (T1 in figure 1) through vaporization of a coolant and transfers this heat to a (hot) reservoir with the temperature T_{hot} (T2) through condensation of the coolant.

A heat pump can be characterized by the Coefficient of Performance, which is often referred to as COP, is defined as the amount of heat transferred per unit of input work required. Mathematically

$$COP = \frac{Q_{hot}}{W} \ (1)$$

Q_{hot} is the heat supplied to the hot reservoir and *W* is the work consumed from the heat pump. For the heat pump, work consumed is in the form of electrical energy to run the compressor (5) and the fan(11). According to the first law of thermodynamics, in a reversible system it can be shown that;

$$Q_{hot} = Q_{cold} + W \ (-Q_L)$$

And

$$W = Q_{hot} - Q_{cold}$$

Q_{hot}: the heat given off by the hot heat reservoir

Q_{cold}: is the heat taken in by the cold heat reservoir

W: applied electrical energy to run the process, i.e. transfer the heat

Q_L: heat lost in the process

$$COP_{heating} = \frac{Q_{hot}}{Q_{hot} - Q_{cold}} \quad (2)$$

For a heat pump operating at maximum theoretical efficiency (Carnot efficiency), the following relation applies;

$$\frac{Q_{hot}}{T_{hot}} = \frac{Q_{cold}}{T_{cold}}$$

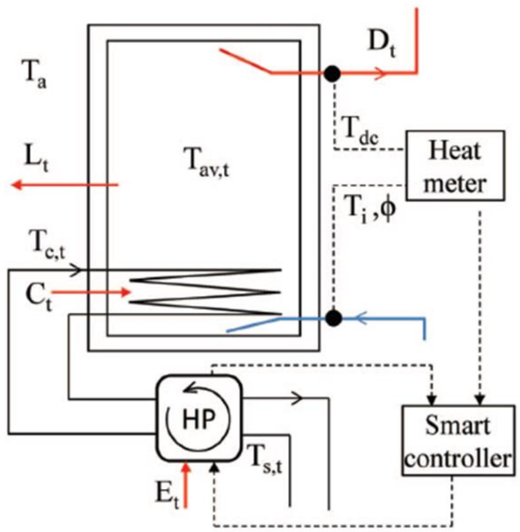
Where T_{hot} and T_{cold} are the aforementioned absolute temperatures of the hot and cold heat reservoirs respectively. Equation 2 then becomes equations 3 and 4;

$$COP_{heating} = \frac{T_{hot}}{T_{hot} - T_{cold}} \quad (3) \text{ or } COP_{heating} = 1 + \frac{T_{cold}}{T_{hot} - T_{cold}} \quad (4)$$

Equations 3 & 4 demonstrate that COP is higher if the temperature difference between hot and cold regions is lower.

Domestic Hot Water (DHW)

DHW is hot water drawn from the top of the storage tank embedded in the heat pump as shown in figure 5. This model essentially describes energy content of thermal storage one of most important aspects of which is thermal stratification which leads to maximum exergy utilization. The storage is categorized into two layers; a top hot layer and one middle mixed layer with temperature $T_{av,t}$. This model predicts, without iterations, both the storage state of charge and heat pump electric consumption of a future charging cycle in a one-step calculation, based on the inlet/outlet flows.



Notation	signification
C_t	charging thermal energy at time t
E_t	heat pump electrical energy consumption
L_t	loss of thermal energy from the storage
D_t	thermal energy demand from the storage
HP	heat pump
Φ	inlet or outlet water flow
T_a	ambient temperature
$T_{c,t}$	charging flow supply temperature
$T_{s,t}$	heat pump source supply temperature
T_{dc}	outlet or discharge water temperature
T_i	inlet water temperature
$T_{av,t}$	average storage water temperature

Figure 13:Typical heat pump combined with storage tank scheme

Unlike the operation of the Nefit VentiLine appliance in the Energy Bar, and for the sake of simplifying this process, the model assumes that the energy produced by the heat pump in the form of hot water is used only for DHW purposes.

An applicable model for the supply from a thermal storage is based on the first law of thermodynamics (energy conservation) which for this case would mean:

$$\Delta S_t = \Delta C_t - \Delta D_t - \Delta L_t \quad (5)$$

ΔS_t: change of stored energy

ΔC_t: change in charging energy

ΔD_t: change in the demand of energy for DHW

ΔL_t: energy (heat) loss with time

ΔT: time interval which in discrete time is the interval (t-1, t)

In the Nefit VentiLine heat is transferred within the 50-liter tank by a coil heat exchanger at the bottom region of that reservoir. Within the storage tank the entire volume of hot water with a uniform temperature moves upwards becoming distinguished from a growing volume of cold water in the bottom region. Nonetheless, the incoming cold-water flow induces some mixing of cold and hot water. By focusing on the discharging of the tank the amount of energy supplied from an initial SoC and the amount of ''useful energy, i.e. as long at $T_{dc} \geq 40$ °C, can be determined.

Assuming that energy supply from the storage tank equals the energy demand, the supplied energy in time interval Δ*t* is calculated with equation 6, whose components are explained by figure 5 above.

$$\Delta D_t = \Delta t * \varphi_w * \rho_w * cp_w * \left(T_{dc,t} - T_{i,t}\right) \ (6)$$

A heat meter would calculate the supplied energy using equation 6. Naturally, a sort of algorithm can then use the results to predict the actual state of charge (SoC, equation 7) of thermal storage after some time (t).

$$SoC_t = \frac{S_t}{S_{\max}} \ (7) \quad 0 \leq SoC_t \leq 1$$

The stored energy at time interval *t*, *St* is determined by equation 8. S_{t-1} is the stored energy at the previous time interval, i.e. *t*−1. The maximum charged energy is determined by equation 9, which is based on the first law of thermodynamics, relating the required thermal energy to the change of enthalpy of the mass of water within the storage.

$$S_t = S_{t-1} + \Delta S_t \ (8)$$

$$S_{max} = V * \rho_w * cp_w * (T_{max} - T_i) \ (9)$$

V: the water volume in the storage,

Tmax: the maximum, uniform temperature of the storage which can be determined by the storage thermostat settings.

During the charging process, heat is transferred from the bottom coil to the water in the storage by the principle of natural convection. The water in the storage is initially cold but its temperature increases gradually during charging.

Linear equations are developed for *Ct* and *Et* and given in equations 10 & 11.

$$\Delta C_t = a * T_{s,t} + b \quad (10)$$

$$\Delta E_t = c * T_{c,t} + d \quad (11)$$

Where: a,b,c and d are constants, or heat pump coil parameters, which are governed by the product and can be obtained from the supplier of the heat pump that is modelled.

Neglecting the coil conductive resistance, the coil temperature approximately equals the condenser temperature. The heat transfer from the coil to the surrounding water in the storage is given by equation 12 which is based on Newton's law of cooling (Moran and Shapiro, 2000).

$$\Delta C_t = h * A * \left(T_{c,t} - T_{w,t}\right) \quad (12)$$

h: the coil heat transfer coefficient

A: the coil outside area

$T_{w,t}$: the surrounding water temperature within the storage tank

The product *h**A* is assumed the same for a complete charging cycle and can be computed using supplier data. When the surrounding water temperature is known, equating ΔCt from equations 10 & 12 gives the condenser temperature Tc,t which in turn is needed to calculate the electric energy consumption ΔE_t. Hence a suitable prediction of the water temperature within the thermal storage around the coil is very important.

When charging from a fully discharged condition, the water temperature within the storage is assumed uniform and the left term of equation 5 is approximated as:

$$(\Delta S_t =) \qquad \rho * V * c_p * T_{w,t} \quad (13)$$

Solving equation 5 yields the average water temperature which is then substituted into equation 12.

Naturally SoC decreases as water is discharged from the storage tank. Hence the following mathematical statement can be established:

$$\frac{\Delta SoC}{\Delta V} = \frac{1}{V} \quad (14)$$

For a given *SoCt* (*SoCmin≤SoCt*≤1), the remaining volume of hot water *Vh*,*t* within the storage can be calculated with equation 14 substituting:

Where: $\Delta SoC = SoC_t - SoC_{min}$ outputs $\Delta V = V_{h,t}$ $\quad (\Delta V = V - V_{h,t})$

Tw,*t* depicted in equation 13, according to the model assuming the storage consists of 2 layers, i.e. an upper layer with a uniform hot temperature and a lower layer with colder temperature, is the average temperature of the lower layer of mixed water volume in the storage, i.e. $V - V_{h,t}$. This temperature is calculated from equation 15 in which the stored energy S_{t-1} is known from the state of the previous time interval.

$$S_{t-1} = \rho * c_p * \left[V_{h,t-1} * (T_{max} - T_i) + \left(V - V_{h,t-1}\right) * \left(T_{w,t} - T_i\right)\right] \quad (15)$$

The total required thermal charging energy is calculated using equations 16 and 17.

$$C_{tot,t} = (1 - SoC_t) * S_{max} \quad (16)$$

$$SoC_{min} \leq SoC_t \leq 1 \quad (17)$$

The duration of the charging process τ_t is calculated with 18.

$$\tau_t = \frac{C_{tot,t}}{\Delta C_t} \quad (18)$$

Δ*Ct* is calculated with 10(/12). The electric power consumption profile *Pe*,*t*∗ of a future charging cycle with discrete time *t*∗ in the future, from a given *SoCt* to fully charged conditions, is estimated using 19 which starts at a value *Pe*,*t*∗*i* and ends with *Pe*,*t*∗*i*+τ. These values are calculated with Δ*Et*, equation 11. *t*∗*i* is some time in the future when charging is initiated, which is a control variable for the smart control system.

$$P_{e,t*} = P_{e,t*_1} + \frac{P_{e,t*_1+T} - P_{e,t*_1}}{\tau} * t^* \qquad [0 \leq r^* \leq \tau] \quad (19)$$

The electric energy consumption of the future charging cycle is calculated with Equation 20, which is the integral of equation 19.

$$E_{tot,T} = \frac{\tau}{2} * \left(P_{e,t*_1} + P_{e,t*_1+T}\right) \ (20)$$

The loss component ΔL_t refers to heat lost to the surroundings and can be calculated by the general heat transfer relation given by equation 21 (Moran and Shapiro, 2000).

$$\Delta L_t = U * A * \left(T_{av,t} - T_a\right) \ (21)$$

Where U*A being the storage heat loss coefficient, assuming constant water density and specific heat, Ta is the ambient temperature while $T_{av,t}$ is calculated with equation 22.

$$T_{av,t} = \frac{V_{h,t} * T_{max} + \left(V - V_{h,t}\right) * T_{w,t}}{V} \quad (22)$$

Central Heating (CH)

A thermal model of the underfloor heating system has to be developed. This is a relatively simple model, more straightforward than the DHW model, focusing on the thermal storage capacity of the heated floor. Thermal capacities and losses are calculated, where P_{hp} has been used to represent the heat supplied by the heat pump, instead of Q to avoid any confusion with previously used parameters. Similarly, P_L has been used to represent heat losses. Calculating the thermal mass (M) of the floor comes first, and can be done using the following equations:

$$V_{floor} = length * width * height \ (23)$$

$$M = V_{floor} * \rho_{concrete} \ (24)$$

Hence the heat transferred to the room is calculated as follows:

$$\Delta P_h = M * c_p * \Delta T \quad (25)$$

Where ΔT is the temperature rise above the reference temperature. Specifically, it is the it is the reference temperature for floor temperature minus the reference temperature for room temperature.

Alternatively, ΔP_h can be calculated by subtracting the heat losses from the heat supplied by the heat pump:

$$\Delta P_h = P_{hp} - P_{Lf} \;\; (26)$$

Where $P_{Lf} = h * A * (T_s - T_a)$ (27)

Ts: the surface floor temperature

Ta: the air temperature

Using a simplified equation for free convection with a heated plate facing upward, the heat transfer coefficient is calculated: $h = 1.52 * (T_s - T_a)^{\frac{1}{3}}$ (28)

while $A = length * width$ (29)

Final Remarks

I feel that the time I have spent at Bosch, up to this point, has been extremely productive. Bosch's environment helped me develop my communication skills through fruitful meetings and daily interaction with colleagues. I learned how to have an essential contribution to an already established team, how to pick and sort out my tasks/activities and how to assist others when needed to.

My colleagues, especially my supervisor and project manager, were helpful and supportive throughout my internship, thus a lot of my improvement as an engineer can be accredited to them. In a nutshell, my internship was a great overall experience and has made me really look forward to starting on my thesis with Bosch.

List of Figures

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Rc excel file screenshot.

Data monitoring excel screenshot.

	value	units	explanation
Rc	0.195272	m^2 K/W	Heat resistance of construction
Rm1	0.00004	m^2 K/W	Heat resistance of the separate layers
Rm2	0.00004	m^2 K/W	Heat resistance of the separate layers
Rm3	0.213415	m^2 K/W	Heat resistance of the separate layers
Rm4	0.00004	m^2 K/W	Heat resistance of the separate layers
Rm5	#DIV/0!	m^2 K/W	Heat resistance of the layer selected by the constructor
Rsi	0.13		Heat transfer resistance surface interior
Rse	0.04		Heat transfer resistance surface exterior
D	0.04	m	Cavity anchor diameter
A	0.001256	m^2	Cavity anchor area
Ainsulation	4.5884	m^2	
Asteel	0.0241	m^2	**Assume 2 (Γ) sides**
Atotal	4.6125	m^2	
Hs	5.125	m	Height of Steel Side
Ls	0.9	m	Length of Steel Side
d1	0.002	m	layer thickness (steel)
d2	0.002	m	
d3	0.06	m	
d4	0.002	m	
d5		m	
α	0.05	-	correction factor for convection and inacurracy in implementation
λ1	50	W/mK	heat conductivity coefficient
λ2	50	W/mK	heat conductivity coefficient
λ3	0.02	W/mK	heat conductivity coefficient (foam)
λ3'	0.281142	W/mK	heat conductivity coefficient (combined materials value)
λ4	50	W/mK	heat conductivity coefficient
λ5			
U	2.737689	W/m2 K	Insulation Value (Lower is better)
SAMPLE CALCULATION - SUB IN VALUES			

Figure 14: Rc excel file screenshot

Fan operation, i.e. air inlet flowrate & compressor power consumption	kWh Meter	How much of electricity is supplied from PV and how much from grid
CH	Flowmeter, Tin, Tout (thermistor/temperature probe)	year round measurement
DHW	Flowmeter, Tin, Tout (thermistor/temperature probe)	year round measurement
COP		heat output / electricity input
Sound rated operation	Bruel & Kjaer 2260 sound level meter	Inside & outside noise level (dB) interval testing

Figure 15: Data monitoring excel screenshot

Variable	Description
cp,w	water specific heat capacity
ρ,w	water density (@25oC entering)
φ,w	water flowrate (used in DHW calculations)
m,w	water mass floweate
T,cw	
T,hw	
cp,ref	refrigerant specific heat capacity
ρ,ref	refrigerant density
φ,ref	refrigerant flowrate
m,ref	refrigerant mass flow
cp,air	air specific heat capacity
ρ,air	air density
φ,air	air flowrate
m,air	air mass flow
h,1	enthalpy at point 1
h,2	enthalpy at point 2
h,3	enthalpy at point 3
h,4	enthalpy at point 4
s,ev	entropy of refrigerant behind expansion valve
s,c	entropy of refrigerant behind compressor
s,evap	entropy of refrigerant behind evaporator
s,co	entropy of refrigerant behind the condenser
T,1	input air temperature
T,2	output air temperature
P,in	**isentropic compression (P,in)**
Φ,OUT	**condensation stage, constant pressure cooling (Qhot)**
P,out	throttle expansion
Φ,in	**constant pressure cooling (Q,cold)**
Q,evap	heat flow received from the environment throuth the evaporator
Q,water	charging water thermal energy
COP (1)	**Coefficient of performace based on water flow**
Qhot	heat supplied from HP (Ct)
Thot	absolute temperature of hot reservoir
Qcold	heat taken in by the cold heat reservoir
Tcold	absolute temperature of cold reservoir
Q_L	Lost power (add if applicable)
W	applied electrical energy to run the process
COP (1)	**Coefficient of performance based on energy flows**
COP (3)	Coefficient of performance based on temperatures