MASTER

Re-commissioning the HVAC of an office building

systematic performance evaluation according L.E.A. : HVAC performance evaluation according the lean energy analysis (L.E.A.), based on a case study

Vink, W.P.J.

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Building Physics and Services
Department of the Built Environment
Den Dolech 2, 5612 AZ Eindhoven
P.O. Box 513, 5600 MB Eindhoven
The Netherlands

www.tue.nl

Re-Commissioning the HVAC of an Office Building: Systematic Performance Evaluation according Lean Energy Analysis

Author
W.P.J. Vink

Student ID:
0827404

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Where innovation starts

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Systematic Performance Evaluation according L.E.A

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Author:

W.P.J. (Werner) Vink (0827404)
Master Building Physics and Services
Eindhoven University of Technology

Department:

Building Service
Unit Building Physics and Services
Department of the Built Environment
Eindhoven University of Technology (NL)

Graduation committee:

prof.ir. W. (Wim) Zeiler	Chair of Committee	Eindhoven University of Technology
ir. G. (Gert) Boxem	Internal member	Eindhoven University of Technology
ir. C. (Charlotte) Philips	Company supervisor	Croonwolter&dros | TBI

Abstract

Compared to their design Heating, Ventilation and Air conditioning (HVAC) systems in newly office buildings are systematically underperforming. Problems are mostly related to controllable parameters. Continuous Commissioning (CCx) is a promising technique to overcome these problems. However, implementation is complex. Re-Commissioning (RCx) can be utilized as a strategic step towards CCx. However, HVAC system complexity gives that RCx isn't always performed effective. The Lean Energy Analysis (L.E.A) gives outcome to effectively perform RCx. This study was motivated to perform RCx according L.E.A as a strategic step to systematically obtain CCx.

L.E.A. is a top-down approach that can be divided in three: design & performance analysis, HVAC performance modeling, and result conclusions & RCx recommendations. RCx according L.E.A. is conducted on an office building of 7.800m^2, completed in early 2012. It contains an Aquifer Thermal Energy System (ATES), electrical water-to-water heat pump (HP), gas fired boiler, ventilation by variable air volume (VAV) and four thermal emission systems. It's concluded that actual consumption is 2,5 times higher than expected. The Air-handling unit (AHU) operations are almost constant in peak demand. Indoor CO_2 concentration is very low. According the VAV control it would mean ventilation would be off. Excessive ventilation gives that heating demand is 5 times higher compared to cooling. In addition ATES has a negative thermal unbalance.

Saving potential is investigated by a model-based approach. By linear regression benchmark models for AHU fan consumption and HVAC thermal behavior are obtained. Representing the design, a deterministic model for AHU fan consumption as function of CO_2 is obtained. Subsequently three ventilation scenarios are simulated: CO_2 upper limit of 1200ppm, 1000ppm and 800ppm. Compared to the benchmark, the most demanding ventilation strategy gives a weekly reduction of 44% on AHU fan electricity. Furthermore, reducing the ventilation rate provides additional improvement on HP-, boiler- and pumping energy consumption. However, measuring HVAC thermal load savings comes with improving the benchmark model.

It's concluded that indoor CO_2 concentration and HVAC energy consumption is excessive. Recommendations on RCx are provided on evaluating the VAV control. When the controllable parameter is defined and solved, the variables that discovered the anomalies (AHU fan electricity-, indoor CO_2-, HVAC thermal energy measurements) are the top variables that continuously need to be commissioned. Incase the VAV is working optimal a benchmark model for the AHU fans need to be obtained. This also needs to be performed for the HVAC thermal load benchmark. Consequently, both benchmarks can be used in the fault detection and diagnose algorithms to continuously commission the performance.

Preface

This report presents my master theses to complete the Master Building Physics and Service at the Eindhoven University of Technology. The research is focused on Re-Commissioning office building HVAC systems by applying the lean energy analysis.

The report is written for a public with some knowledge in mechanical- and building physics engineering. In case any interest exists in lean thinking and/or energy savings, I do invite you to read the report. Most content is explained in such a way that it's understandable for people with no or less technical background.

Throughout the research my graduation committee have helped me in making decisions and keeping the end goal in sight. First I want to thank Wim Zeiler and Gert Boxem on their guidance. Especially their feedback on methodology formulation was helpful. Second I want to thank Charlotte Philips for her guidance, feedback and the complete freedom to do my research at Croonwolter&dros | TBI.

Eindhoven, 23th August 2016,

Werner Vink

Content

Acronyms and definitions

AHU	Air handling unit	
ASHRAE	American Society of Heating, Refrigerating, and Air-Conditioning Engineers	
ATES	Aquifer thermal energy system	
BMS	Building management system	
CCx	Continuous Commissioning	
CO_2	Carbon Dioxide	[ppm]
COP	Coefficient of perfromance	[-]
C_r	CO_2 concentration in volume	[ppm]
C_s	CO_2 concentration in ambient air	[ppm]
CWD	Croonwolter&dros | TBI	
EIS	Energy Information System	
FDD	Fault Detection and Diagnose	
HEX	Heat exchanger	
HP	Heat pump	
HVAC	Heat, ventilation and air conditioning	
IAQ	Indoor air quality	
L.E.A.	Lean Energy Analysis	
m	Room ventilation mass flow	$[m^3/s]$
MBCx	Monitoring based commissioning	
NaN	Not a Number	
P	Amount of occupants	[-]
PP	Power plant	
PV	Photovoltaic panels	
$Q_{AHU\ Extract}$	Electricity office AHU extraction fan	[kWh]
$Q_{AHU\ Supply}$	Electricity office AHU supply fan	[kWh]
$Q_{HVAC\ Cooling}$	HVAC thermal cooling load	[kWh]
$Q_{HVAC\ Heating}$	HVAC thermal heating load	[kWh]
RCx	Re-Commissioning	
Retro-Cx	Retro-commissioning	
S	CO_2 generation rate per occupant	[ppm/s]
SFP	Specific fan power	$[kW/(m^3/s)]$
SOC	State of charge	
SPBED	Specific primary building-related energy demand	
TC	Thermal comfort	
Te	Ambient dry bulb temperature	[°C]
Ti	Indoor air temperature	[°C]
TU/e	Eindhoven University of Technology	
V	Room volume	$[m^3]$
VAV	Variable air volume	

1. Introduction

This report presents a quantitative study for a master thesis Building Physics and Services (BPS) at the Eindhoven University of Technology (TU/e). The study is performed in collaboration with Croonwolter&dros | TBI (CWD). Chapter 1 introduces the research.

1.1. Problem Analysis & Relevance of Research

Western energy consumption increases [1]. Worldwide depletion of fossil fuels and resultant effects on climate change has led to the need to obtain/retain a more sustainable energy system [1,2]. Approximately 40% of the final energy use worldwide can be accounted to the residential and commercial sector. In western countries approximately 50% of their energy demand is related to heating, ventilation and air conditioning (HVAC) [3].

Performance of HVAC systems in western countries, especially non-residential, is substandard [4]. In 2007 it's concluded that 70% of the HVAC systems in Dutch office buildings are underperforming. Results are non-optimal- indoor conditions and energy efficiency [5]. It's concluded that most HVAC problems can be assigned to the exploitation phase [4-6]. Consequently it indicates that a large energy reduction potential in HVAC system operations is present.

Origin of most HVAC exploitation problems is related to controllable parameters. These can be divided in two: system- control strategies and maintenance. Following a common example regarding a control and maintenance related problem is given:

I. System control strategies:
Office building control strategies often result in excessive conditioning of indoor air. ±30% of the annual heating/cooling cost is related to fresh air treatment. It's not unusual that spaces are partially or even unoccupied. Time and rate of ventilation are often fixed. Result is excessive ventilation and unnecessary thermal energy demand [7-9]. Commissioning new control strategies can give outcome [7].

II. Periodic maintenance
Inefficiencies in HVAC systems can be found in unknown defaults of installation components [4,5]. Incase defaults result in bad comfort conditions, complains by the occupants generally stimulate action. Incase comfort conditions are accepted and no periodic monitoring is applied, long-term energy waste can be the result. Continuous performance monitoring can give outcome [4].

1.1.1. Building Exploitation Cost

Humans spend a high percentage of their time indoors (±90%). Therefor quality of the indoor built environment plays a critical role in overall health. Thermal comfort (TC) and indoor air quality (IAQ) are the occupant comfort parameters that need to be satisfied by HVAC operations. It's shown that poor comfort conditions on a short time interval (hourly/daily) have a significant effect on occupant productivity [12-14].

Human resources related costs are the largest in total building exploitation. For a typical office building around 90% of the business operation costs are related to salaries and benefits of the staff (see figure 1.1) [15,16]. In order to simulate productivity, organizations have great interest in retaining a high quality of indoor comfort [12,15].

Studies show that TC and IAQ in office buildings are often in bad conditions [5,13,14]. Although it's found difficult to quantify the influence on the one's productivity, it's shown that by increasing TC and IAQ occupant productivity can increase in the order of 1-10% [13,14]. Occupant salaries by far include the largest share on exploitation. Consequently the effect of poor HVAC maintenance on productivity related cost could be enormous. Continuously monitoring the performance gives outcome in managing these risks [4,21].

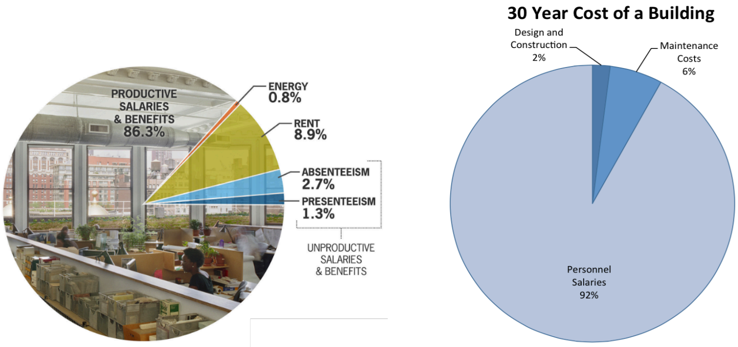

Fig. 1.1: Left, operation cost of a company as a tenant [15]. Right, operation cost for an office building over a 30-year period [16].

1.1.2. Building HVAC Demand

Satisfying occupant comfort is most critical to the operational cost of a business. However, cost related to long-term energy inefficiency can become significant. Studies report that annual HVAC related energy savings for the non-residential building stock are between 5-30% [4-7]. Furthermore, energy policies and sustainability awareness gives that companies are increasing their interest to preserve energy consumption, while maintaining comfort [17].

Controllable & Non-Controllable Parameters

Building HVAC operations starts with a certain building use and ambient conditions (Input). It subsequently gives output on indoor conditions and energy consumption. The HVAC performance efficiency depends on building physics, HVAC- hardware, control strategies and quality of maintenance. Building & HVAC parameters can be divided in controllable and non-controllable [18]. An overview of input-, output-, controllable- and non-controllable parameters is given (see figure 1.2).

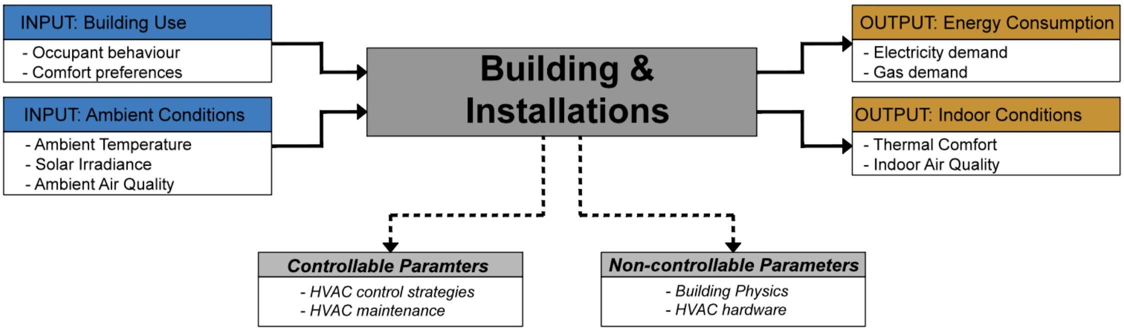

Fig. 1.2: Schematic overview building HVAC performance related parameters.

Over the years systematic legislation updates resulted in decreasing losses regarding non-controllable building and HVAC parameters. Subsequently efficiency losses through controllable parameters have become more sensitive [18]. For newly installed office buildings (built after 1995 [19]) it's shown that the potential to improve performance can be mainly found in the controllable parameters [5,18].

As previously discussed, excessive conditioning of indoor air is a common example of energy waste. Monitoring studies give that rate of occupancy is generally below 60% [8]. However, HVAC systems operate according design control strategies: using simplified and/or unrealistic inputs regarding building use [5-7]. As a result HVAC control strategies aren't able to efficiently fulfil actual demand. Control strategy modification in regard to actual building behaviour can give outcome [6-9].

Periodic maintenance is critical when retaining optimal operations. Inefficiencies in current HVAC systems can often be found in unknown defaults of installation components. Common examples are not properly working valves, hydraulic leakages and/or systems that are operating on the input of a defect sensor [4-6,20]. Hence a high quality of maintenance is essential in retaining efficient HVAC system performance.

1.1.3. Re-Commissioning HVAC: systematic performance assessment

Continuous commissioning (CCx) is widely discussed to prevent controllable parameter related problems. Implementing CCx comes with sophisticated monitoring- and control systems [4,21-23]. In order to systematically obtain a CCx process, literature discusses a combination of re-commissioning (RCx) and monitoring-based commissioning (MBCx) [4,22].

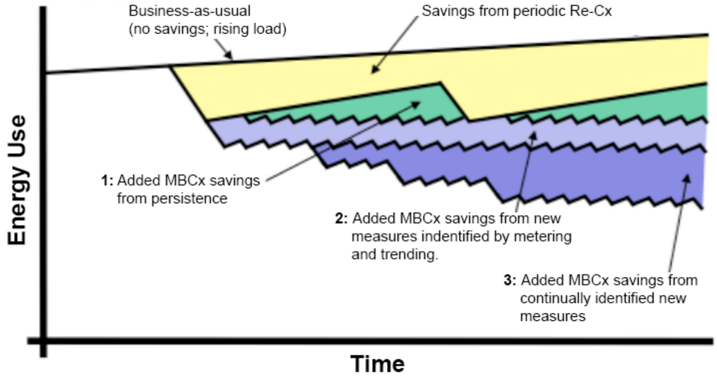

Fig. 1.3: Three streams of additional efficiency improvement (modified from [4]).

Goal of this combination is to obtain more and more performance efficiency (see figure 1.3). First step implements energy information systems (EIS) and fault detection and diagnosis (FDD) tools. Second step emphasizes savings from the EIS and FDD. Third step emphasizes the development of the CCx process, continually identifying new measures while simultaneously improving the tools [4,22].

Because HVAC system complexity has increased, identification of inefficient controllable parameters has become more intense. It's shown that RCx methods do not always addresses the most inefficient controllable parameters [10,22,23]. Consequently, the RCx-MBCx combination isn't optimally deployed.

The Lean Energy Analysis (L.E.A.) method aims to avoid these risks. L.E.A. emphasizes the on-going elimination of non-value added activities by a top-down approach. It starts with quick and abstract energy use breakdowns and assigning it to functions. Subsequently, discovery of energy saving potential is promoted by graphical data analysis and modelling [25,26]. L.E.A. can be dived in three: analysis, modelling and saving potential.

RCx according L.E.A.

First step is on case study design analysis and evaluating the actual performance. Regarding the design a performance is expected. By means of a top-down approach the design expectations are subsequently compared to the performance evaluation. The first step ends with concluding the discovery of inefficiencies.

Second step emphasises the modelling of possible performance improvement. From the concluded inefficiencies, the problem with the most saving potential will act as scope. Subsequently a benchmark and design model is built to define saving potential. Simulations are performed and results are compared.

Third step is on concluding the simulation results and defining RCx recommendations. Because of the top-down approach efficiencies are often identified on an abstract level. Therefore solving the actual inefficient controllable parameter often includes further research. Finally, RCx recommendations are formulated in consideration of repeating L.E.A. on a more detailed level.

In relation to CCx, if the L.E.A. method is feed with a high granularity of data the better inefficiencies can be traced [26]. The top-down approach of L.E.A. emphasises that is will be repeated on a more and more detailed level [25]. In addition the granularity of input data will increase. Consequently, L.E.A gives outcome in systematically obtaining CCx. By reinvesting the obtained savings in repeating L.E.A. the method contributes in the development of EIS and FDD tools.

1.2. Research Introduction

Compared to their design HVAC systems in newly office buildings are systematically underperforming. Results are lower comfort conditions and higher energy consumption profiles. Research concludes that during the exploitation most problems can be found in HVAC system controllable parameters [4-6,10,11].

CCx is widely discussed to prevent these problems [4,22,23]. However, implementation is complex [22,23]. RCx gives outcome on periodically increasing the quality of HVAC performance [21]. Moreover, it gives outcome to be utilized as a strategic step towards CCx [4,22]. However, HVAC system complexity gives that RCx isn't always performed effective [11,25]. L.E.A. gives outcome in effectively performing RCx.

1.2.1. Objectives

Literature indicates HVAC in newly installed offices is underperforming. Hypothetically a high potential on improvement of the performance exist. By means of a case study (introduced in chapter 3) this hypothesis is investigated according the following objectives:

I. While considering CCx, utilizing RCx to identify inefficient critical controllable parameters regarding the HVAC performance of a newly installed office building.
II. While considering CCx, providing RCx recommendations regarding the adjustment of critical controllable parameters to improve the HVAC performance of a newly installed office building.

1.2.2. Questions

The objectives are translated into the following research question and sub questions.

"How can RCx be utilized as a first step in the process to obtain CCx regarding HVAC systems in the existing office building stock?"

Sub Questions

I. According RCx what are the critical controllable HVAC parameters of the case study, and to what extent do they influence the HVAC performance?
II. Which datasets are needed to apply RCx on the case study HVAC, and how can the dataset be extended in regard to CCx?
III. Which data properties are essential to obtain HVAC benchmark models related to the case study, and what is its potential in regard to the RCx process?

1.3. Method of Research

To effectively address inefficient controllable HVAC parameters, the research methodology is formulated according L.E.A [25,26]. Following the applied research method is given (see figure 1.5).

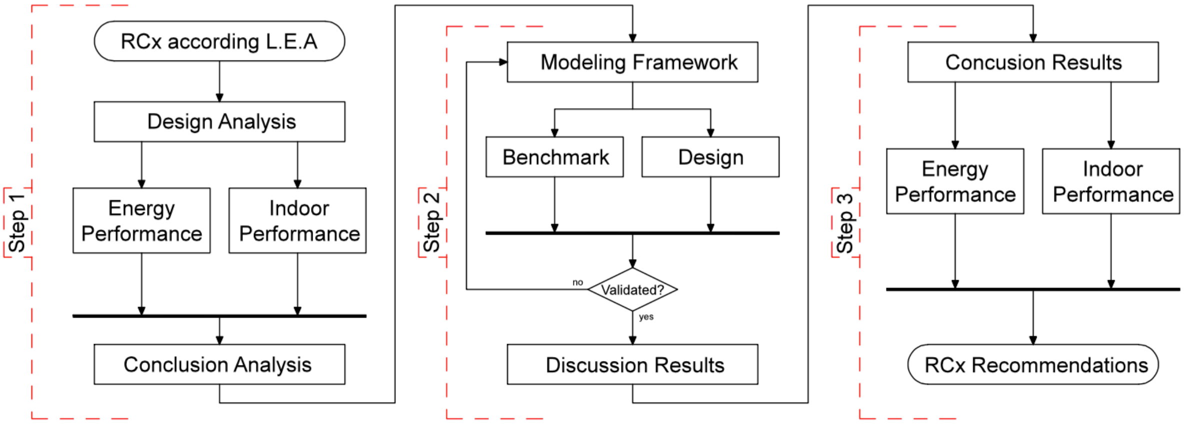

Fig. 1.5: Research methodology for RCx office building HVAC.

Step 1

A case study is selected, its design is analyzed and HVAC related performance data is obtained. Subsequently, a performance analysis is conducted according a top-down approach. Finally potential inefficiencies regarding HVAC controllable parameters are concluded.

Step 2

The inefficiency with the highest saving potential is investigated by a model-based approach. Benchmark- and design models are created. Subsequently simulations are performed and results are discussed.

Step 3

Regarding the first research objective conclusions are made on behave of HVAC performance and improvement potentials. Regarding the second research objective, RCx recommendations are provided to optimize HVAC performance.

1.4. Report Outline

Chapter 2 describes the theoretical framework regarding HVAC RCx according L.E.A. Chapter 3 gives the case study design analysis and respectively acquisition, normalization and reliability of HVAC related performance data. Chapter 4 discusses the performance analysis on energy consumption and indoor conditions.

Chapter 5 describes the performance modeling and discusses the results. Chapter 6 provides the conclusions on HVAC performance and RCx recommendations in more detail. Finally, chapter 7 gives the answerers to the research questions.

2. Framework: HVAC RCx according L.E.A.

Literature widely discusses the inefficient performance of HVAC in newly office buildings [4-6]. Inefficiencies are mostly related to HVAC controllable parameters [4-6,10,11]. Although implementation is seen as complex, CCx has the potential to overcome these inefficiencies [21-23]].

RCx can be utilized as a strategic step towards CCx. However, HVAC system complexity gives that RCx isn't always performed most affective [11,25]. The Lean Energy Analysis (L.E.A) gives outcome to overcome these risks. By a top-down approach the L.E.A. method emphasizes that RCx is performed effectively at least cost [25,26]. Starting from top level, the system performance is systematically evaluated downwards. L.E.A. for HVAC can be dived in three:

1. Design & performance analysis.
2. HVAC performance modeling.
3. HVAC result conclusions & RCx recommendations.

2.1. Step 1: Design & Performance Analysis

First step in L.E.A is the HVAC design & performance analysis. Following a schematic overview of the performance analysis process is given (see figure 2.1).

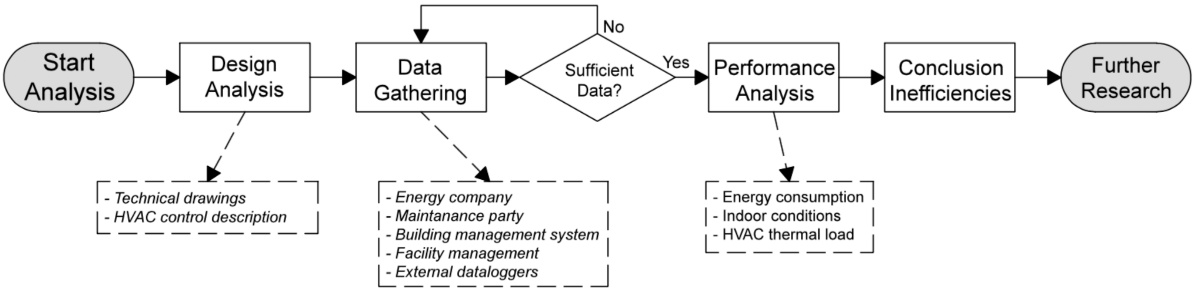

Fig. 2.1: Flow chart regarding the HVAC performance analysis process.

By means of technical documentation the case study design is analyzed. The documentation needs to contain information on HVAC system operations and building construction physics. HVAC in newly office buildings are often equipped with a lot of sensors [4,5]. Therefore design analysis needs to be performed in consideration of data acquisition opportunities.

Subsequently HVAC related performance data is gathered. Energy companies can provide historical data regarding the main- electricity and gas consumption. The maintenance party can provide historical data on a more detailed system level. Facility management (FM) gives outcome in understanding the actual building use. Incase additional data is needed the data acquisition opportunities are known from the design analysis.

If the HVAC design is understood and the dataset is sufficient, performance analysis can be initiated. According the top-down approach, the actual performance analysis starts by examining variables situated at the end of the process. For HVAC this generally means analysis of indoor conditions and main energy (gas and electricity) consumption. By graphical analysis the behavior of variables is obtained and anomalies can be detected in an early phase.

From the detected anomalies the rate of inefficiency is concluded. Subsequently, the inefficiency with the highest saving potential will act as the scope for further research.

2.2. Step 2: HVAC Performance Modeling

Second step in L.E.A is modeling the concluded HVAC inefficiencies. Following a schematic overview of the performance modeling process is given (see figure 2.2).

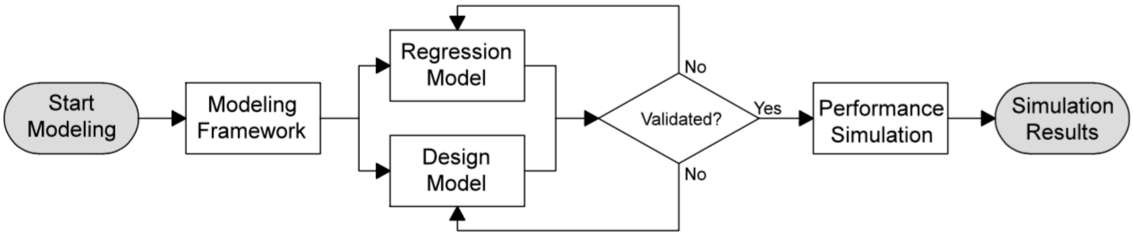

Fig. 2.2: Flow chart regarding the HVAC performance modeling process.

Modeling the physical building performance is a complex and time-consuming process. L.E.A. aims to reduce time consumption. In regard to the detected inefficiencies, the framework will only include models that simulate the variables needed. Modeling is divided in two: benchmark- and design models.

The benchmark model represents the empirical situation. These models are obtained by linear regression. The multi-parameter regression depends on the case [25,40]. In general ambient temperature (Te) is a dominant variable in HVAC demand. However, incase of CO_2 controlled ventilation the influence of building occupancy behavior needs to be considered [40,41]. Subsequently, the obtained models are validated by historical trend analysis. Following an example of a three-parameter regression process is given (see figure 2.3).

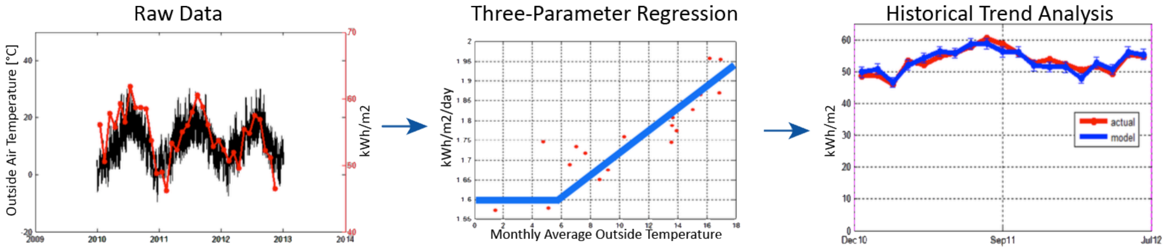

Fig. 2.3: Process overview of two-parameter regression (modified from [26]).

A design model can be obtained in various ways. For an abstract comparison a larger benchmark database of similar buildings can be used. Incase information is needed on a more detailed system level, deterministic modeling gives outcome. Main fundamental of the approach is a low level of time-consumption. Deterministic models are often built during the design of an office building. Incase this model is present it can be used. If not a design model needs to be obtained in a low amount of time.

It both the models are validated, simulations are performed. The benchmark model is simulated according empirical settings. The design model is simulated according design settings. Subsequently, the simulation results are compared.

2.3. Step 3: Result Conclusions & RCx Recommendations

The performance analysis concluded inefficiencies. In addition simulations quantify the saving potential. In regard to the first two steps, step 3 of L.E.A. concludes the HVAC performance on indoor conditions and energy consumption. Furthermore, to quantify savings it concludes the improvement of the benchmark models.

L.E.A is a top-down approach. Subsequently it depends on system complexity if the method targets the critical controllable parameter. If the critical parameter is known, RCx recommendation will be on potential adjustments. If not, the method identified the area where the most critical controllable parameter is situated. In addition recommendations are made in regard to initiating further research.

3. L.E.A. Step 1: Design Analysis

From the CWD maintenance portfolio the Ziggo office building in Leeuwarden, Netherlands is selected. Chapter 3 describes the design analysis. First, the technical analysis of the case study design is described. Second, the acquisition, normalization and reliability of HVAC performance data are described.

3.1. Case Study Design

Developed for mainly call center employees of Ziggo, the design emphasizes the stimulation of occupant productivity and a sustainable use of energy. It has a gross floor area of 7.800m^2 divided over five stories. The building is able to house 540 employees. The built is completed in early 2012 [27]. Following a photo impression of the interior and outdoor façades is given (see figure 3.1).

Fig. 3.1: Impression Ziggo office building Leeuwarden, Netherlands (pictures from [27]).

The case has a calculated energy performance coefficient (EPC) of 0,516 [33]. Furthermore, the design received a BREEAM-NL Excellent- and LEED Platinum label; first of it's kind in the Netherlands [27,33]. Consequently, the case is equipped with a variety of sustainable measures:

- 292 photovoltaic panels (457m^2)
- LED light acting on occupancy and daylight
- Gray-water circuit
- High insulation value (Rc: ±5,0m^2K/W)
- Ventilation by variable air volume (VAV)
- Aquifer thermal energy system (ATES)
- Electrical powered heat pump (HP)

Because of the presence of ATES, according Dutch guidelines the HVAC system needs to be divided in three: demand side, power plant (PP) and ATES [28]. Building- construction physics, use and HVAC installations form the demand side. The power plant (PP) includes the HP, boiler and heat exchanger (HEX). The ATES includes the wells, well pumps and a facility to provide additional cold regeneration.

Appendix A.2, figure a2.1 gives the principles regarding HVAC thermal energy system. Appendix A.2, figure a2.2 gives a schematic system overview for a heating and cooling operation. Fist, building- construction physics and use are described. Second, the HVAC installations are described. Third, the PP is described. Fourth, the ATES is described.

3.1.1. Demand Side: Building Physics & Use

Divided over five stories, the building includes two atria (4500m^3), 6 office gardens (13840m^3), 1 restaurant (1990m^3), kitchen (165m^3) and hallways/toilets (2125m^3). Ceiling height is generally 2.84m high. Excluding both atria the HVAC conditioned building volume is ±18.000m^3. Including both atria the total HVAC conditioned building volume is ±23000m^3.

The 6 office gardens represent 540 working desks. The building is open between 06:00-23:00h. Default indoor temperature (Ti) is 21°C, 24 hours a day. For a building zone heating and cooling set point is respectively 21°C and 22°C. Building façades are highly insulated. Rc-value of the façade is 5,0 m^{2}K/W. U-value of the external glass is 1,6 W/m^{2}K. Infiltration (qv;10) is 0,2 dm^3/s.m^2. Appendix A.1 gives the building construction properties in detail.

3.1.2. Demand Side: HVAC systems

The HVAC system includes climate floors, climate ceilings, air handling units (AHU) and radiators. The central heating and cooling system distributes thermal energy to the emission installations. Figure 3.2 gives an overview of the central system. Appendix A.2, figure a2.1 and a2.2 give the principles regarding the complete thermal energy system.

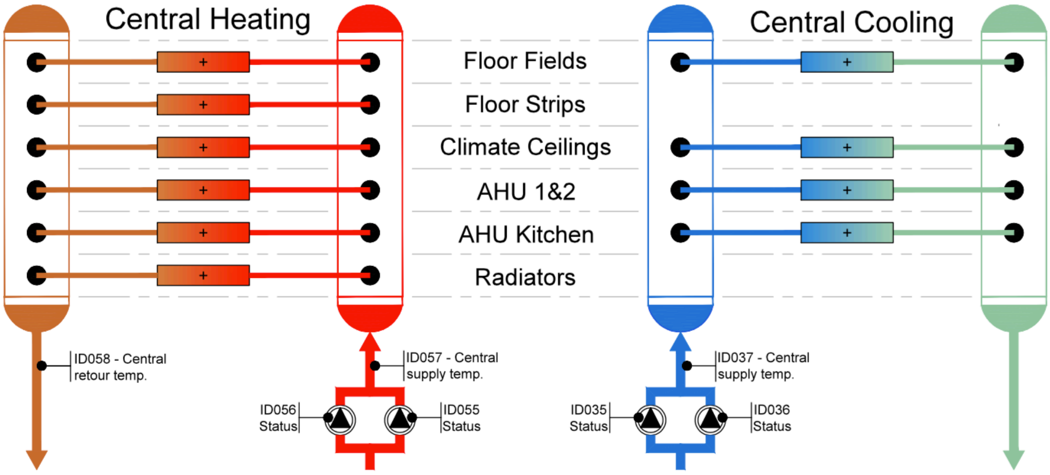

Fig. 3.2: Overview central heating and cooling system (IDs according Appendix B.1.1).

Variable-flow pumps maintain the water pressure in both systems. As a function of the ambient temperature (Te), the central water supply temperature is determined according the control curves (see figure 3.3).

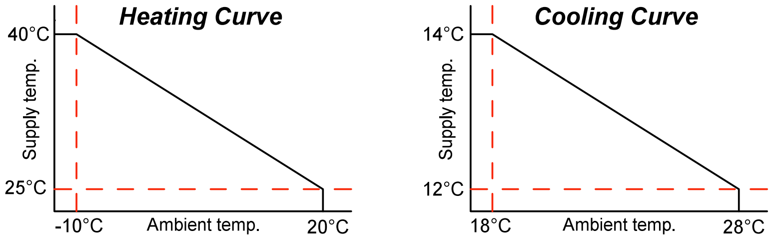

Fig. 3.3: Control curves for central supply temperature heating and cooling.

Climate Floor

The climate floor can be divided in strips and fields. Adjacent to the façade, floor strips are present at all floors. Floor fields are present at the first and second floor. Both systems operate 24 hours a day. Floor strips and fields are controlled separately. Floor strips can provide heating. Water supply temperature is between 20-36°C. Floor fields can provide heating or cooling. For heating the supply temperature is between 20-26°C. For cooling the supply temperature is between 16-19°C. Appendix A.2.1 describes the system principles in detail.

Climate Ceiling

The climate ceiling is situated in the restaurant and offices. Per building zone it's controlled individually. Each zone contains several ceiling modules. Furthermore, the occupant can locally influence the operation of a set of modules. Through local thermostats standard Ti set point of 21°C can be adjusted with 1,5K. The central water supply temperature for heating is between 25-36°C. For cooling the central supply water temperature is between 16-18°C. Because per building zone the system operates individually, heating and cooling can be provided simultaneously. The system operates 24 hours a day. Appendix A.2.2 describes the system principles in detail.

Air Handling Units

Three independently operating AHU systems are installed. Activated manually, the kitchen is ventilated by a single AHU. For the restaurant, offices, toilets, hallways and atria two AHU's are installed. Ventilation is active between 06:00-23:00h. Ventilation for the restaurant and offices is performed by a VAV. At a constant rate air extraction of the toilet rooms and hallways is done separately. Supply air temperature for all AHU's is between 18-20°C. Summer night ventilation can be activated for the office AHU's. Appendix A.2.3 describes the system principles in detail.

Radiators

Radiators are present at the ground and first floor. The radiator group also contains an air curtain, situated at the entrance at the East façade. Appendix A.2.4 gives the system principles.

3.1.3. Power Plant

The PP is responsible to meet HVAC thermal demand. The PP contains an HP, two stratified thermal buffers, gas fired boiler and HEX. By a countercurrent HEX the PP is connected to the ATES. Consequently the PP is partly responsible for ATES State Of Charge (SOC). Following an overview of the PP is given (see figure 3.4).

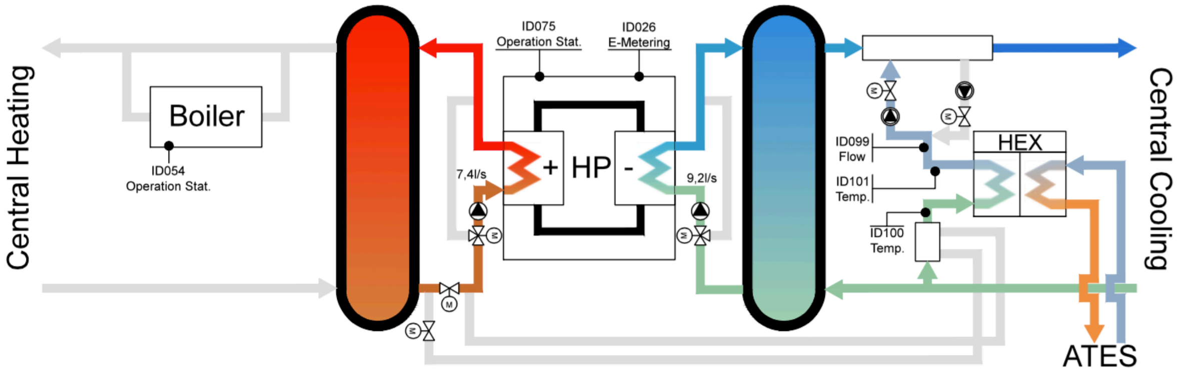

Fig. 3.4: Overview PP with HP in cooling mode (IDs according Appendix B.1.1).

The PP has six different modes of operation. Following the operation modes are given:

1. HP and HEX warm well;
2. HP, HEX warm well and boiler;
3. Heat balance (no operation);
4. HEX cold well;
5. HEX cold well and HP;
6. HEX cold well and boiler.

The central- heating and cooling water temperature is respectively between 25-40°C and 12-14°C. Extraction temperature of ATES warm well is between 10-15°C. Consequently the water temperature needs to be increased by the HP. In case the HP isn't sufficient the boiler is invoked.

For cooling the central supply temperature is in the same range as the extraction temperature of ATES cold well (7-12°C). Subsequently, heat transfer through the HEX is generally sufficient to satisfy cooling demand. If not, the HP is invoked as chiller. Appendix A.2.5-8 discusses respectively the HP, thermal buffers, boiler and HEX in detail.

3.1.4. ATES

Thermal energy storage is performed by a doublet system. Each well contains it's own variable pump and pressure controlled injection valve. For the cold well extra regeneration can be invoked. Following an overview of the ATES is given (see figure 3.5).

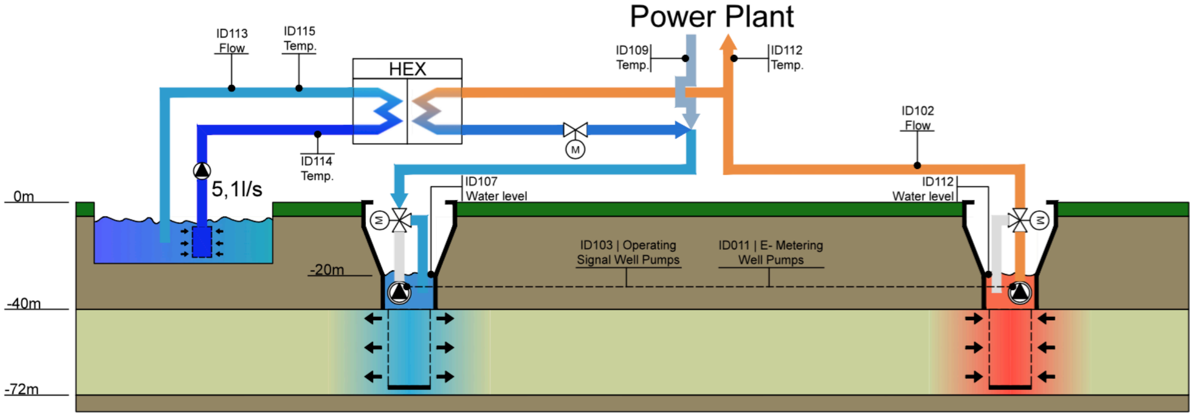

Fig. 3.5: Overview ATES during heating mode and extra cold charging enabled (IDs according Appendix B.1.1).

The groundwater (GW) conditions need to satisfy Dutch legislation (art. 6.4 Waterwet [26]) and the license granted. The wells are equipped with similar underwater pumps. Both pumps are limited at a lower and upper pumping rate of respectively 6,5m^3/h and 33m^3/h.

Additional regeneration for the cold well can be enabled. Because maximum pump capacity is 39m^3/h, 6m^3/h is always available to use for extra cold charging. GW of the warm well is transported to a HEX that exchanges energy with water of the nearby canal. Activation of extra regeneration is enabled manually. Appendix A.2.9 describes respectively the aquifer legislation, well pumps and regeneration facility in detail.

3.2. Data Acquisition, Normalization & Reliability

For the case at hand HVAC related performance data is acquired. Consecutively, the acquired data is normalized and the reliability is examined. First, the process of data gathering is described. Second, data normalization is described. Third, examining the reliability of the acquired data is described.

3.2.1. Data Acquisition

HVAC related performance data is acquired from five sources: Department Telecontrol at CWD, room conditions from building management system (BMS), room conditions from TU/e data loggers, ambient conditions from KNMI [29], and periodical occupancy counts from facility management (FM).

Telecontrol

Regarding the Ziggo Office a dataset of 173 variables is obtained by CWD, department Telecontrol (see Appendix B.1.1). Measurement lengths vary between April 2012 and February 2016. Concerning the PP and ATES most operation status, physical- (temperatures and flows) and energy measurements are logged. Concerning the demand side mainly electricity and thermal energy measurements are logged. The dataset doesn't contain indoor condition measurements.

Indoor Conditions

For the reception, restaurant and offices the indoor condition measurements are obtained between November 2015 and January 2016. Through the BMS 10 Ti and 9 CO_2 measurements are logged (see Appendix B.1.2). To calibrate the BMS measurements, TU/e data loggers where installed on the second floor (see Appendix B.1.3).

Ambient Conditions

Ambient conditions are obtained from the KNMI weather station database Leeuwarden, Netherlands [29]. It includes information about temperature, humidity, solar radiation, wind direction and rainfall. According the Raaff method KNMI solar radiation data is converted to direct and diffuse radiation [32].

Occupancy

Over the year's FM of Ziggo incidentally identified building occupancy. Counts where performed during weekdays by FM employee Melle Schippers. In 2013, two incidental counts where performed. In 2015, a more extensive occupancy counting was performed (see Appendix B.1.3).

3.2.2. Normalization

To simplify the performance analysis the acquired data is normalized. First, normalization of the Telecontrol dataset is described. Second, normalization of indoor conditions dataset is described.

Telecontrol

From the 173 variables 104 are relevant. According the previously discussed system boundaries the variables are classified (see Appendix B.2.1). Measurement lengths deviate, varying between 15/04/2012 – 01/02/2016. Data log intervals vary between month, day, hour, 10 minutes, minute and log of change.

A lot of variables include time gaps. Furthermore, data analysis needs to be done with equal vector lengths. Subsequently, an algorithm is built that equals the vector lengths and identifies data gaps (see Appendix B.2.2). When a data gap is detected the cell is filled with 'Not a Number' (NaN).

Indoor Conditions

Between 3/11/2015 – 01/02/2016, BMS indoor condition measurements are logged every 10 minutes. Limited BMS access resulted in data gaps. Missing data points are replaced by NaN. Between 14/10/15 – 1/02/2016, TU/e data loggers measured indoor conditions every 10 minutes. Vector lengths of both datasets are made similar to each other, representing a time length of 04/11/2015 – 01/02/2016.

3.2.3. Reliability

Data analysis comes with considering the reliability. Research is performed on HVAC related data [30,31]. The examined datasets where mainly extracted from BMS's. It's concluded that a variety of reasons could give uncertainty. Appendix B.3 describes the process of examining the reliability of the acquired data in detail.

Telecontrol

Regarding the Telecontrol dataset it's discovered that a lot of variables give uncertainty on measurement processing and missing/incomplete content. E.g. varying ways of data logging and insufficient measurements to define system dynamics. Regarding the ATES measurements accuracy of temperatures and flows are known. The rest is unknown. Appendix B.3.1 describes the reliability of the Telecontrol dataset in detail.

Indoor Conditions

Measurement accuracy of TU/e transmitters is known. Measurement accuracy of the BMS CO_2 transmitters is known. Comparison of CO_2 results shows similarity for higher values. For lower values deviation can go up to 130ppm. Measurement accuracy of BMS Ti is unknown. Comparison with TU/e measurements gives an average deviation of 0,5^{o}C. During peak values deviation can go up to 1,5^{o}C. Appendix B.3.2 describes the reliability of the indoor conditions dataset in detail.

4. L.E.A. Step 1: Performance Analysis

Chapter 4 describes the performance analyses according the top-down approach of L.E.A. First, the approach of analysis is described. Second, respectively the analysis of energy consumption, ATES and HVAC is described. Finally, the performance analysis is discussed.

4.1. Analysis Breakdown

HVAC systems in office buildings are systematically underperforming. According the problem analysis office HVAC related problems are often found in the controllable parameters. However, system complexity gives that adjustments aren't always optimal [4-6]. L.E.A. emphasizes a top-down approach to discover inefficiencies at least cost. The top-down performance analysis starts with variables at the end of the process that are related to controllable parameters. In case of unexpected results further research could be initiated [25,26].

The HVAC related system is divided in demand side, PP and ATES. By means of HVAC, goal of the demand side is to satisfy indoor conditions (IAQ and TC). Goal of the PP is to satisfy HVAC thermal demand. Goal of ATES is to contribute in delivering thermal energy. The complete process results in total energy consumption. Each component has its contribution. The relationship of each component in regard to each other and total energy consumption is given (see figure 4.1).

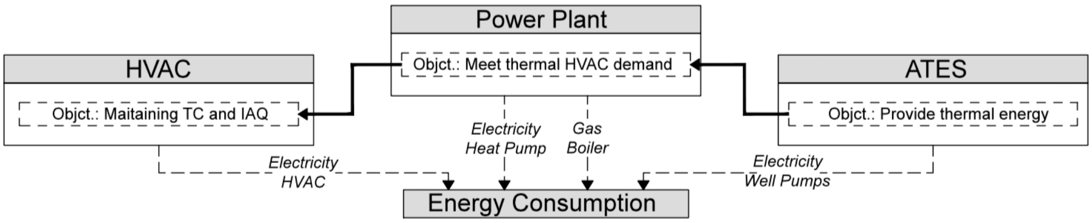

Fig. 4.1: Mutual relationship of case study system components and their contribution to total energy consumption.

From the design analysis a certain performance is expected. Total energy consumption is a parameter including information about all three components. Therefore total energy consumption is considered as a top-level variable. However, physical conditions of ATES and HVAC simultaneously need to be considered when analyzing the HVAC related energy consumption [10,11]. Consequently, the performance analysis flow chart for the Ziggo office building is formulated as followed (see figure 4.2).

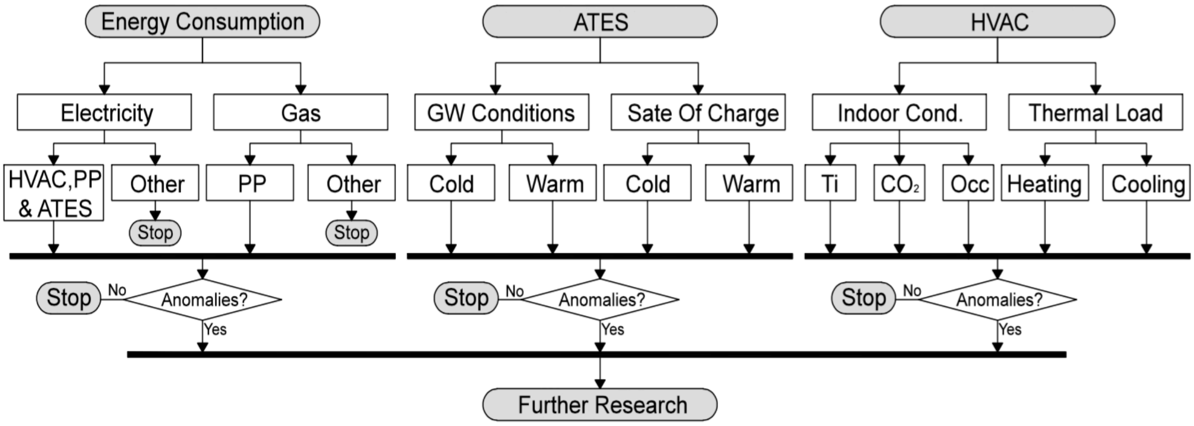

Fig. 4.2: Case study top-down HVAC performance analysis flow chart.

Interdependency gives energy consumption-, ATES- and HVAC analysis are initiated simultaneously. Influence of HVAC on total energy consumption is significant [3]. Gas- and electricity analysis is performed to identity the HVAC related consumption and its behavior. ATES- GW conditions and SOC are related to the system performance efficiency. Consequently, GW conditions and SOC for respectively the warm- and cold well are analyzed. Indoor conditions and thermal load determine the quality of HVAC performance. Ti, CO_2 concentration and occupant behavior are indoor variables effecting HVAC thermal load. Consequently, indoor conditions and thermal load are analyzed.

4.2. Energy Consumption Analysis

Gas- and electricity consumption are related to HVAC operations. Consequently, the quantitative performance of both parameters is analyzed. First, analysis of total energy consumption is described. Second, analysis of electricity consumption is described. Finally, analysis of gas consumption is described.

4.2.1. Total Energy Consumption

During design the building energy performance is calculated. Representing an EPC of 0,516, an average annual specific primary building-related energy demand (SPBED) of 340MJ/m^2/year is expected [33]. For 2013 and 2014 the complete annual energy consumption is known. The empirical results are compared to the average Dutch office building- and calculated consumption (see figure 4.3).

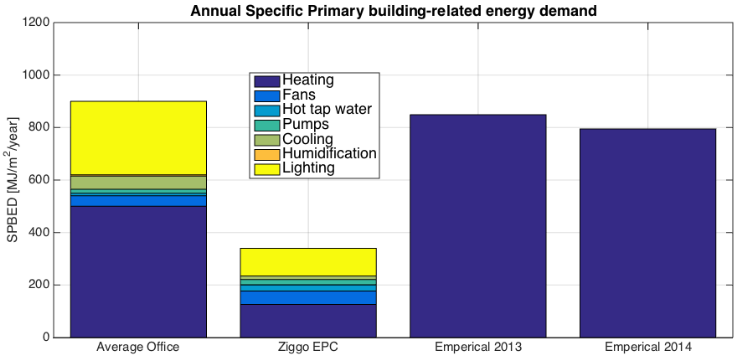

Fig. 4.3: Comparison annual primary energy consumption Ziggo office.

Conversion factors for respectively electricity (ID003) and gas (ID033) are 2,5 and 1 [35]. 1m^3 natural gas equals 31,65MJ/m^3 [35]. The annual measured electricity (ID004) generated by the PV system and the plug & process loads are subtracted. It's assumed that 33% of the annual electricity use is plug & process related [36].

For 2013 and 2014 the annual SPBED consumption is respectively 2.5 and 2.3 times higher than expected. If the EPC calculation is performed correctly, this indicates a reduction potential of approximately 70%.

4.2.2. Electricity Consumption

A wide variety of electricity measurements are obtained. Te is dominant in determining HVAC operations. Main electricity measurement (ID003) is broken down in relation to Te. Subsequently, the part sensitive to Te is obtained (see figure 4.4 and Appendix C.1.1, figure c1.1).

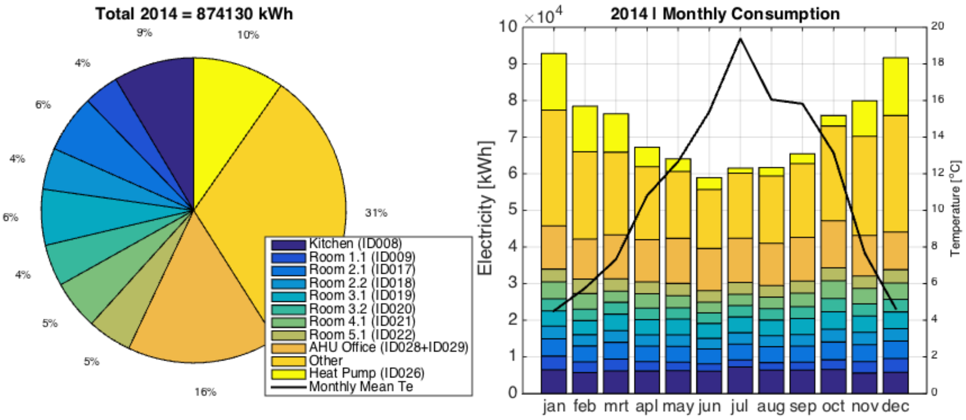

Fig. 4.4: 2014 electricity consumption breakdown.

Room measurements include the consumption of lighting and office appliances. The AHU measurement includes the supply- and extraction fan. Change in consumption in relation to a change in Te is minimal. The 'other' measurement represents the unidentified electricity consumption. It's shown that 'other' decreases with increasing Te, indicating a relation to HVAC. Furthermore, HP consumption decreases with increasing Te. According design specifications this is expected.

HP electricity behavior is related to 100% of the HVAC conditioned building volume. Consequently examining the HP behavior in more detail can discover inefficient operations. For 2014 hourly insight regarding Te, main- and HP electricity consumption is given (see figure 4.5).

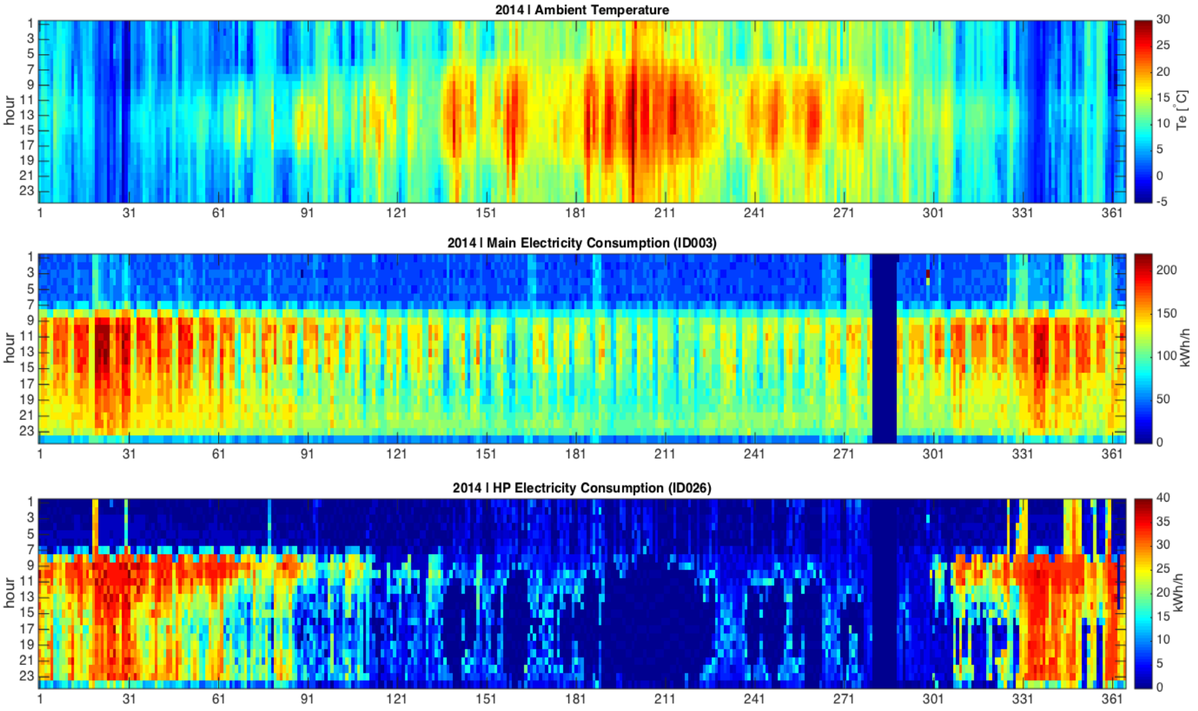

Fig. 4.5: Carper plot 2014 ambient temperature, main- and HP electricity consumption (between day 280-290 is data gap).

Main consumption gives a clear pattern on weekdays and weekends (also see Appendix C.1.1, figure c1.2). The difference is related to plug & process loads (Appendix C.1.1, figure c1.3). This means a difference in occupancy. Due to the presence of VAV a weekday/weekend pattern in HP consumption behavior is expected. This is not the case. HP peak consumption equals 53kWh/h, giving that the HP is mainly operating in partial load.

Main and HP consumption generally occurs between 06:00-23:00h. This is similar to the office AHU operations. After 23:00h less HP consumption is shown. Peak HP consumption occurs during the morning and evening. Average Te during the night is lower compared to daytimes. Design analyses gives Ti is maintained at 21°C, 24 hours a day. Therefore a heating demand during night times is expected. Consequently, HP consumption for respectively night (00:00-06:00h) and daytimes (06:00-00:00h) is examined (see figure 4.6).

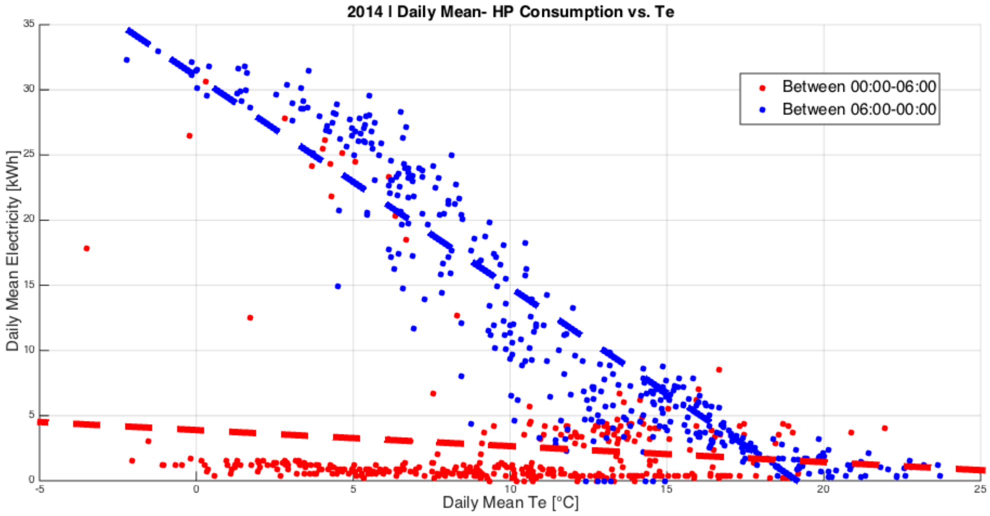

Fig. 4.6: Per day, 2014 mean- HP electricity consumption vs. Te.

Trend lines show that HP activity for Te < 15°C is significantly higher between 06:00-00:00h. During the night ventilation is off, reducing heating demand. In contrast the occupant related internal load (body heat, lighting, desktop computers) and mean Te are lower, increasing heating demand. Consequently interest arises in the following:

1. If heating demand during night times reduces significantly, what is the internal load and ventilation behavior at daytimes?
2. If the HP doesn't satisfy heating demand during night times, what are the operations of the boiler?

Internal Load & Ventilation

Room electricity measurements include local HVAC-, lighting- and appliances consumption. Lighting reacts on daylight and occupancy. The 540 computers represent a big part of the appliance related consumption. Ventilation is performed as a function of CO_2 concentration. In addition room- and AHU measurements both contain information regarding occupant behavior. Consequently, internal load and ventilation are examined by room- (ID009, ID017-ID022) and office AHU fan (ID028) measurements (see figure 4.7).

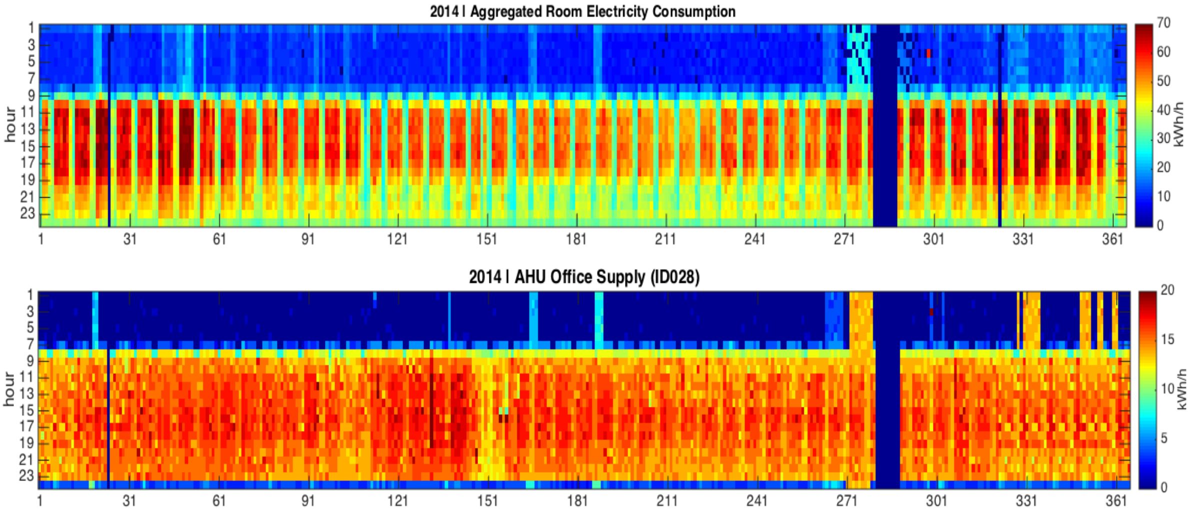

Fig. 4.7: Carper plot 2014 room- and HP electricity consumption (data gap between day 280-290).

Room consumption decreases after 18:00h. The pattern between weekdays and weekends consumption is clearly visible. Decrease in room consumption is related to a decrease in occupancy, thus CO_2 concentration (further explained in chapter 4.4.1).

Due to the VAV control a similar pattern in office AHU fan consumption is expected. This is clearly not the case. According the specific fan power (SFP) the office AHU supply fan equals an almost constant air supply rate of 48.000m^3/h. According design this almost equals the full operation capacity (see Appendix A.2.3). Appendix C.1.1, figure c1.4 gives that the office AHU 2014 pattern is similar for almost the complete measurement period. Consequently, it's concluded that exceeding ventilation occurs between 06:00-23:00h.

4.2.3. Gas Consumption

Gas consumption is related to the boiler and kitchen. Main (ID033) and kitchen (ID034) gas consumption are measured. Consequently, ID033 minus ID034 represents the boiler consumption. Gas consumption is broken down (see Appendix C.1.2, figure c1.4). More than 90% of annual gas consumption is related to boiler operations. As expected, boiler gas consumption reacts inverse to Te.

It's shown that HP consumption during the night is very low. In addition interest arose in boiler operations during the night. Consequently, hourly insight regarding boiler gas consumption is obtained (see figure 4.8 and Appendix C.1.2, figure c1.5).

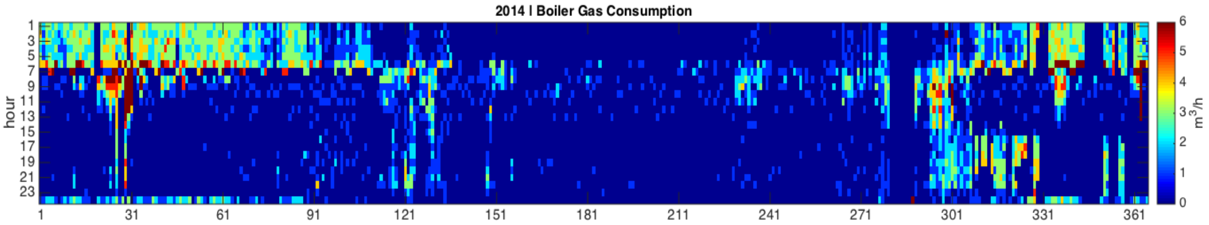

Fig. 4.8: Carper plot 2014 boiler gas consumption (data gap between day 280-290).

For colder months it's clearly shown that boiler gas consumption mainly occurs during night times. Boiler has a waterside efficiency of 108%. Peak boiler operations equals' 283kWh/h (see Appendix A.2.7). This equals a maximum gas consumption of 26,8m^3/h. For both night and day operations the boiler mainly operates in partial load.

Central heating supply water temperature is determined as a function of Te (see Appendix A.2.7). The boiler operates as a function of the supply water temperature, thus Te. Between 00:00-06:00h (night) and 06:00-00:00h (day) the relation between boiler consumption and Te is examined (see figure 4.9).

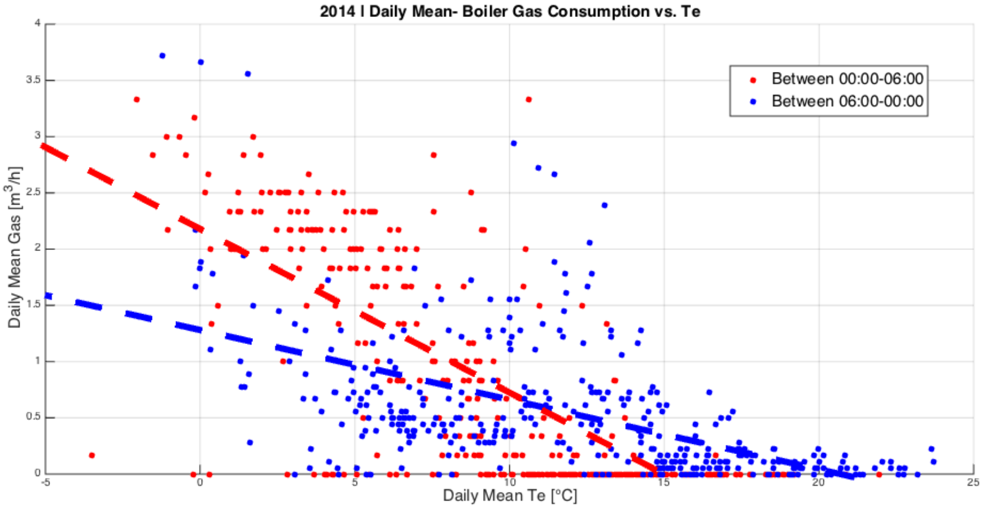

Fig. 4.9: 2014 daily mean- boiler gas consumption vs. Te.

For Te > 15°C gas consumption during daytimes is higher. This indicates the boiler satisfies heating demand when HP is in cooling operations. For similar Te, gas consumption during the night is significantly higher. In consideration of the HP consumption pattern, it's concluded that the boiler satisfies HVAC thermal heating load during night times. It looks like the shift between both systems is related to clock settings. However, this is not known.

Office AHU on/off operations are similar to the obtained shift. Moreover, office AHU operations significantly affect the central heating behavior (further explained in chapter 4.4.2). Incase the office AHU operations are off; retour temperature of the central heating can be higher. In addition, retour temperature is too high so HP isn't invoked. However, the delta temperature between the supply and set point can be from a size that the boiler eventually is enabled. Again, this is unknown.

4.3. ATES Analysis

Quality of ATES influences the energy efficiency of the PP, thus HP and boiler. ATES operations come with legal boundaries (see Appendix A.2.9). Data acquisition gives flow-, temperature- and thermal energy measurements at the ATES side (see figure 3.4 & 3.5). Respectively the analysis of GW conditions and ATES SOC are described.

4.3.1. Groundwater Conditions

Warm (ID112) and cold (ID109) well temperatures are logged every 10 minutes. GW flow (ID102) is logged if a change is observed. On/off operation of respectively the warm- (ID106) and cold (ID105) well pump is logged in case a change is observed. ID102, ID105 and ID106 are normalized to 1-minute vectors. Well temperatures are interpolated from 10- to 1-minute vectors.

Frist daily behavior of ATES operations is examined. To obtain GW injection and extraction conditions, the flow (ID102) and temperatures (ID109, ID112) are multiplied by the operating signal of the well pumps (ID105, ID106). It's concluded that ATES operations mainly occur between 06:00-23:00h (see Appendix C.2.1, figure c2.1). In addition daily mean GW well temperature during operations is examined (see figure 4.10 and Appendix C2.1, figure c2.2).

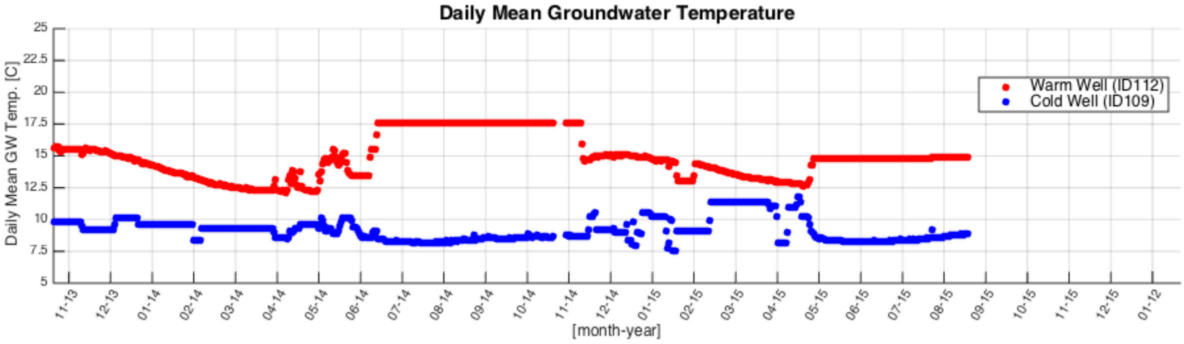

Fig. 4.10: Daily mean ATES well temperatures for ID109 and ID112.

Regarding the warm- and cold well injection temperature unexpected trends are shown. Furthermore, cold well extraction temperature between June and October 2013 gives a decreasing trend (see Appendix C2.1, figure c2.2). Dutch soil temperature at 70 meters depth is ±10°C [11]. Cold well injection temperature before June 2013 is logged at 9°C. From a thermodynamic perspective it's impossible the cold well temperature decreases during extraction. The reliability of ID109 and ID112 is questionable. Therefore hourly data logged between October 2013 and August 2015 is examined (see figure 4.11).

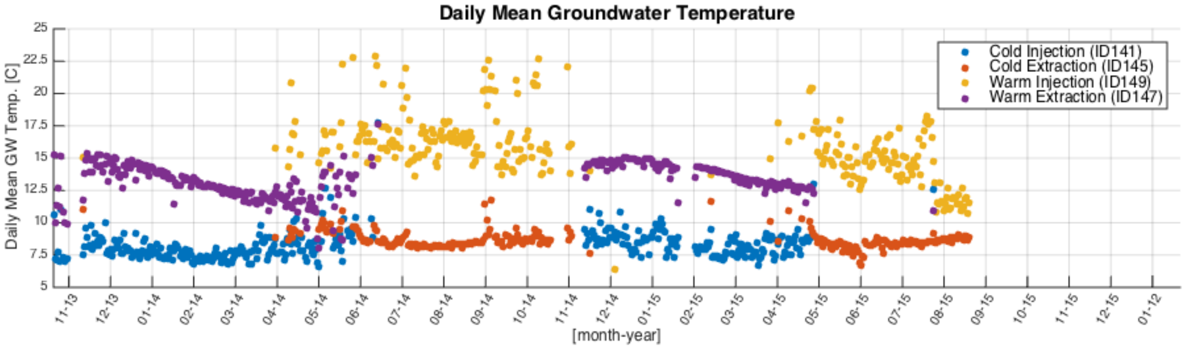

Fig. 4.11: Daily mean ATES well temperatures for ID141, ID145, ID147 and ID149.

Temperature trends of both the warm- and cold well are logical. Design GW temperatures during heating mode are 10-15^{o}C (warm well extraction) and 5-7^{o}C (Cold well injection). Empirical warm well extraction temperature satisfies design. Cold well injection temperature exceeds design conditions (GW temp. > 7^{o}C). For cooling the design temperature is 7-12^{o}C (cold extraction) and 15-25^{o}C (warm injection). Cold well extraction temperature satisfies design. Besides August 2015, warm well injection temperature also satisfies design conditions. Monthly mean GW delta temperature for a heating and cooling operation is respectively between 4–6^{o}C and 3–8^{o}C (see Appendix C2.1, figure c2.2).

It's concluded that the cold well injection temperature is too high. This has a negative affect on the cold well extraction temperature for the following season. As a result pumping debit needs to increase in order to satisfy the building cooling demand. It also increases the change that the HP is invoked as a chiller.

Te is a dominant variable in thermal building demand. ATES operates as a function of building demand. Consequently, GW flows in relation to Te gives insight regarding the ATES operation efficiency. Appendix B.3.1 gives GW flow data (ID102) is reliable. Daily mean GW flows for both heating and cooling mode are between 8-20m^3/h (see Appendix C2.1, figure c2.2). Following the behavior of GW flow as a function of Te is examined (see figure 4.12).

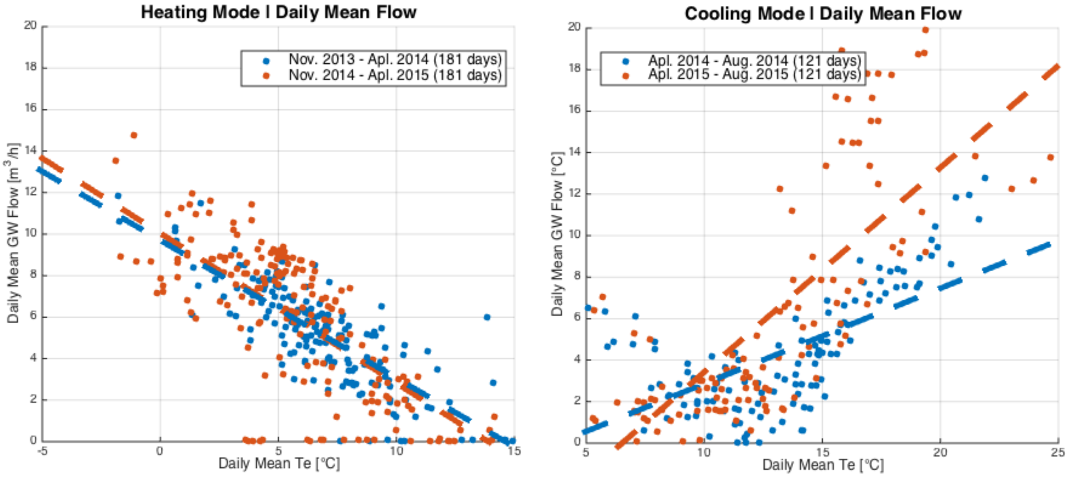

Fig. 4.12: Daily mean- GW flow vs. Te.

Heating operations trend lines are in a similar range. For cooling operations the GW flow in 2015 is significantly higher than 2014. For both periods internal load behavior shows similarity (see Appendix C.1.1, figure c1.3). It seems the warm well injection temperature has decreased. Hourly well pump electricity in relation to GW well temperatures gives more insight. Unfortunately, well pump measurements aren't sufficient.

4.3.2. ATES State Of Charge

As previously shown, warm- and cold well temperatures by respectively ID112 and ID109 aren't reliable. Thermal energy storage is logged by ID095 and ID096. The data is considered reliable (see Appendix B.3.1). Thermal balance is calculated according equation 4.1. Consequently, annual and monthly ATES SOC is examined (see table 4.1 and Appendix C.2.2, figure C2.2).

$$Balance_{ATES} = \frac{Q_{heat}-Q_{cold}}{Q_{heat}+Q_{cold}} \qquad (4.1)$$

Table 4.1: yearly data ATES SOC.

Year	Cold Charging [MWh]	Heat Charging [MWh]	Thermal Unbalance [%]	Pumped GW Warm->Cold [m^3]	Pumped GW Cold->Warm [m^3]	Total Pumped GW [m^3]
2012	81	126	22	9916	6612	16529
2013	330	125	-45	48100	12585	60686
2014	139	175	11	21456	19813	41270
2015	112	92	-10	17581	15147	32729
Total	662	518	-10	97055	54157	151216

In general Dutch ATES systems have a positive thermal unbalance [10]. ATES and HVAC results show building heating demand is higher than cooling (further explained in chapter 4.4.2). Between April 2012 and August 2015 a negative thermal unbalance is present (a surplus of cold storage). Between February and April 2013 regeneration was active. This period has a significant contribution in the 45% negative energy storage of 2013. Regarding 2015, the negative unbalance is already 10%. For September till December mainly a building heating demand is expected. In addition, the negative thermal unbalance will grow even further.

According permit it's allowed to annually replace 600.000m^3 of GW (see Appendix A.2.9). For 2013 and 2014 the annual replaced GW is respectively 10% and 7% of the legislated amount. Average Dutch ATES GW replacement is 40% of the legislated amount [37]. In comparison, the case study GW replacement is very low.

Compared to 2013, daily mean GW flow for cooling operation in 2014 is higher (see figure 4.12). As previously discussed, no well pump electricity measurement in relation to well temperatures can be examined. In addition the thermal energy storage can provide outcome. To investigate ATES performance efficiency the thermal energy storage as a function of Te is examined (see figure 4.13).

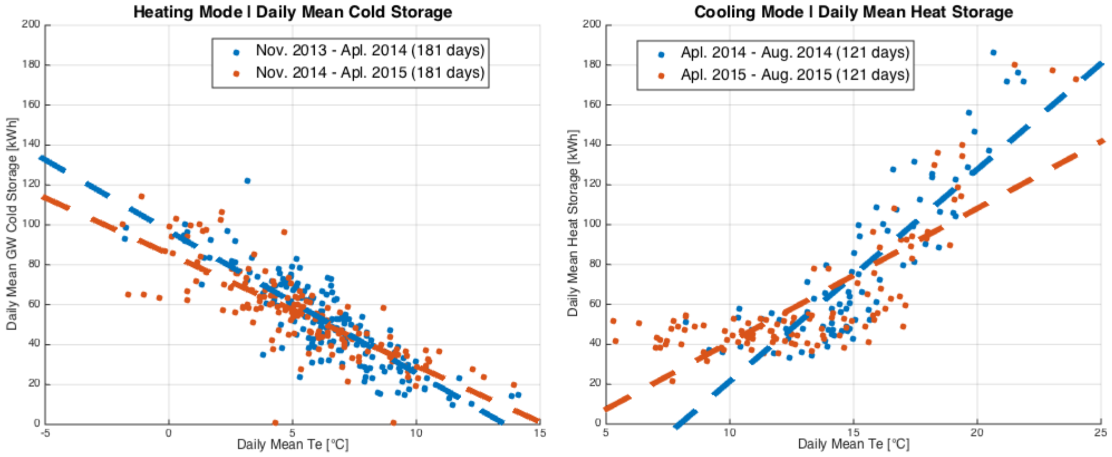

Fig. 4.13: Daily mean- aquifer thermal storage vs. Te.

During heating mode the cold storage for both wells is in a similar range. Regarding the flow trend line of 2015 (see figure 4.12), regeneration efficiency slightly decreased. For similar Te conditions the heat storage in 2015 decreased in regard to an increased mean GW flow. Compared to 2014, it's concluded that 2015 warm well regeneration efficiency has decreased. The warm injection temperature is the main variable responsible for the increase in flow. If no extra heat regeneration will be provided, warm well performance will decrease. Eventually it will increase well pump- and HP electricity consumption in heating mode.

4.4. HVAC Analysis

HVAC operations need to maintain TC and IAQ. Together with internal load and ambient conditions this determines the HVAC operations and consequently HVAC thermal load. Indoor conditions are therefore examined on Ti, CO_2 and occupancy. Thermal load is examined by aggregating the measurements performed on sub system level. Respectively the indoor conditions- and HVAC thermal load analysis is described.

4.4.1. Indoor Conditions

By means of Ti and CO_2 concentration the restaurant and office rooms are examined. Reliability as discussed in Appendix B.3.2 needs to be considered. Hourly analysis is performed for respectively November-, December 2015 and January 2016 (see figure 4.14 and Appendix C.3.1, figure c3.1).

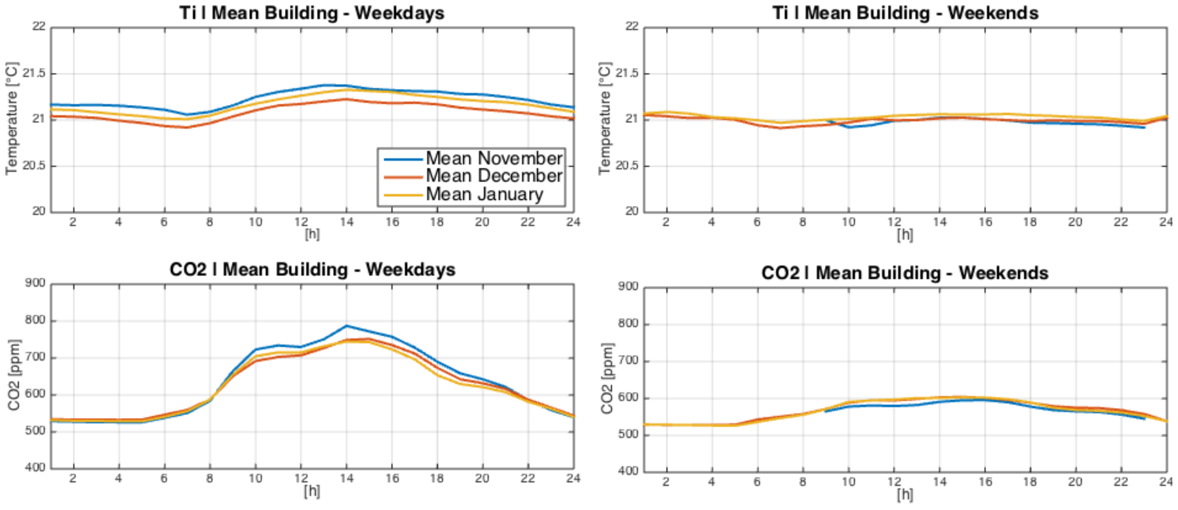

Fig. 4.14: Hourly mean building Ti & CO_2 concentration. Ti room 2.2 and CO_2 room 1.1 excluded (see Appendix B.3.2).

Building mean Ti is ±21°C. During weekdays Ti increases at 08:00. It reaches peak levels between 13:00-14:00h. For weekends less deviation in Ti is obtained. Ti of room 1.1 changes between 10:00-15:00h. It's highly likely this is related to an increase of occupant related internal load. Ti of room 4.1 and 5.1 are respectively ±20,5°C and ±20,8°C. According FM complains on TC most often come from these rooms

Average outdoor CO_2 concentration in the Netherlands is between 300-500ppm [38]. During weekdays and weekends the indoor CO_2 concentration at 06:00 starts to rise from 550ppm. Appendix B.3.2 concludes that the actual indoor CO_2 concentration is 450ppm. According FM the first employees starts at 07:00h. Consequently, if the outdoor CO_2 concentration is below 500ppm a decrease at 06:00 is expected. Regarding the TU/e measurements this trend is visible (see Appendix B.3.2). It's concluded outdoor CO_2 concentration is below 450ppm.

Compared to weekdays, weekend CO_2 concentration during office hours is significantly lower. For both weekdays and weekends peak levels are researched at 14:00h. After 18:00h the building mean concentration decreases. In consideration of weekly room electricity behavior- (see figure 4.7) it's concluded building occupancy during weekends is lower. In consideration of daily electricity behavior (see Appendix C.1.1, figure c1.3) it's concluded that building occupancy decreases after 18:00h.

Office AHU fan consumption between 06:00-23:00h is constant at 48.000m^3/h. This almost equals the design maximum (52.000m^3/h). 60% (30.400m^3/h) is related to the office rooms. Minimal VAV ventilation equals 20% of 30.400m^3/h. For CO_2 lower than 700ppm, ventilation rate is 0 (see control curve Appendix A.2.3). For CO_2 equal to 800ppm, VAV set point is 15% (4600m^3/h). Graphical analysis of CO_2 in relation to office AHU fan electricity concludes that a high rate of exceeding ventilation occurs.

Occupancy Counts

In 2013 two incidental occupancy counts where performed per office room (see figure 4.15). In 2015 a more extensive occupancy count was performed per office floor (see figure 4.15 and Appendix C.3.1, figure c3.2).

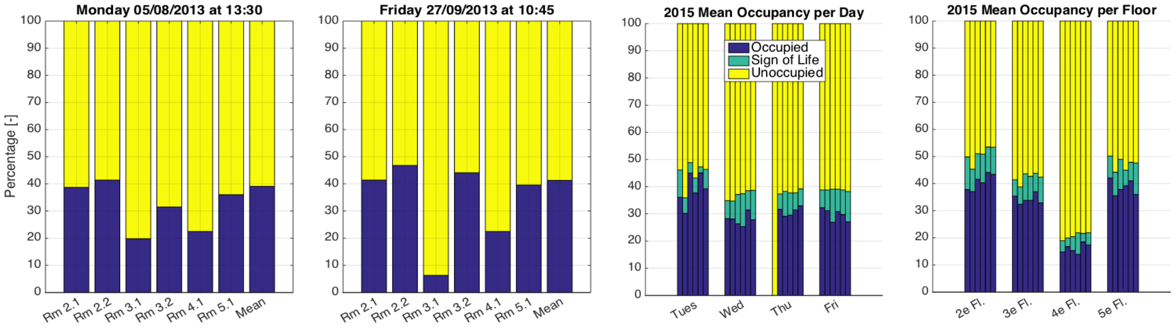

Fig. 4.15: Percentage building occupancy counts.

The counts performed in 2013 give a total mean building occupancy of ±40%. For room 3.1 and 4.1 the average occupancy is even lower. Regarding the 2015 count, mean building occupancy between 10:00-15:00h is 40% (Monday excluded due to insufficient data). Again occupancy on floor four is significantly lower. It's concluded that peak building occupancy equals 40%.

According Dutch legislation a minimal ventilation debit of 25m^3/h per person is mandatory [39]. 60% is related to ventilating the office rooms (30.400m^3/h). In regard to the 40% occupancy (216 people) the minimal ventilation would be 5400m^3/h. Results show ventilation is performed constant (48.000m^3/h). Assuming 28.400m^3/h is related to the offices, it's concluded that ventilation is 5,3 times higher than minimal required.

4.4.2. HVAC Thermal Load

Four different emission systems can provide heating and/or cooling. A wide variety of thermal energy measurements are acquired. Annual and monthly insight on HVAC thermal heating and cooling load is obtained (see figure 4.16 and appendix C.3.2).

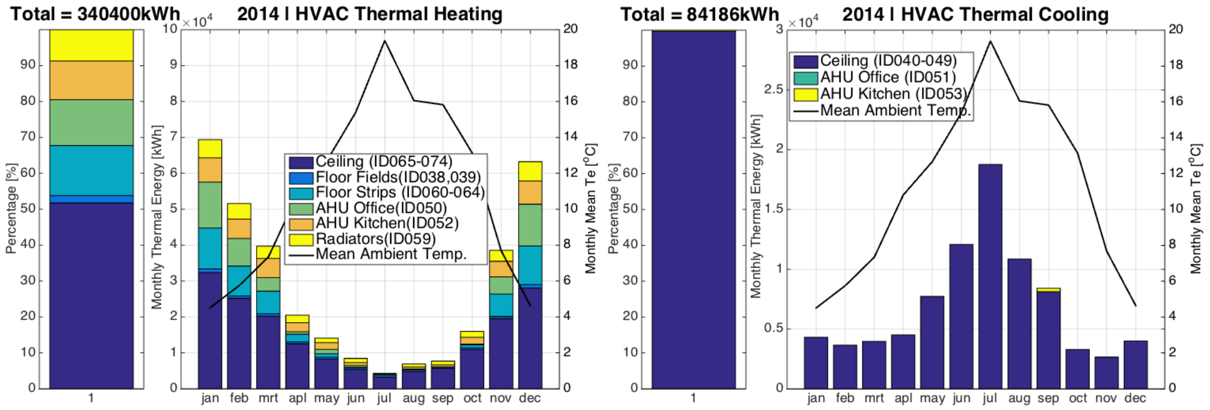

Fig. 4.16: 2014 HVAC thermal loads for heating (left) and cooling (right).

In general Dutch office buildings have a slightly higher cooling demand [10]. The case study has a significantly higher heating demand. HVAC heating demand for 2013 and 2014 is respectively 6 and 4 times higher. Transmission losses are low (Rc = 5m^{2}K/W). Building occupancy (internal load) is relatively low. Rate of ventilation per occupant is high. Although office AHU's are equipped with heat recovery, it looks like thermal losses through ventilation are significant. Consequently, insight on daily HVAC thermal load is obtained (see figure 4.17).

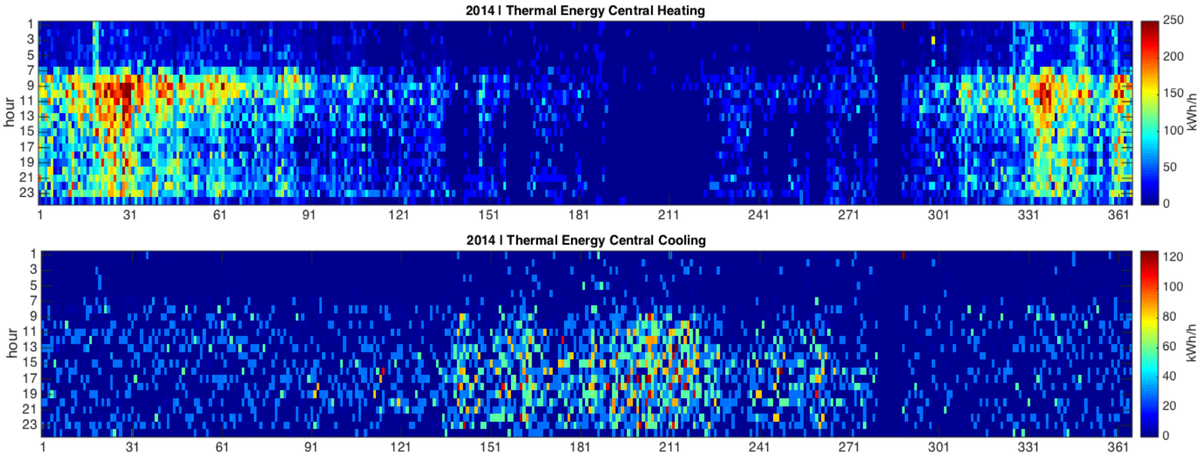

Fig. 4.17: Carper plot 2014 HVAC heating and cooling load (kitchen AHU excluded).

The effects of office AHU operations on HVAC thermal load are significant. Similar to office AHU operations, heating and cooling load mainly occurs between 06:00-23:00h. Peak heating demand occurs during the morning and evening. Between 23:00-06:00h mainly a heating load is present. As previously shown, this heating demand is mainly satisfied by boiler operations. The influence of AHU operations on HVAC thermal load is even more visible when taking the hourly mean values (see figure 4.18).

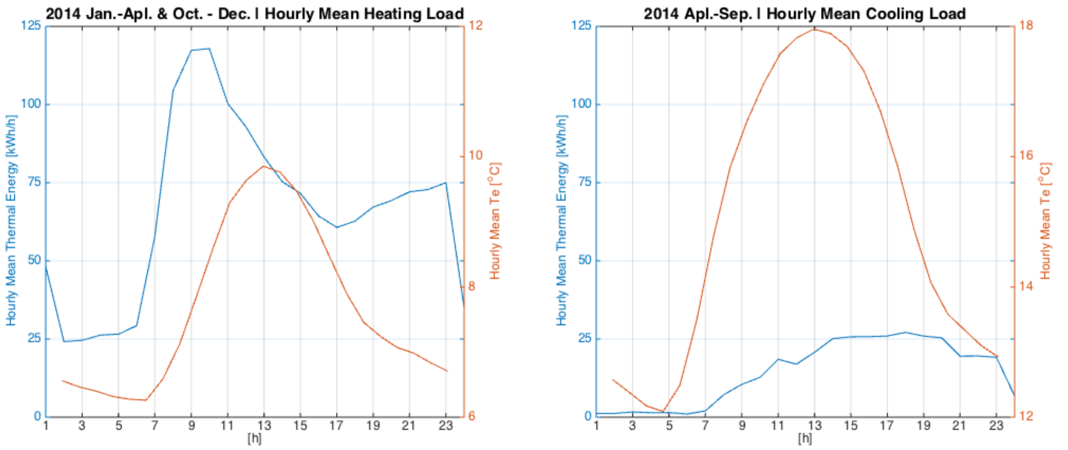

Fig. 4.18: 2014 hourly mean- HVAC thermal load (kitchen AHU excluded).

Because transmission losses are low, thermal behavior in relation to internal load and ventilation is more sensitive. Hourly mean heating load during the night is 25kWh/h. Similar to the start of the office AHU's, at 06:00h mean heating load increases almost up to 115kwh/h. It's concluded that exceeding ventilation significantly increases HVAC heating load.

From chapter 4.4.1 it's known that building occupancy related internal load significantly increases at 09:00h (see Appendix C.1.1, figure 1.3). Subsequently internal load at 09:00h decreases. After 17:00h internal load decreases. Simultaneously heating load starts to increase. It's concluded internal load has a significant influence on thermal heating behavior.

Cooling load starts to increase at 07:00h and peaks at 15:00h. The climate ceiling provides the cooling capacity (see figure 4.16). Consequently, the HRW of the AHU is sufficient to acquire the set point supply air temperature. Because the ventilation rate is high, the extraction air takes a lot of heat in a building zone away. Subsequently, cooling load on the climate ceiling drops. It's concluded that exceeding ventilation lowers the HVAC cooling load. Furthermore the occupancy trend is less shown in the cooling demand. It's concluded that occupancy related internal loads doesn't significantly affect cooling behavior.

Between 06:00-23:00h a heating and cooling load occurs simultaneously (figure 4.17 and Appendix C.3.2, figure 3.5). The office building zones contain floor fields/strips, climate ceiling and ventilation. Subsequently, to a single building zone heat and cold can simultaneously be provided by a combination of systems. To obtain more insight in the behavior of HVAC thermal load, hourly insight for both heating and cooling is obtained (see figure 4.19 and Appendix C.3.2, figure c3.6).

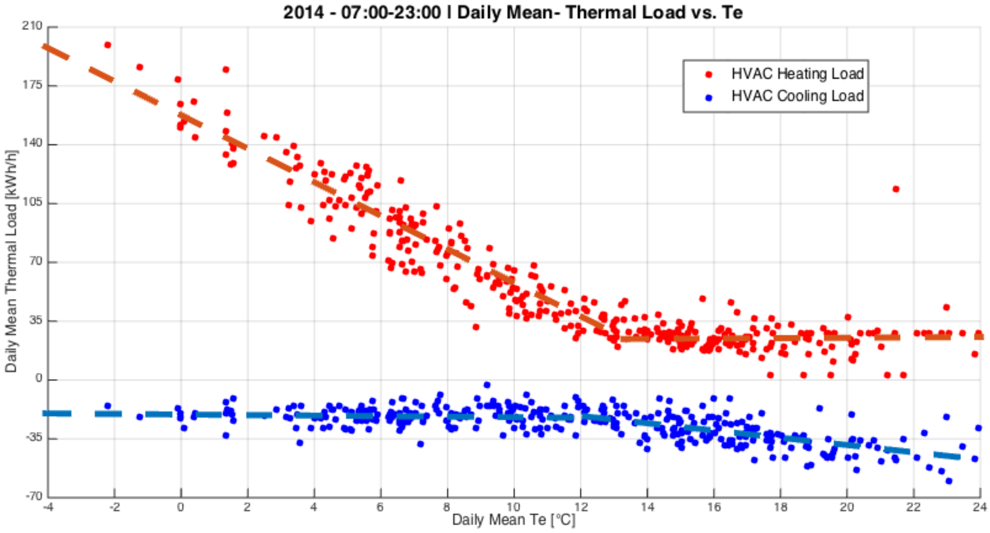

Fig. 4.19: 2014 daily mean- HVAC thermal load vs. Te (kitchen AHU excluded).

Change point between heating and cooling occurs at Te = 13°C. For Te < 13°C, heating load increases. Simultaneously daily mean cooling base load is 15kWh/h. For Te > 13°C, cooling load increases. At the same time a daily mean heating base load of 25kWh/h is present. 2014 trend lines give the base load for both heating and cooling in a constant range. However, trend lines of 2012 and 2013 are showing increasing cooling loads for a decreasing Te (see Appendix C.3.2, figure c3.6).

The monthly analysis gives this cooling load is related to the climate ceiling (see figure 4.16). In regard to the case study design it's plausible heating and cooling is simultaneously delivered to a building zone. Another possibility is the climate ceiling valves on sub system level are not working properly (see system principle Appendix A.2.2, figure a2.6). Subsequently, cold and hot water is getting mixed in a climate ceiling module.

4.5. Discussion Performance Analysis

Building energy performance is significantly higher than expected. The L.E.A. top-down analysis discovered inefficiencies. To actually solve these inefficiencies further research is needed. Initiating further research needs to be done in consideration of the amount of work in relation to the possible result. In regard to the first research objective (see chapter 1.2.1) the improvement potential of the following four inefficiencies are discussed and concluded:

1. Office AHU excessive ventilation
2. Boiler operations at night times
3. ATES Well Performance
4. Simultaneously increasing heating and cooling load

4.5.1. Excessive Ventilation

Ventilation is annually responsible for 15% of the total electricity consumption (131MWh). In regard to the indoor condition analysis it's concluded the VAV isn't working properly. In regard to the peak building occupancy, ventilation is 5,3 times higher than minimal required. The rate of excessive ventilation during the weekends is even higher. Consequently a large reduction on office AHU fan electricity consumption exists.

The following calculation indicates the reduction potential: building occupancy between 06:00-23:00h is 60% (324 people), outside CO_2 is 450ppm, inside CO_2 concentration need to kept on 800ppm, CO_2 emission per office worker is 0.018m^3/h [42]. According ASHRAE 62-2001 this equals a supply of 52m^3/h per occupant [42]. Assuming electricity fan consumption is linear related to ventilation rate, total office room ventilation drops to 16.850m^3/h. In regard to a current office ventilation of 28.400m^3/h this means a reduction of 40%. On total ventilation (48.000m^3/h) it means a reduction of 24%.

Incase the VAV is working according design the effect on HVAC thermal load behavior will be significant. It's shown that when office AHU operations are invoked, heating load at 07:00h is almost four times higher compared to 05:00h. Between 02:00-06:00h the 2014 mean heating load is 26kWh/h. Between 06:00-23:00h mean heating is three times higher (80kWh/h). This significantly increases the HP electricity consumption (see figure 4.20). Furthermore, it increases central heating pumping debit and boiler gas consumption.

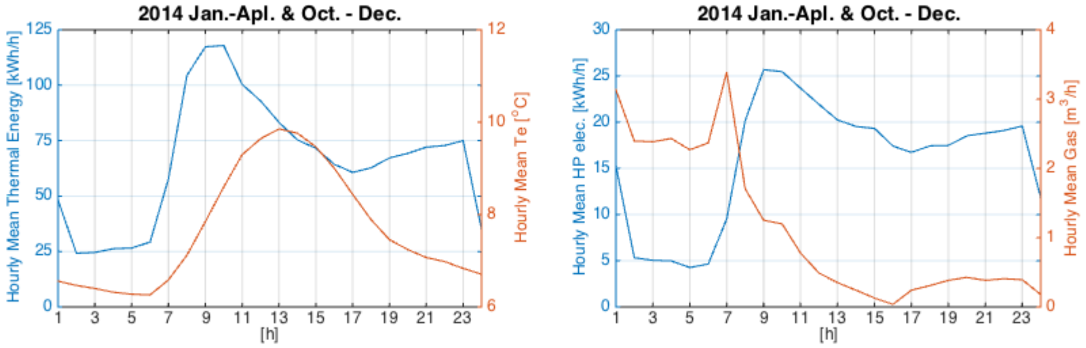

Fig. 4.20: 2014 hourly mean- HVAC heating load, Te, HP electricity- and boiler gas consumption.

4.5.2. Boiler Night Operations

During the night thermal heating demand is satisfied by the boiler. Between 02:00-06:00h mean heating load is 26kWh/h. At the same time mean boiler gas consumption is 2,8m^3/h (see figure 4.20). Gas energy content is 31,65MJ/m^3. In regard to a boiler efficiency of 108% (COP = 1.08, see Appendix A.2.7) this equals a mean energy supply of 26kWh/h.

Boiler mean gas consumption between 19:00-23:00 is 0,4m^3/h. According a COP of 1,08 this equals 4kWh/h of heat. Mean HVAC thermal heating load is 70kWh/h. Consequently the HP delivers 66kWh/h of heat. Mean HP electricity consumption is 18kWh/h. Consequently the HP operates with a COP of 3,6. This is 3,3 times more efficient compared to boiler operations. Although COP in regard to HP partial load operations can deviate [28], it's reasonable the HP COP will be higher than 1,08. However, emission factors needs to be considered [35].

4.5.3. ATES Well Performance

Due to the high HVAC heating demand a negative thermal unbalance is present. Regarding legislation the measured period is still within bounds (-10%). However, the significant difference between building heating- and cooling demand will stimulate the growth of the negative thermal unbalance. As previously discussed, the excessive ventilation is mainly responsible for the high heating demand. Lowering the ventilation rate reduces the heating demand. Eventually this will decrease the difference between the warm- and cold well regeneration.

Mean warm injection temperature for respectively 2014 and 2015 is 16,8°C and 14,5°C. Consequently, this will decrease the warm well extraction temperature and eventually increase HP electricity consumption. Compared to 2014, it's concluded that 2015 warm well regeneration efficiency has dropped (see figure 4.12 and 4.13).

The cold well injection temperature exceeds design conditions (8°C). Subsequently the extraction temperature is stable around 9°C. Incase of a lower injection temperature in relation to a similar amount of pumped GW the extraction temperature will drop. This will increase the cold well cooling efficiency. It's concluded that the cold well injection temperature is too high.

4.5.4. Simultaneously Heating & Cooling

Between 06:00-23:00h heating load linear increases for Te < 13°C. Simultaneously trend lines in 2012 and 2013 are showing an increasing cooling trend. This is unexpected. It's concluded that two scenarios can occur: 1 – emission systems in a single building zone are providing heating and cooling simultaneously, 2 – hot and cold water circuit are mixing due to leaking values in the climate ceiling.

Due to the quality of sub system measurements it's hard to compare thermal heating and cooling measurements on a detailed time scale. Consequently, additional measurements (i.e. sub system flow and temperature) would give more insight.

4.5.5. Conclusion Controllable Parameters

Of the four inefficiencies discussed, it's clearly shown that excessive ventilation has on enormous effect on increasing office AHU fan electricity and HVAC heating load. Consequently, it's concluded that the underperforming VAV is the area where the most critical controllable parameter is situated.

Optimization of the VAV control will improve the performance of the office AHU electricity consumption, building heating demand and ATES thermal balance. In regard to the second research objective, step 2 of L.E.A. will be on benchmarking and identifying saving potential in relation the excessive ventilation.

5. L.E.A. Step 2: Performance Modeling

L.E.A. emphasizes that problems need to be solved in small batches at least cost. The inefficiency with the highest saving potential acts as the scope for L.E.A. step 2. Chapter 5 describes the performance modeling. Respectively the modeling framework, benchmark modeling, design modeling and potential savings are described. Finally, the performance modeling is discussed.

5.1. Modeling Framework

In regard to the process flow in chapter 2.1.2 (see figure 2.2), first a modeling framework is determined. Main aspect in the framework is low labor intensity. The modeling framework is determined according the following flow chart (see figure 5.1).

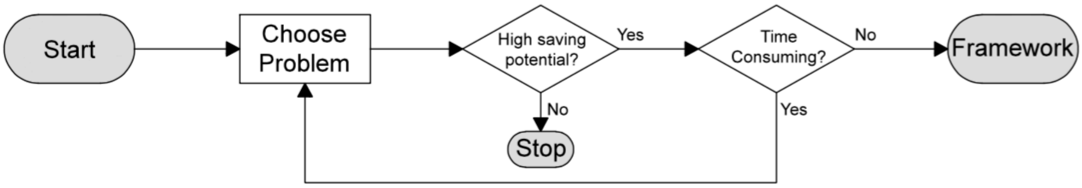

Fig. 5.1: Applied flow chart in defining the modeling framework.

5.1.1. Improvement Potential

Step 1 of L.E.A. defined four inefficiencies/problems. It's concluded that office AHU excessive ventilation is the area where the most inefficient controllable parameter is situated. Improvement of office AHU operations would give reduction on AHU electricity- and HVAC thermal heating related energy consumption.

5.1.2. Modeling – AHU Electricity

In regard to the office AHU fan electricity, ventilation rate between 06:00-23:00h is almost constant. Indoor conditions give a low CO_2 concentration. It's concluded excessive ventilation is present. Properly working VAV will give change on AHU fan electricity as a function CO_2. Consequently a benchmark model is obtained by two-parameter regression with fan electricity consumption as a function of indoor CO_2 concentration.

Indoor conditions analysis provides information on occupant behavior. One equation is capable of describing room ventilation behavior in relation to the occupant [20,34,42]. Design details regarding ventilation are known (see Appendix A.2.3). Empirical indoor conditions data gives outcome on validating the model. A low labor-intensive design model can be obtained to determine possible AHU electricity savings.

5.1.3. Modeling – HVAC Thermal Load

Excessive ventilation significantly increases the HVAC heating load. In addition it increases heating related energy consumption (HP, central heating pump, boiler, ATES). The central heating performance efficiency is a multi objective problem [40]. E.g. HP COP, where ingoing evaporator is a function of the ATES. The dataset is insufficient to acquire these performance insights.

The ventilation rate between 06:00-23:00h is almost constant. Internal loads and Te are the varying parameters in HVAC thermal load. Literature discusses model uncertainty in relation to internal loads [40,41]. However, dataset is considered insufficient to define occupant before 09:00 and after 17:00. Subsequently, a two-parameter HVAC- heating and cooling load model as a function of Te is obtained.

The case study HVAC system is complex. Modeling these systems and their mutual interference comes with a large set of equations [34]. Moreover, a low quality on HVAC system related measurements are obtained (see Appendix B.3.1). This increases the uncertainty in model validation. No model is obtained that is built during design. It's concluded that a deterministic modeling approach for thermal behavior is time-consuming. Therefore no time is spent on modeling the influence of different VAV conditions on thermal load behavior.

5.2. Benchmark Models

Benchmark models related to office AHU operations (06:00-23:00h) are obtained. Respectively the office AHU electricity- and HVAC thermal load benchmark models are described.

5.2.1. AHU Electricity

AHU fan electricity and CO_2 data of November-, December 2015 and January 2016 is used. AHU fan electricity is hourly data. CO_2 data is logged every 10 minutes. The hourly AHU fan data is extrapolated to 10-minute vectors. Following the supply fan (ID028), extraction fan (ID029) and 10-minute building mean CO_2 concentration are given (see figure 5.2).

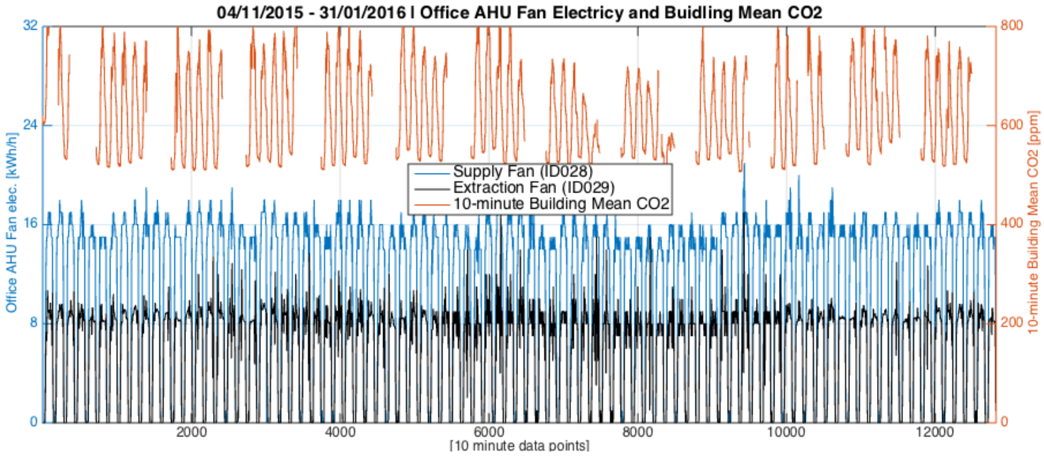

Fig. 5.2: November-, December 2015 and January 2016 AHU fan electricity and hourly building mean CO_2.

As previously described, office AHU fan electricity consumption between 06:00-23:00h is from interest. Subsequently for all three months the data between 06:00-2300h is obtained. In addition regression is performed between fan electricity as a function of CO_2 (see figure 5.3).

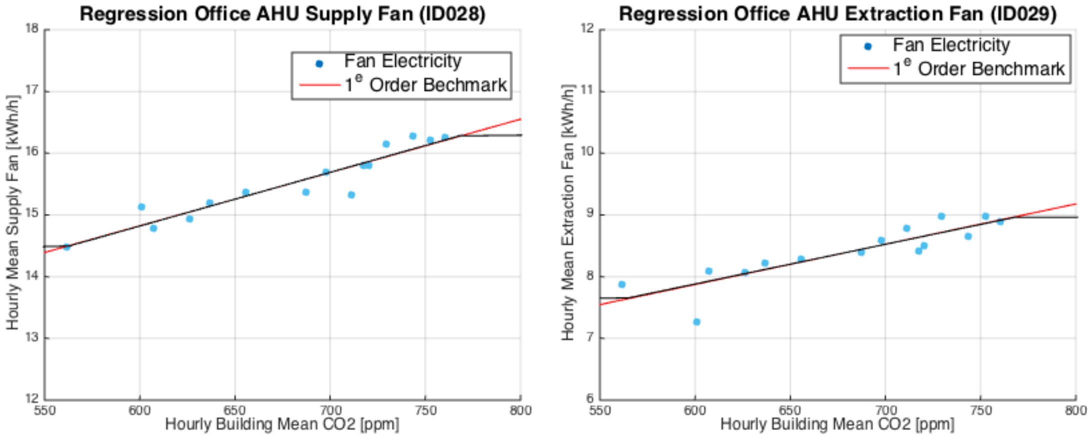

Fig. 5.3: Regression for 10-minute mean- supply and extraction fan as a function of 10-minute building mean CO_2.

The regression gives that fan electricity shows some increases in regard to an increasing CO_2. However, it also shows the ventilation rate is excessive in regard to the VAV control curve (see Appendix A.2.3, figure a2.10). Following the benchmark models are given (see equation 5.1 and 5.2).

If 6-23h, and
560 > CO2 < 760

$$\rightarrow \quad Q_{AHU\ Supply} = 0.01036 * \mathrm{x} + 8.353 \quad (R^2{:}\,0{,}9614) \qquad (5.1)$$

If 6-23h, and
560 > CO2 < 760

$$\rightarrow \quad Q_{AHU\ Extract} = 0.00516 * \mathrm{x} + 4.931 \quad (R^2{:}\,0{,}8562) \qquad (5.2)$$

According the coefficient of determination (R^2) both models acquire a good fit. In addition simulation and result analysis is performed (see Appendix D.1.1). It gives that the simulation results are close to that of the measurements.

5.2.2. HVAC Thermal Load

Chapter 4.4.2 discusses the influence of internal loads (see figure 4.18). Regression is performed on thermal load as a function of Te. To reduce the influence of occupant behavior the regression is based on data between 09:00-17:00h. In regard to the domain of Te, heating and cooling data of respectively 2013 and 2014 is used (see figure 5.4). Kitchen thermal energy measurements (ID052, ID053) are excluded.

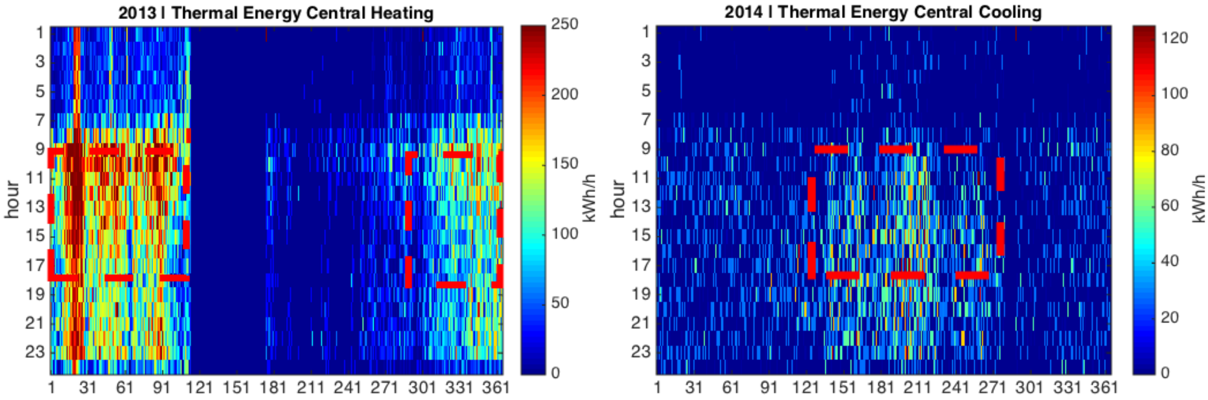

Fig. 5.4: Periods of interest for heating and cooling regression.

The periods outlined in figure 5.4 are used. In addition Te data similar the outlined periods is obtained. In regard to the change point as discussed in chapter 4.4.2 (see figure 4.19), heating and cooling data is excluded for respectively Te > 13°C and Te < 13°C. Subsequently regression is performed (see figure 5.5).

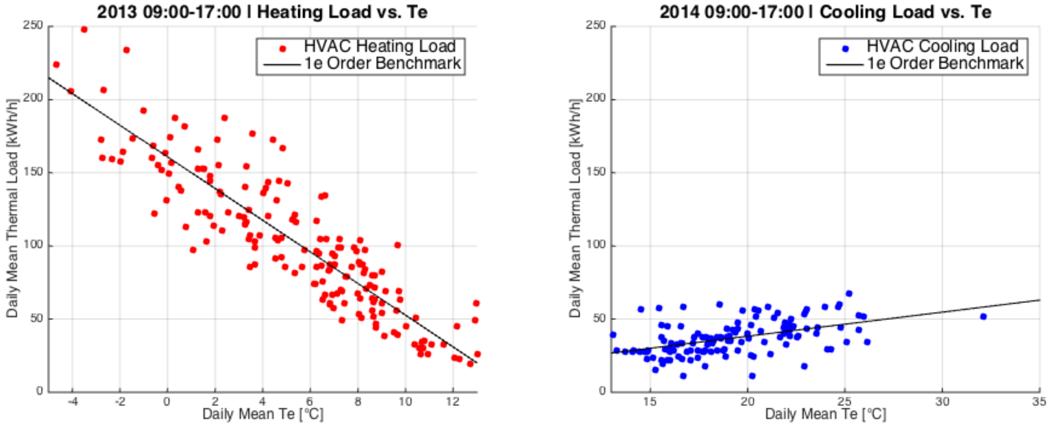

Fig. 5.5: Regression HVAC thermal- heating and cooling.

Regression gives expected trends. The dispersion is related to the data log time interval, variation in solar irradiance and weekdays/weekend occupancy. Following the benchmark models are given (see equation 5.3 and 5.4).

If 9-17h, and Te < 13°C ➔ $$Q_{HVAC\ heating} = -10.822 * \mathrm{x} + 160.86 \quad (R^2: 0{,}8013) \qquad (5.3)$$

If 9-17h, and Te > 13°C ➔ $$Q_{HVAC\ Cooling} = 1.6437 * \mathrm{x} + 5.4622 \quad (R^2: 0{,}242) \qquad (5.4)$$

According the coefficient of determination (R^2) the heating model acquires a good fit. Regarding the cooling model a low fit is obtained. In addition simulation is performed and results are analyzed (see Appendix D.1.2).

The heating model shows similarity on trend. For cooling the model produces results in a similar range, however actual data fit is very low (5%). Mean absolute error for the cooling model is lower compared to heating. However, in percentage a higher deviation for cooling needs to be considered.

5.3. Design Model

As discussed in 451, the design-modeling framework is focused on the office AHU variable ventilation. Respectively the theory and validation is discussed.

5.3.1. Ventilation Office AHU

The design model simulates the VAV behavior in relation to indoor CO_2 concentration. By means of the following differential (see equation 5.5 [21,34]) the indoor CO_2 concentration is simulated using the Matlab-Simulink S-function.

$$V\frac{dC_r}{dt} = P \cdot S + m_t \cdot C_s - m_t \cdot C_r \qquad (5.5)$$

With:

m	Room ventilation mass flow	$[m^3/s]$
S	CO_2 generation rate per occupant	[ppm/s]
P	Amount of occupants	[-]
C_r	CO_2 concentration in volume	[ppm]
C_s	CO_2 concentration in ambient air	[ppm]
V	Room volume	$[m^3]$

Per person, occupant CO_2 emission rate is assumed to be 0,31 L/min [42]. Outdoor CO_2 concentration is assumed to be 450ppm (see chapter 4.4.1). Appendix D.2.1 gives the occupancy profile per room.

The VAV control is modeled according the settings described in Appendix A.2.3. Appendix D.2.2 gives the ventilation properties for each room. Fan electricity consumption is assumed to be linear related to ventilation rate. For the supply and extraction fan the SFP is respectively 1,122 kW/(m^3/s) and 0,612 kW/(m^3/s).

5.3.2. Validation Office AHU

Reliability of the BMS CO_2 measurements is discussed (see Appendix B.3.2). Consequently validation for CO_2 is performed in regard to building mean- and room 2.2 (see figure 5.6).

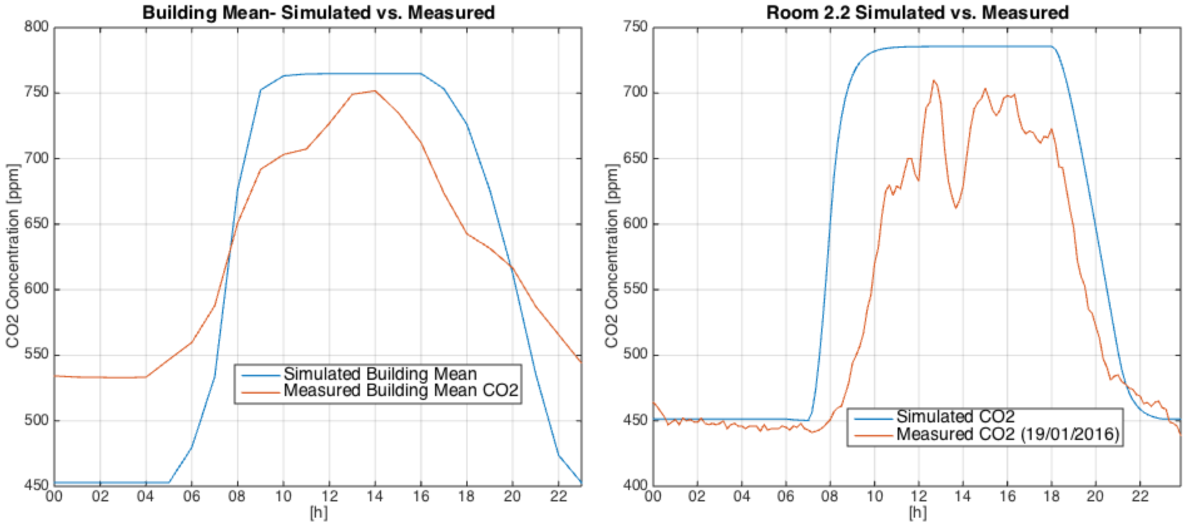

Fig. 5.6: Simulated and measured CO_2 concentration (room 1.1 excluded from building mean calculation).

Simulation results are in a similar range as the empirical measurements. Simulated CO_2 concentration is ±50ppm higher. Compared to the TU/e measurements a similar trend is obtained. Trend of the building mean concentration deviates especially for CO_2 < 550ppm. As discussed in Appendix B.3.2, this is related to the reliability of the BMS measurements.

5.4. Saving Potential

According design the VAV control has an upper CO_2 limit of 1200ppm. Consequently, CO_2 concentration below 1200ppm is considered as excessive in regard to occupant comfort. Building occupancy is relatively low. In addition CO_2 emission is low. Since the empirical situation is ventilating almost at maximum rate, fan electricity savings can already be obtained for CO_2 limits lower than 1200ppm. The reduction on office AHU fan electricity is defined for the following three scenarios: upper limit- 1200ppm, 1000ppm and 800ppm (see figure 5.7).

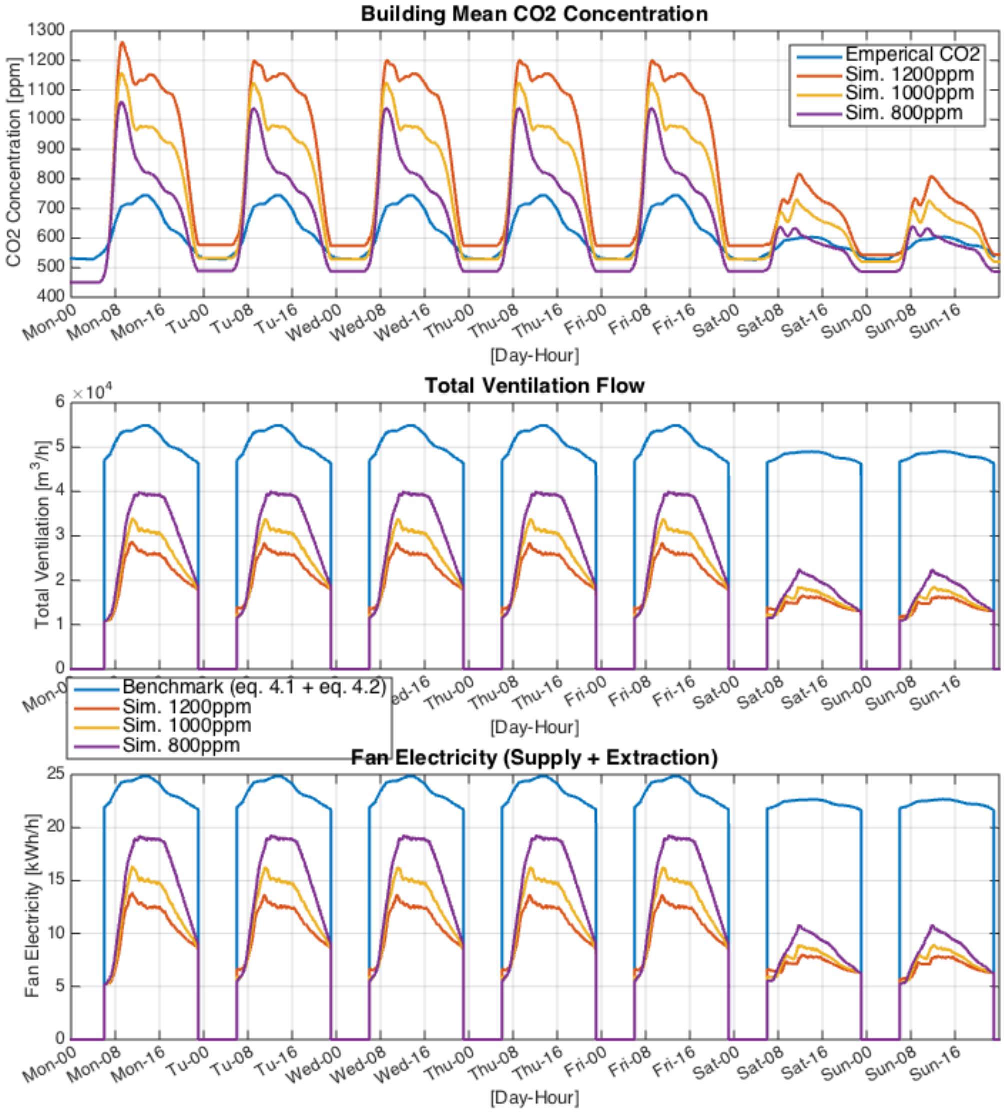

Fig. 5.7: Simulated CO_2, ventilation flow and fan electricity consumption.

All three scenarios come with savings on fan electricity consumption. During weekends the savings are even higher. Following the fan electricity results are given (see table 5.1).

Table 5.1: Office AHU fan electricity consumption.

Scenario	Tuesday [kWh]	Saving [-]	Saturday [kWh]	Saving [-]	Full Week [kWh]	Saving [-]
Benchmark	400	100%	380	100%	2760	100%
1200ppm	185	-54%	120	-68%	1150	-58%
1000ppm	208	-48%	127	-66%	1290	-53%
800ppm	252	-37%	142	-62%	1535	-44%

5.5. Discussion Performance Modeling

The benchmark for AHU fan consumption is performed by two-parameter regression. Although it‘s far out of the design control bandwidth, regression gives the ventilation rate reacts in relation to indoor CO_2. A supply- and extraction fan model is obtained by linear regression as a function of building mean CO_2. Both the supply and extraction model acquire a good fit. Consequently they can be used to measure fan electricity performance after modifications.

To reduce data dispersion, benchmarks models for HVAC thermal behavior are performed for data between 09:00-17:00h. Regression is performed for HVAC thermal load as a function of Te. The heating model acquires a good fit. In consideration of similar building occupancy, it can be used to measure changes in HVAC heating behavior between 09:00-17:00h.

The cooling model produces a low fit. It’s concluded that solar irradiance has a more significant effect on cooling. Including solar irradiance in the benchmark would give outcome on model improvement [41]. Furthermore, thermal measurements are logged every 10MJ. Because cooling is low, time interval of logging thermal energy increases. Measurements on central cooling temperature and flows can give outcome to obtain more accuracy on thermal energy calculations.

From the counts performed by FM assumption are made on room occupancy. Subsequently, in relation to CO_2 and room electricity measurements the rate of occupancy before 09:00h and after 17:00h where determined. Validation gives that the simulated results show similarity on trends. Furthermore, the simulated CO_2 concentration is generally higher. This results in a higher ventilation rate. Consequently, it provides pessimism in calculating the energy saving potential.

According design the upper ventilation limit is 1200ppm. CO_2 concentration below 1200ppm is considered as excessive in regard to occupant comfort. In regard to the upper limit of 800ppm, simulation gives that for weekdays the electricity consumption would be 60% compared to benchmark. For weekends the daily consumption would be 55% in regard to the benchmark. Although the calculation assumes fan electricity consumption is linear related to ventilation rate, a significant reduction already is shown for the most energy demanding ventilation strategy. Moreover, the reduction of ventilation would decrease the HVAC heating load. This will provide additional reduction on HP electricity-, boiler gas- and pumping consumption.

6. L.E.A. Step 3: RCx Recommendations

Chapter 6 describes step 3 of L.E.A. In addition to step 1 and 2, step 3 of L.E.A. concludes the HVAC performance and gives recommendations on performing RCx on a more detailed system level. First, conclusions on HVAC performance are described. Second, RCx recommendations are described.

6.1. Conclusion HVAC Performance

6.1.1. Indoor Performance

Mean building temperature equals design condition: 21°C. However, from FM it's known that complains on TC often occur on the fourth and fifth floor. Analysis gives that the mean temperature in room 4.1 and 5.1 are respectively 20,5°C and 20,8°C. In regard to the reliability (see Appendix B.3.2) additional measurements are needed to conclude the level of TC.

Building mean CO_2 is very low. Compared to an indoor CO_2 of 1000ppm, research concludes that an indoor CO_2 concentration of 600ppm improves the occupant performance on a scale of 11-23% [43]. However, according design an upper CO_2 limit of 1200ppm is allowed. Subsequently the indoor CO_2 concentration and related energy use are considered excessive.

6.1.2. Energy Performance

The HVAC energy performance is below expectations. In regard to the calculated EPC, the case study has the potential to drop 70% in energy demand. The top-down analyses discovered four inefficiencies: excessive ventilation, boiler night operations, ATES well performance, and simultaneously increasing heating and cooling loads. It's concluded that the excessive ventilation has the highest saving potential: reducing AHU fan electricity, reducing HVAC thermal heating demand and reducing the growth of the negative ATES unbalance.

For the most energy demanding ventilation scenario, L.E.A. step 2 concludes a 44% reduction on AHU fan electricity consumption. In regard to an electricity price of 0,04€/kWh [44], a yearly saving of €2500 in regard to AHU fan consumption can be monetized. Additional savings in regard to HVAC thermal behavior increases the monetization. However, quantifying these savings comes with improving the thermal benchmark models in relation to internal load.

6.2. RCx Recommendations

Recommendations on RCx are made in regard to reducing the rate of excessive ventilation. The recommendations emphases RCx according L.E.A: obtaining most result at least cost. The system has 9 VAV- and two AHU fan controllers. Following the ventilation system principle is given (see figure 6.1).

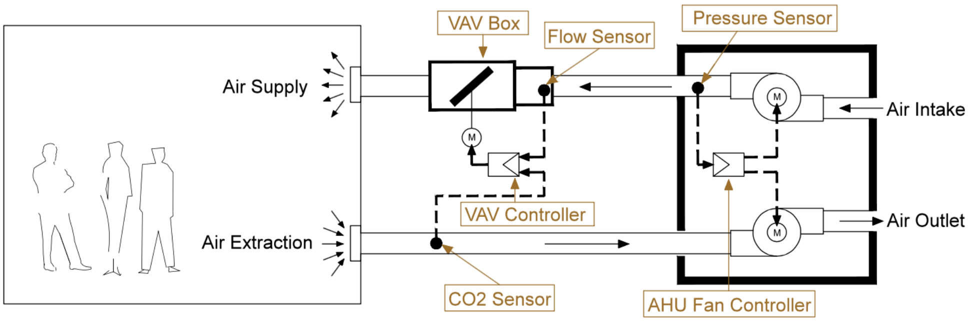

Fig 6.1: Schematic overview case study ventilation system regarding airflow.

In regard to the amount, it would be less time consuming to first check the functioning of one of the AHU fan controllers. It's recommended to check the controller input and output signals. Incase of anomalies, the controllable parameter needs to be defined. Subsequently the status of the defined parameter in the second AHU controller needs to be checked. If case of no anomalies, the same analyses needs to be performed for one VAV box. If an anomaly is detected the controllable parameter needs to be defined. Subsequently this parameter needs to be checked in all 9 VAV boxes.

7. Research Conclusions

Inefficient HVAC performance in newly office buildings is most often related to HVAC controllable parameters. CCx is seen as a promising solution to overcome these problems. However, implementation is complex. This study was motivated to perform RCx according L.E.A as a strategic step to systematically obtain CCx.

7.1. Main Research Question

How can RCx be utilized as a first step in the process to obtain CCx regarding HVAC systems in the existing office building stock?

Existing office building generates a lot of HVAC variable related data. The more variables simultaneously are implemented in a CCx approach, the higher the complexity, the higher the change CCx isn't performed most effective. RCx according L.E.A. emphasizes that most information is obtained with the least amount of variables. By a top-down approach anomalies are discovered in an early phase. Subsequently it gives outcome to quickly identify the area where the inefficient controllable parameter is situated. When the inefficient controllable parameter is adjusted; the top variable(s) that discovered the anomalies will act as CCx input. In addition, variable data representing optimal operations will be used for benchmarking the situation. Subsequently the obtained benchmark model will act as part of the FDD algorithm to detect future anomalies.

7.2. Sub Research Questions

I. According RCx what are the critical controllable HVAC parameters of the case study, and to what extent do they influence the HVAC performance?

The most critical controllable parameter is related to the office ventilation system. When active the office AHU's are constantly operating in almost full capacity. It's concluded that AHU fan electricity could decrease with 44%. The excessive ventilation significantly increases HVAC thermal heating demand. Compared to night times HVAC thermal heating demand is three times higher. In addition it has a negative influence on ATES, generating a negative thermal unbalance (-10% over the measured period).

II. Which datasets are needed to apply RCx on the case study HVAC, and how can the dataset be extended in regard to CCx?

Indoor conditions are top-level variables. This data isn't included in the maintenance database of CWD. From the indoor CO_2- and AHU fan electricity data the top-down approach discovered excessive ventilation. Consequently, CCx for ventilation comes with input of indoor CO_{2-} and AHU fan electricity data. In regard to ATES performance the well pump electricity data is currently insufficient. To define the systems COP this data is mandatory. CCx in regard to ATES performance comes with input of hourly well pump electricity data.

III. Which data properties are essential to obtain HVAC benchmark models related to the case study, and what is its potential in regard to the RCx process?

In general, the data log time interval of all variables in regard to a problem need to be equal. The interval needs to be defined in regard to system dynamics. Regarding the AHU fan benchmark a 10-minute interval on indoor CO_2 concentration- and AHU fan consumption data would be sufficient. To determine the interval for the HVAC thermal benchmark the influence of ventilation and internal load needs to be examined in more detail. Furthermore, separation on occupant- and solar irradiance related internal load data gives outcome to increase model accuracy. Subsequently, the model would be capable to measure the performance improvement more accurate.

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Content

A. Appendix – Case Study

A.1. Building Construction

Table a1.1 gives the building zone properties. Table a1.2 gives the building facade properties. Figure a1.1 gives the floor plans. Figure a1.2 gives the urban planning. Figure a1.3 gives the cut sections. Figure a1.4 gives the construction details of the building façade.

Table a1.1: Building zone properties.

Room	Area [m^2]	Volume [m^3]	Seats	Function	Occupied	Heating [°C]	Cooling [°C]
First Floor							
1.1	699,70	1987,15	218	Restaurant	-	21	22
Other	348,34	965,48	-	Toilets/Hallway/ Reception/Kitchen	-	21	22
Second Floor							
2.1	723,01	2095,17	99	Office - Call Center	07:00-22:00	21	22
2.2	723,01	2095,17	77	Office - Facilities	09:00-18:00	21	22
Other	168,59	454,90	-	-	-	21	22
Third Floor							
3.1	723,01	2095,17	99	Office - Call Center	07:00-22:00	21	22
3.2	723,01	2095,17	82	Office - Call Center	07:00-22:00	21	22
Other	168,59	454,90	-	Toilets/Hallway	-	21	22
Fourth Floor							
4.1	944,63	2728,41	88	Office - Call Center	07:00-22:00	21	22
Other	75,58	207,53	-	Toilets/Hallway	-	21	22
Fifth Floor							
5.1	944,63	2728,41	95	Office - Call Center	07:00-22:00	21	22
Other	75,58	207,53	-	Toilets/Hallway	-	21	22
Atria							
North	169,21	2061,17	-	-	-	21	22
South	207,68	2895,24	-	-	-	21	22
Total	6694,57	23071,40	758				

Table a1.2: Building façade properties.

Construction	Surface [m^2]	Rc-value [m^2K/W]	U-value [W/m^2K]	ZTA [-]	r [-]
West Façade					
Façade area	498	5,0	0,19		
Window area	482,1		1,60	0,3	0,75
South Façade					
Façade area	277,7	5,0	0,19		
Window area	227,2		1,60	0,3	0,75
East Façade					
Façade area	490,0	5,0	0,19		
Window area	490,0		1,60	0,3	0,75
North Façade					
Façade area	118,8	5,0	0,19		
Window area	150,5		1,60	0,3	0,75
Roof					
Façade area	1662,1	5,0	0,19		
Window area	430,9		1,60	0,3	0,75
Ceiling above parking garage					
Façade area	838,8	5,0	0,19		
Total Facade	3885,4				
Total Window	1780,7				

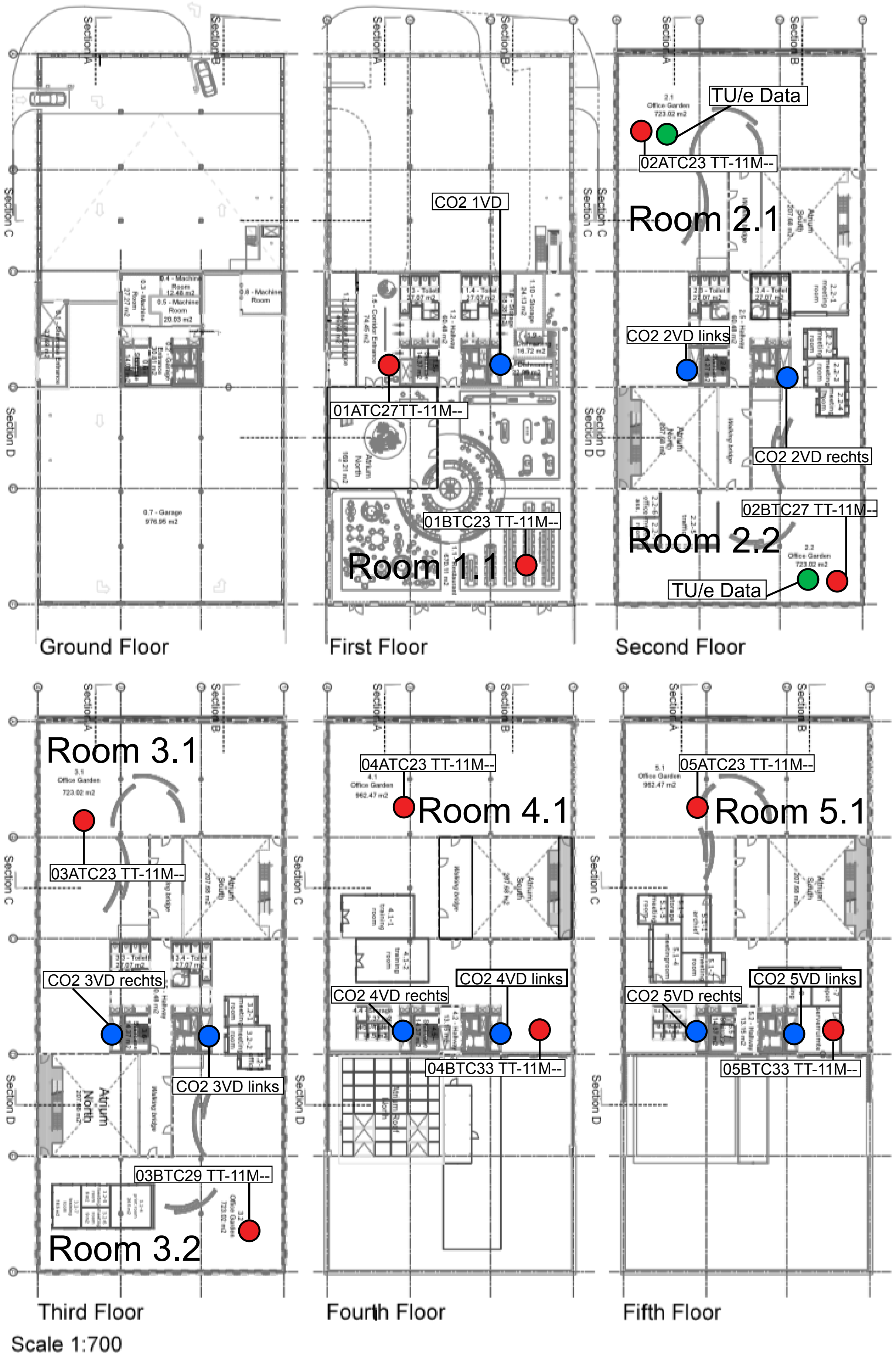


Fig. a1.1: Floor plan Ziggo office building.

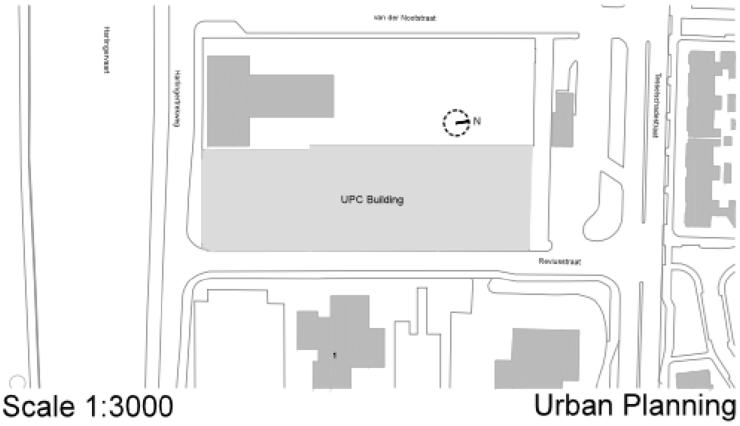


Fig. a1.2: Urban Planning Ziggo office building.

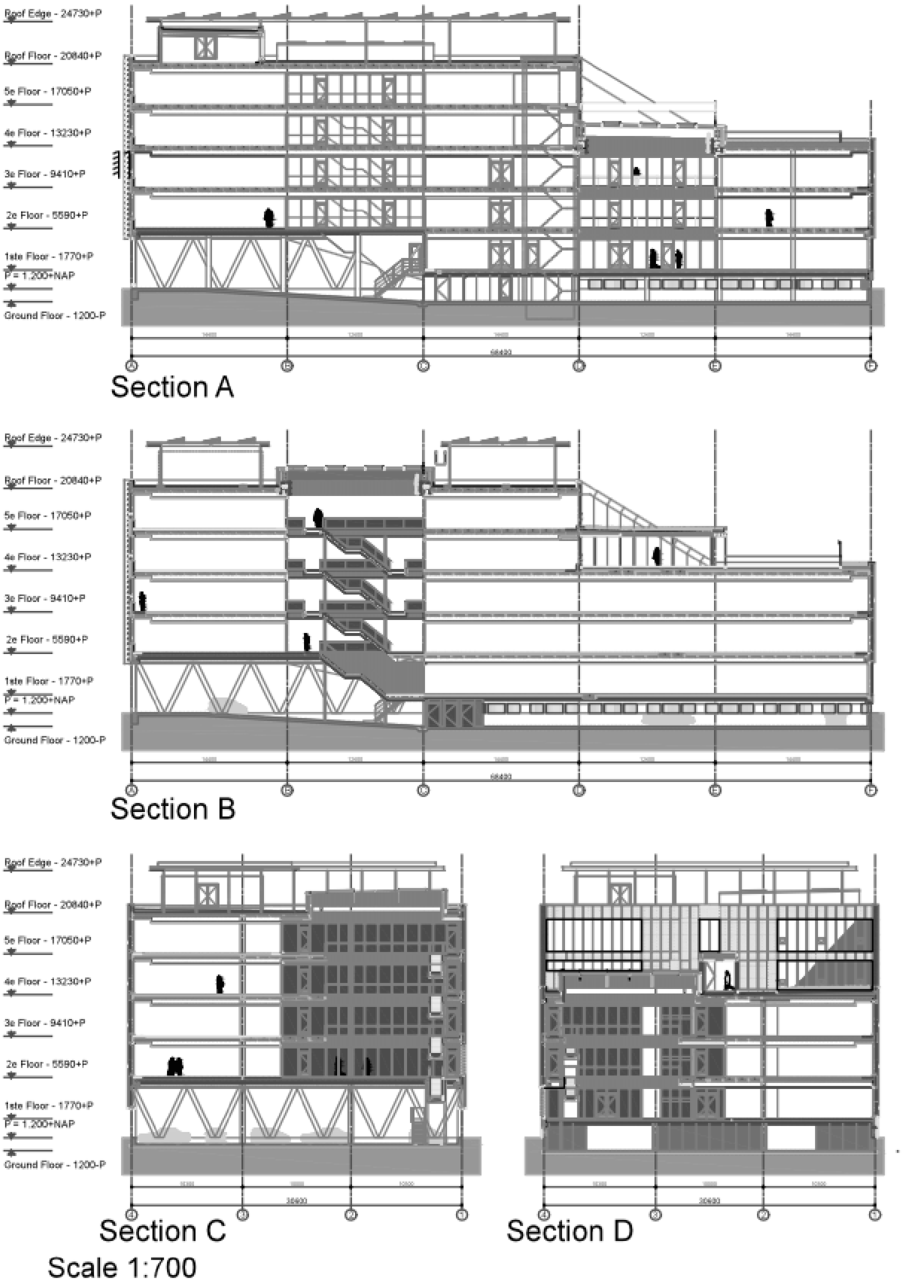


Fig. a1.3: Cut sections Ziggo office building.

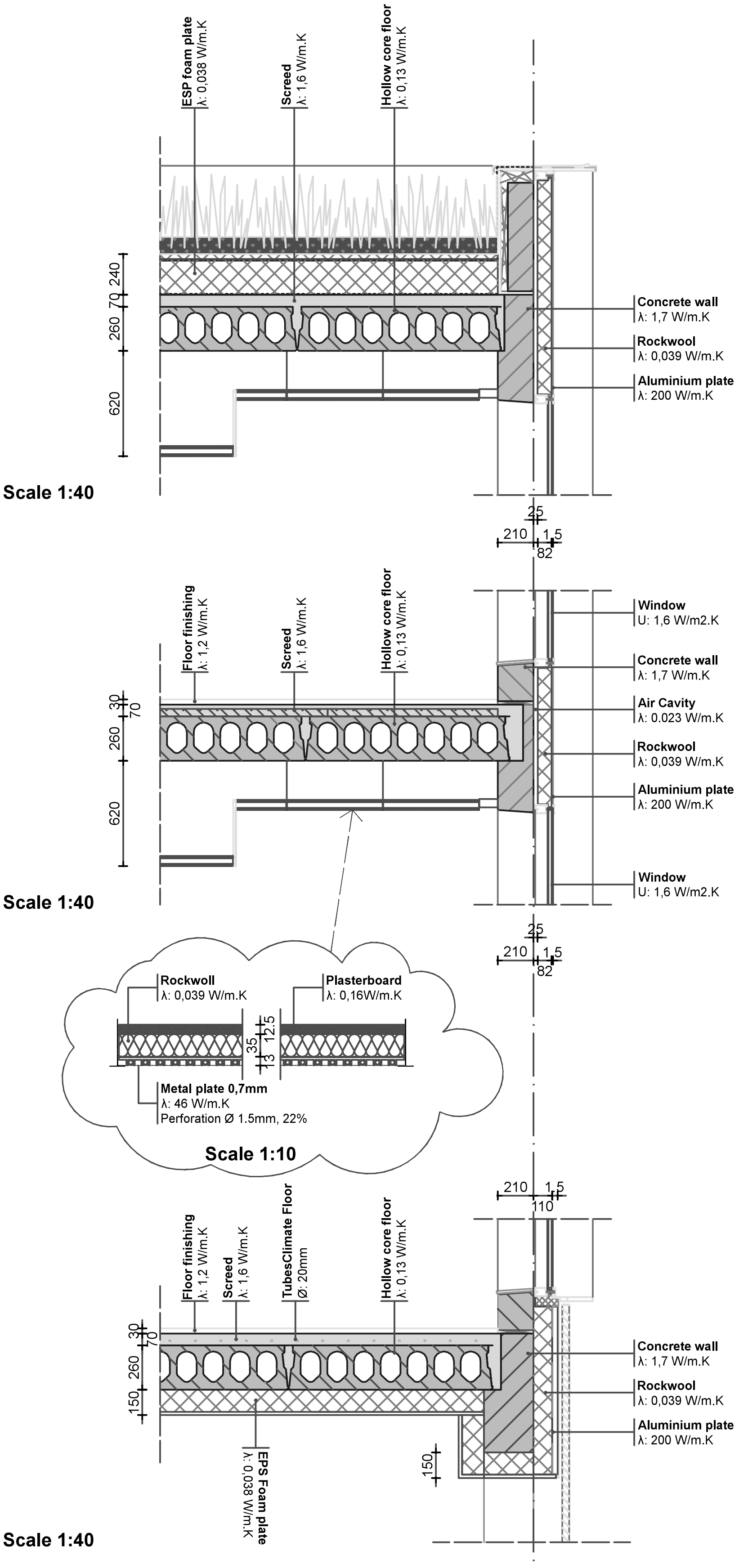


Fig. a1.4: Facade construction details Ziggo office building.

A.2. HVAC related Systems

Connected to the central- heating and/or cooling, thermal emission is performed by four systems: climate-floor, ceiling, AHU's and radiators. Thermal energy demand of the central heating/cooling is satisfied by the PP. The ATES provides and stores thermal energy by exchanging energy with the PP. Following the system principle regarding HVAC thermal energy is given (see figure a2.1). Furthermore, a schematic system overview regarding a heating and cooling operation is given (see figure a2.2).

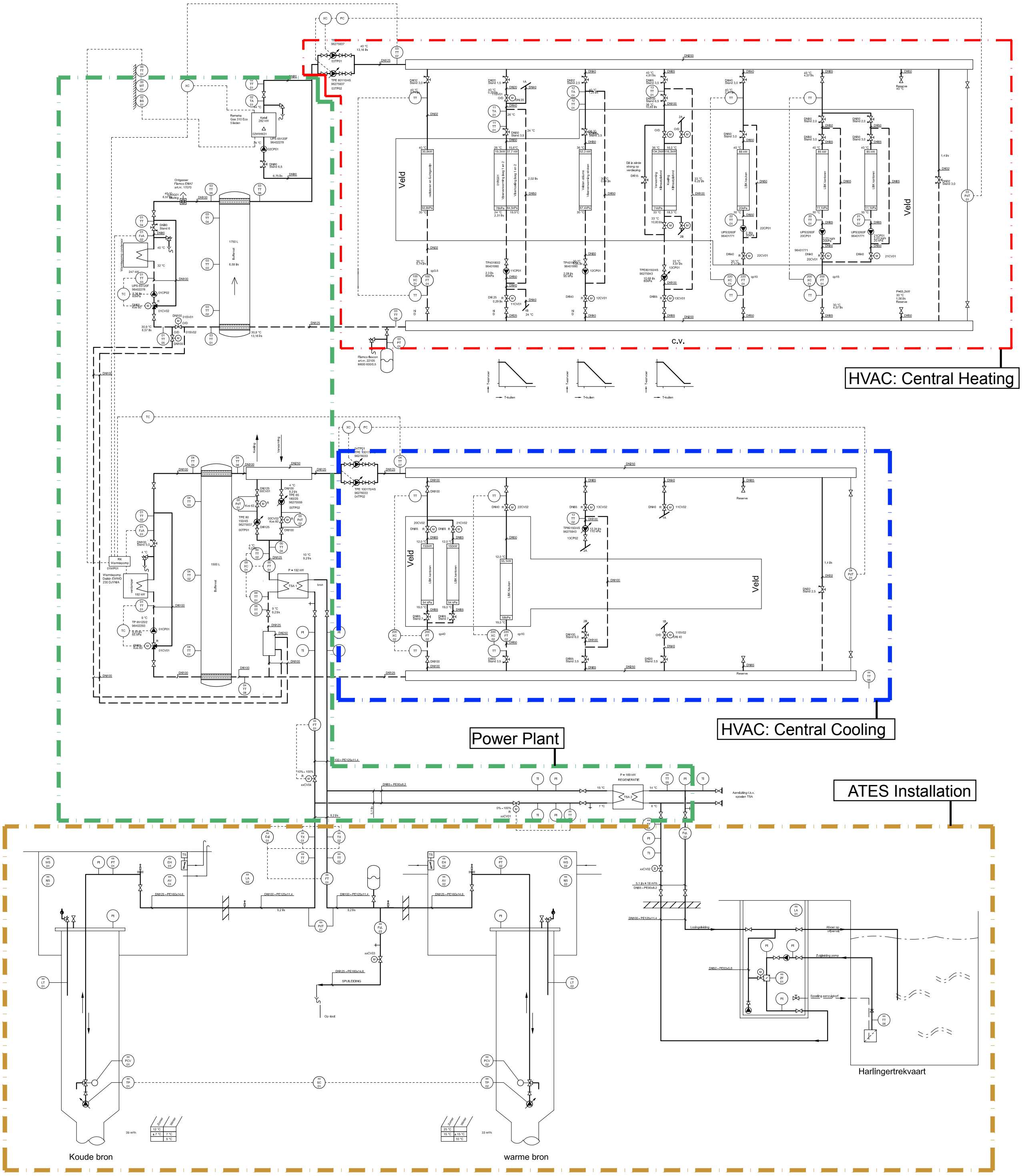
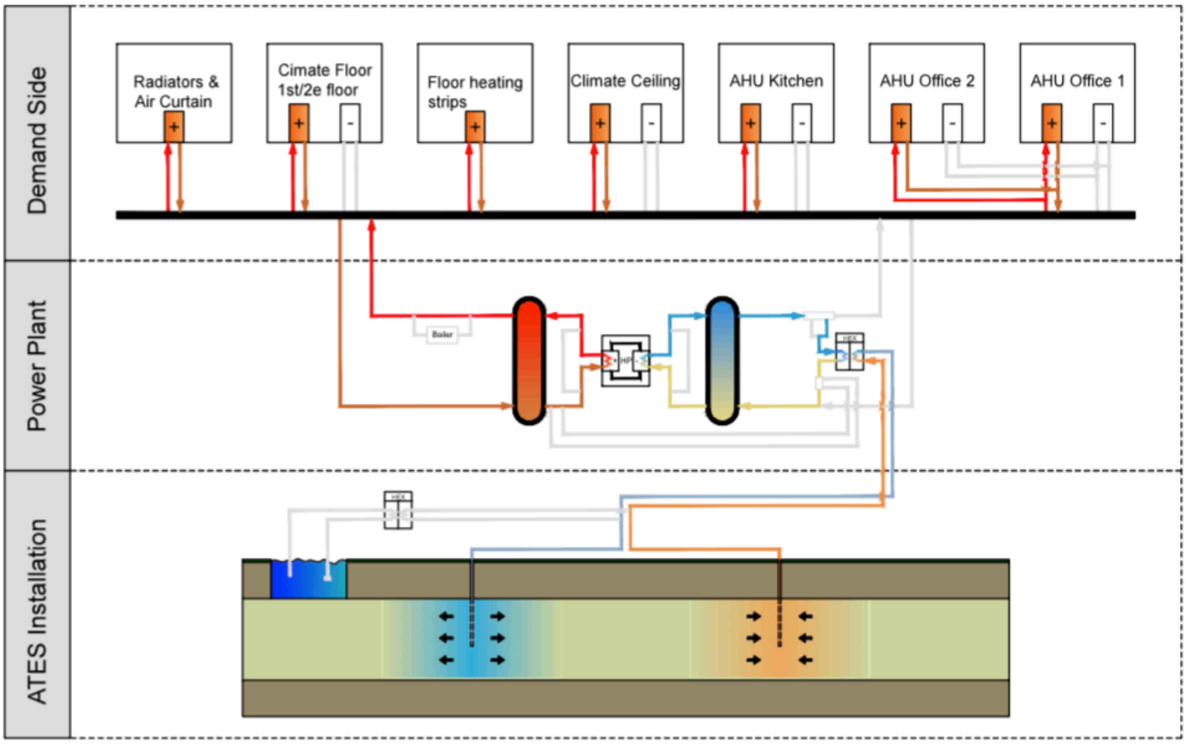


Fig. a2.1: Installation principle ATES and HVAC system Ziggo office building.

Heating mode



Cooling mode

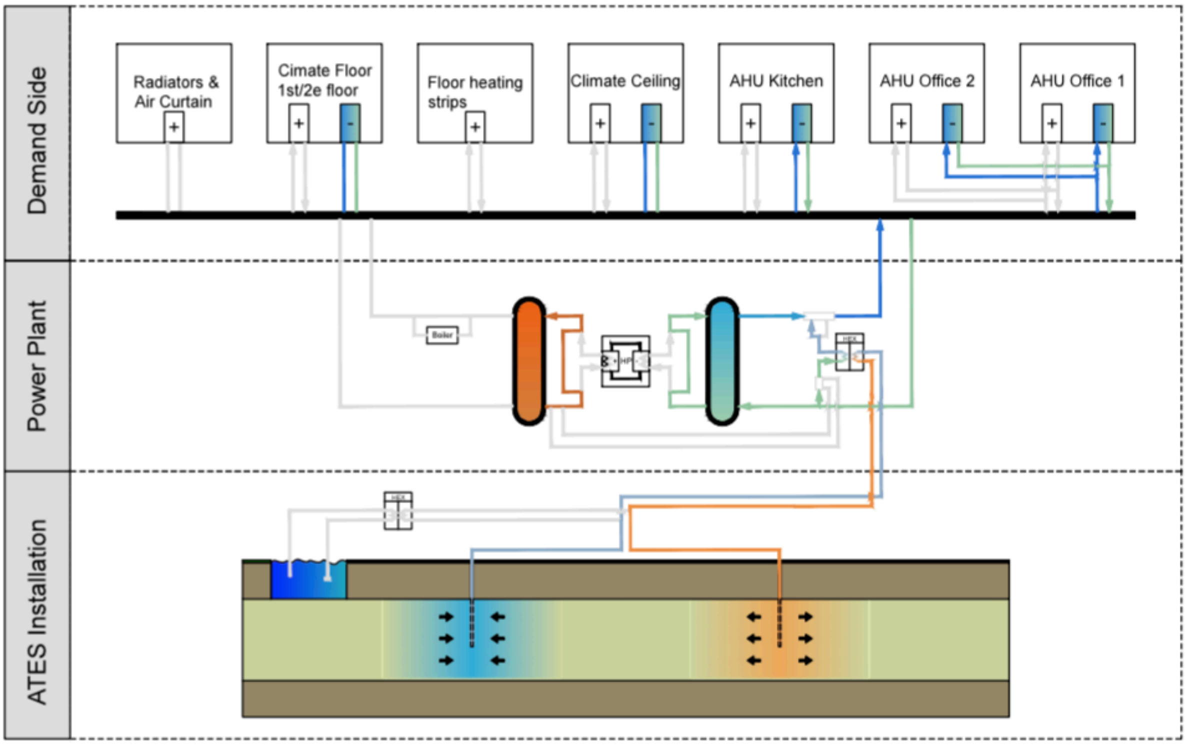


Fig. a2.2: Schematic overview thermal energy system for a heating and cooling operation.

A.2.1. Climate Floor

Following the system principles for the floor strips and fields are given (see figure a2.3: illustrated values are maximum). Figure a2.5 gives the location of the floor- fields and strips in the building.

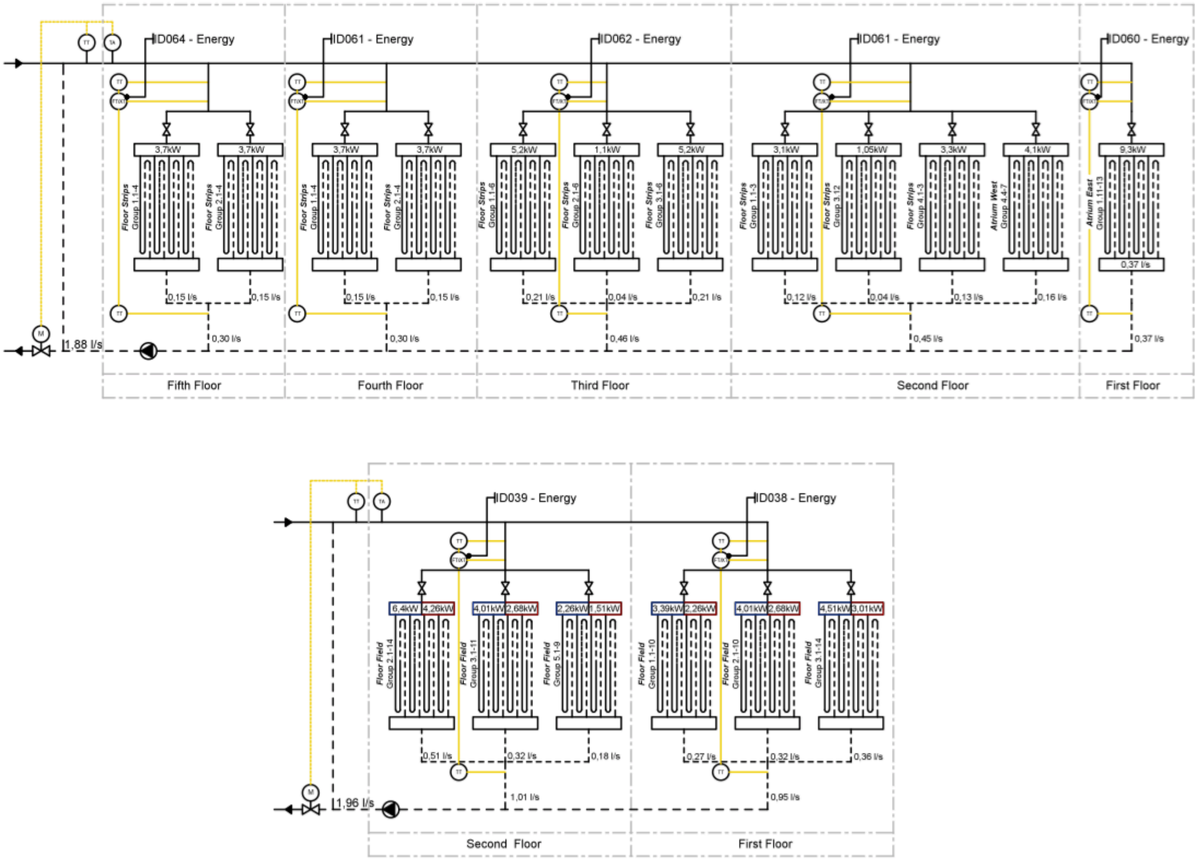


Fig. a2.3: System principle floor strips (above) and fields (below) (IDs according Appendix B.1.1).

The strips and fields are controlled separately. Floor strips can only provide heating. Floor fields can provide heating or cooling. Medium flow in both control groups is kept constant. To obtain the required temperature a motorized control valve - situated at the central return pipe - controls the water mixture. The water supply temperature is determined according control curves (see figure a2.4).

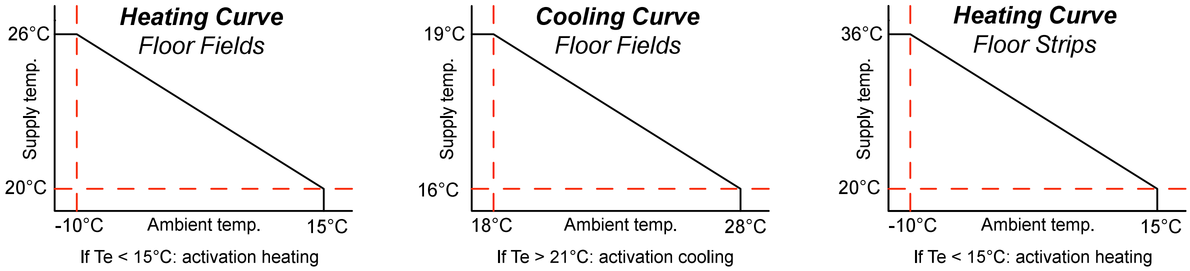


Fig. a2.4: Control curves climate floor system.

Fig. a2.5: Climate floor Ziggo office building.

A.2.2. Climate Ceiling

Following the system principles are given (see figure a2.6: illustrated values are maximum). Figure a2.8 gives the location of the climate ceiling within the building.

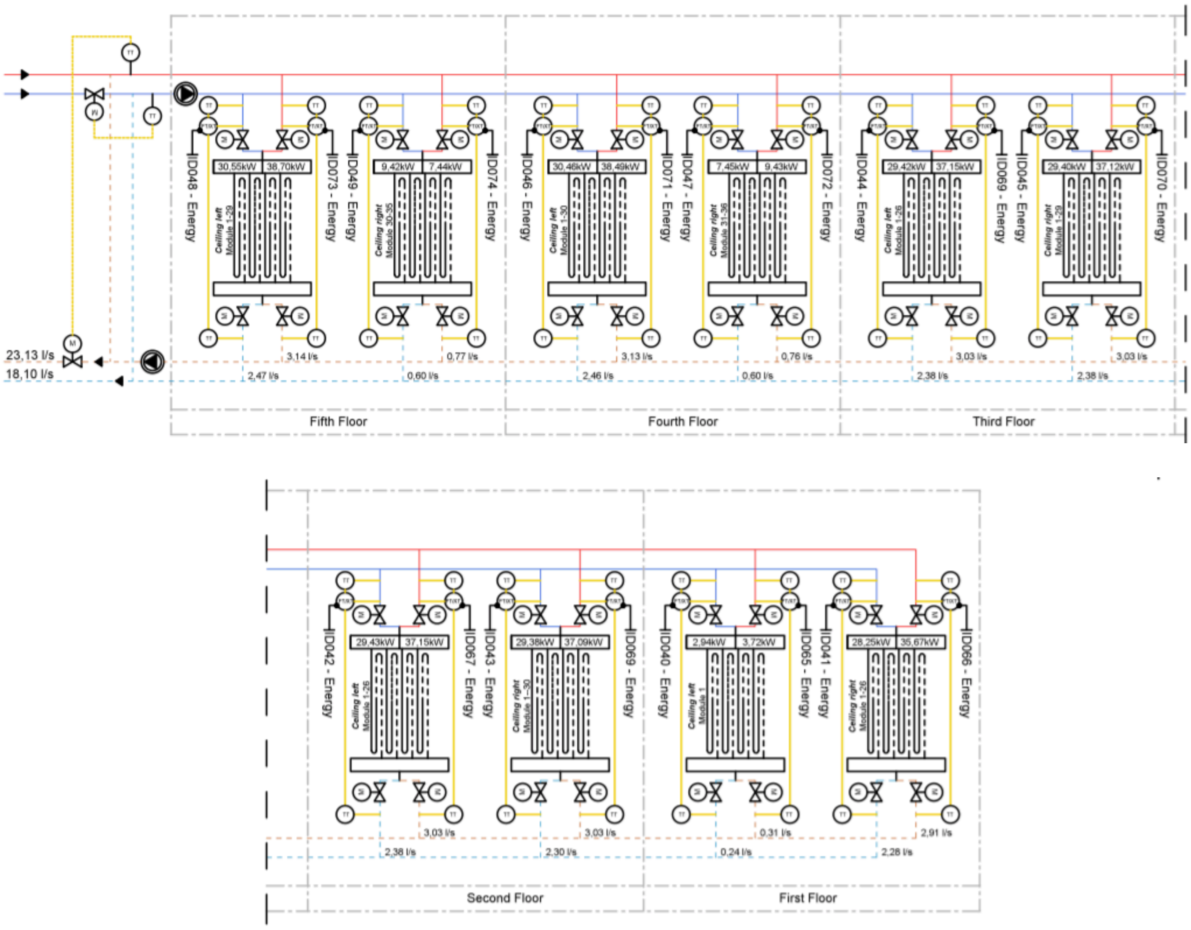
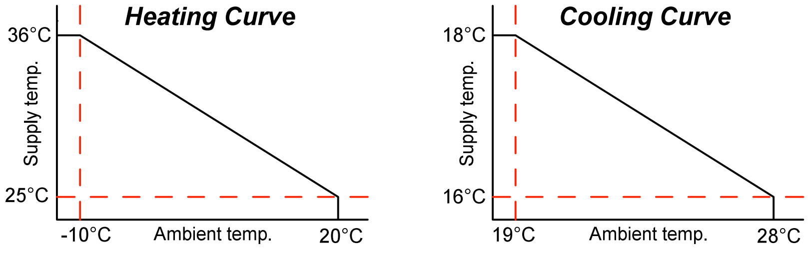


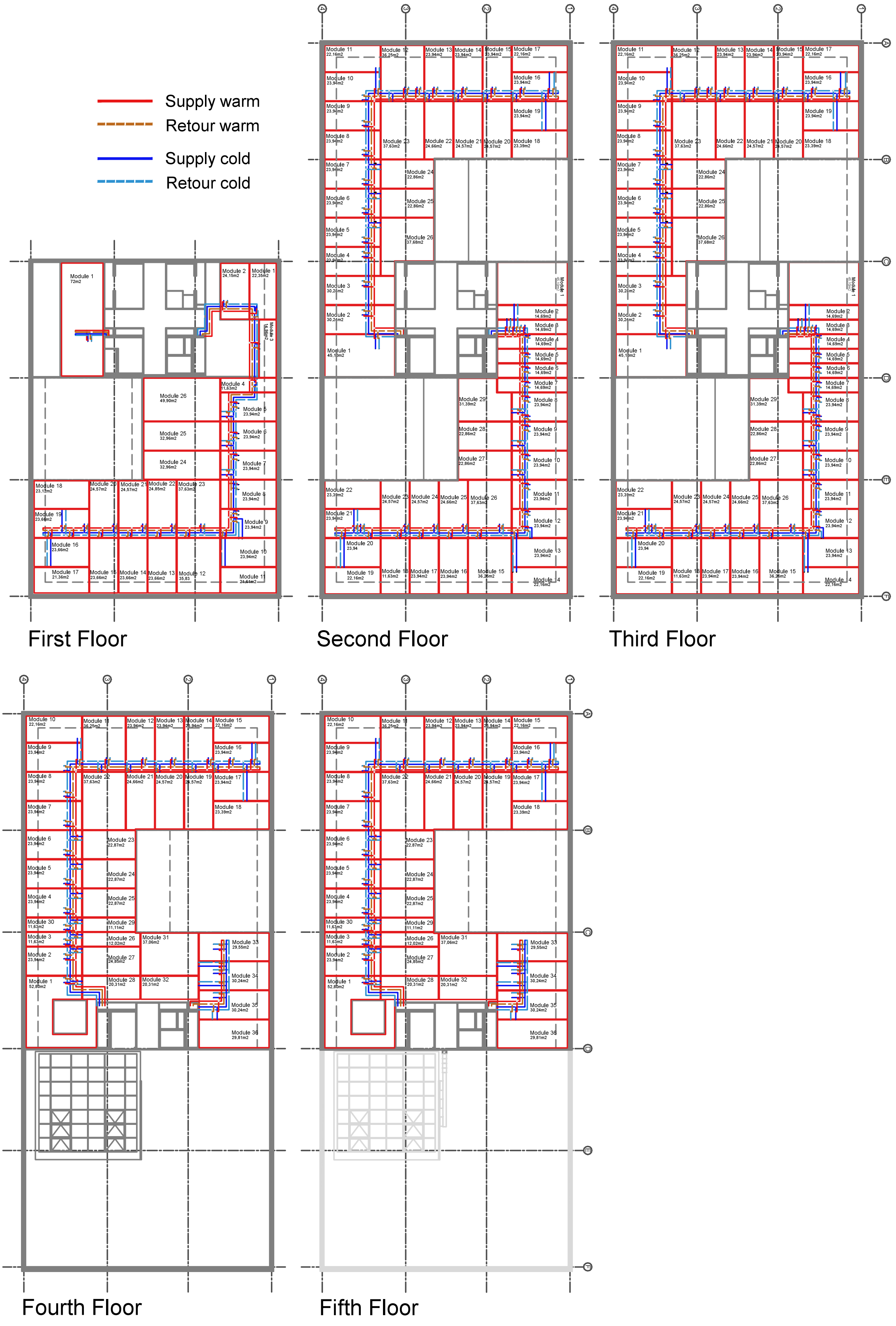
Fig. a2.6: System principle climate ceiling (IDs according Appendix B.1.1).

Climate ceiling water temperature is controlled by motorized values. Personalization of the climate is performed by adjustment of the flow. Consequently, a variable-flow pump maintains the system water pressure. The water supply temperature is determined according the control curves (see figure a2.7).



Te < 18°C: activation heating

Fig. a2.7: Control curves climate ceiling system.



Scale 1:700

Fig. a2.8: Climate ceiling Ziggo office building.

A.2.3. Air Handling Units

Following the ventilation system principles the AHU's are given (see figure a2.9: illustrated values are maximum). Figure a2.12 gives the ventilation principle throughout the building. Figure a2.13 gives the location of the ventilation system in the building.

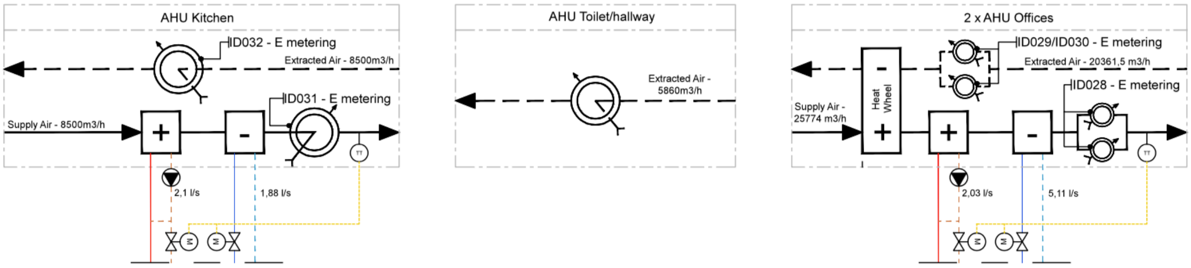


Fig. a2.9: Principles AHUs (IDs according Appendix B.1.1).

VAV ventilation set point is determined according the ventilation curve (see figure 2.10). VAV set point 0% equals 20% of maximum ventilation rate. If $CO_2 < 600$ppm, ventilation is shut down For both the kitchen and office AHU's specific fan power (SFP) for respectively supply and extraction are 1,122 kW/(m^3/s) and 0,612 kW/(m^3/s).

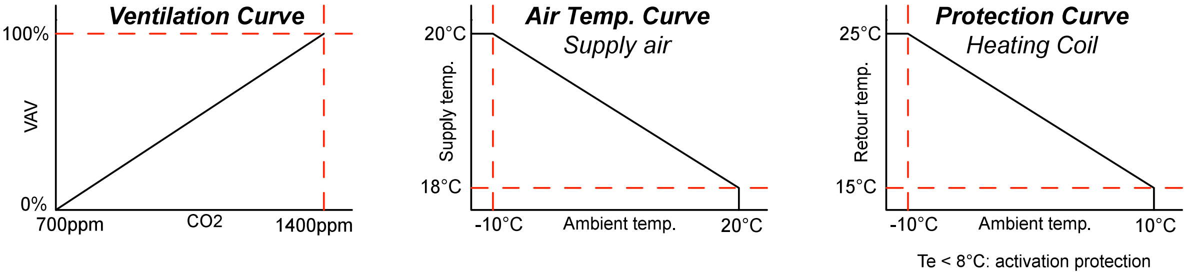


Fig. a2.10: Control curves AHU's.

Supply air temperature of all AHU's is determined according the air temperature curve (see figure 2.10). As a function of the supply air temperature set point, motorized control valves manage the thermal energy emission (see figure 2.11). For the heating coil the control valve is situated at the return pipe. For the cooling coil the control valve is situated at the supply pipe. To prevent freezing, retour water temperature of all heating coils is controlled by a protection curve (see figure 2.10).

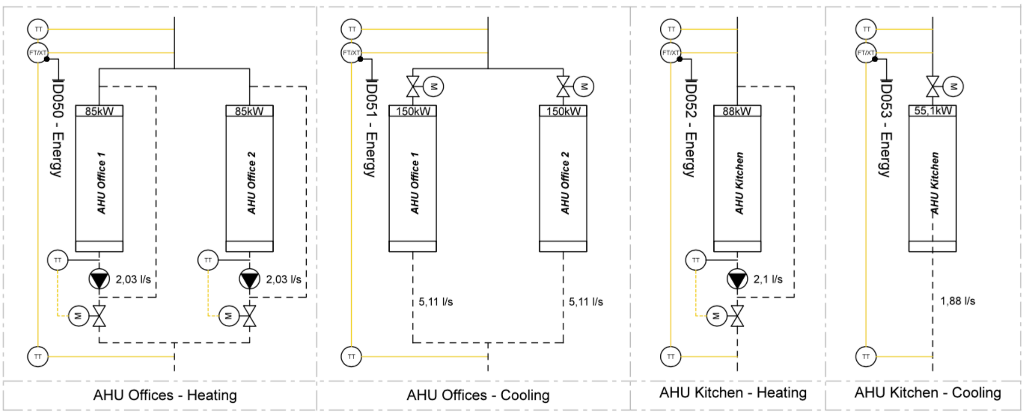


Fig. a2.11: Principles AHUs heating and cooling coil (IDs according Appendix B.1.1).

The office AHU's are equipped with a heat recovery wheel (HRW). The HRW is activated as a function of the difference between the supply and retour air temperature. If temperature difference > 2K, HRW operates at 100%. If temperature difference < 0.5K, it's shut down. Average thermal recovery is 70%.

During summer period's the office AHU's can be activated for night ventilation. It's activated between 23:00-06:00 if Ti > 23°C, Te > 15°C, and the difference between each other (dT=Ti-Te) > 3K. It's blocked/deactivated if Ti < 21°C, or Te < 13,5°C, or dT < 1K.

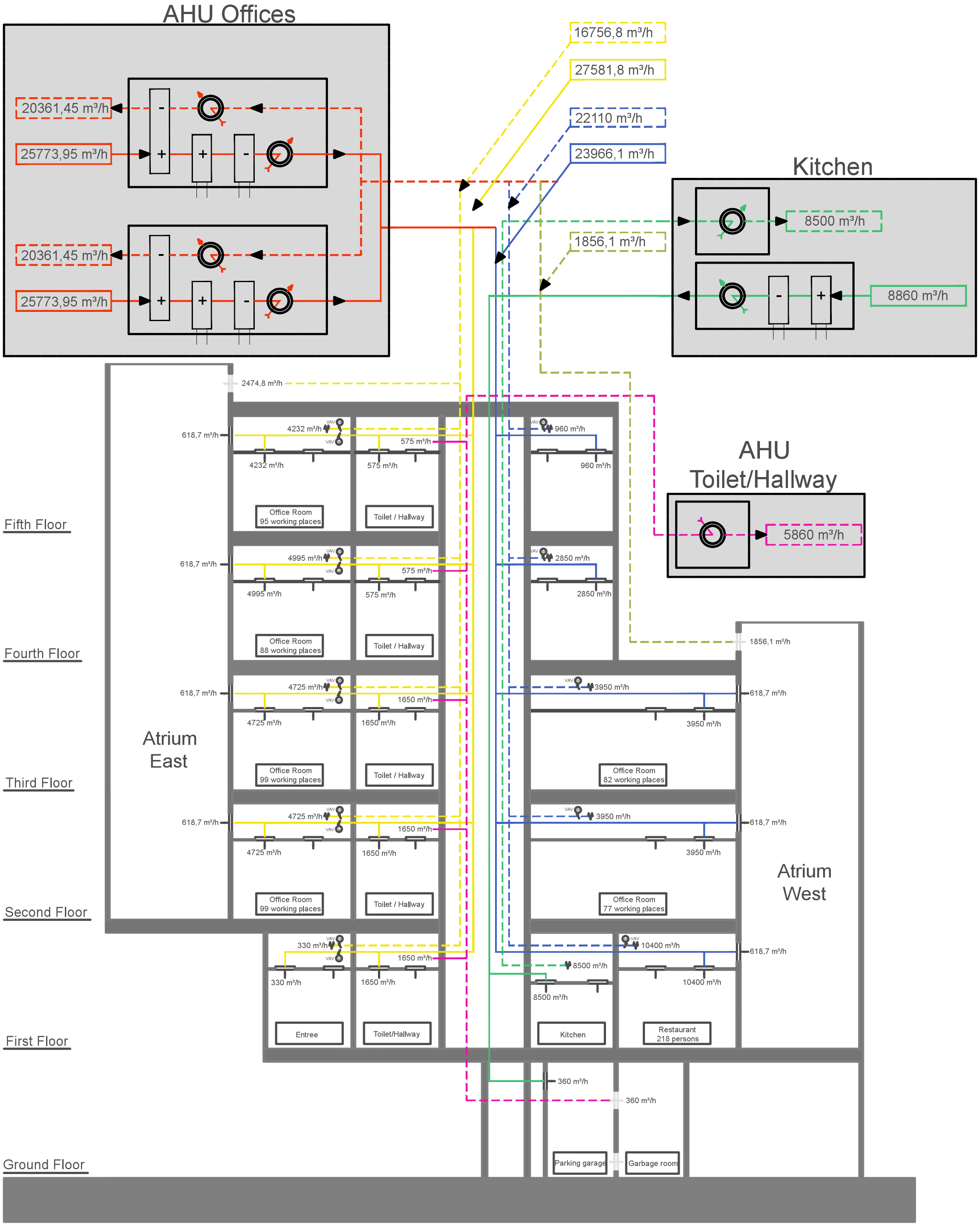


Fig. a2.12: Overview ventilation principle Ziggo Office (presented values are maximum).

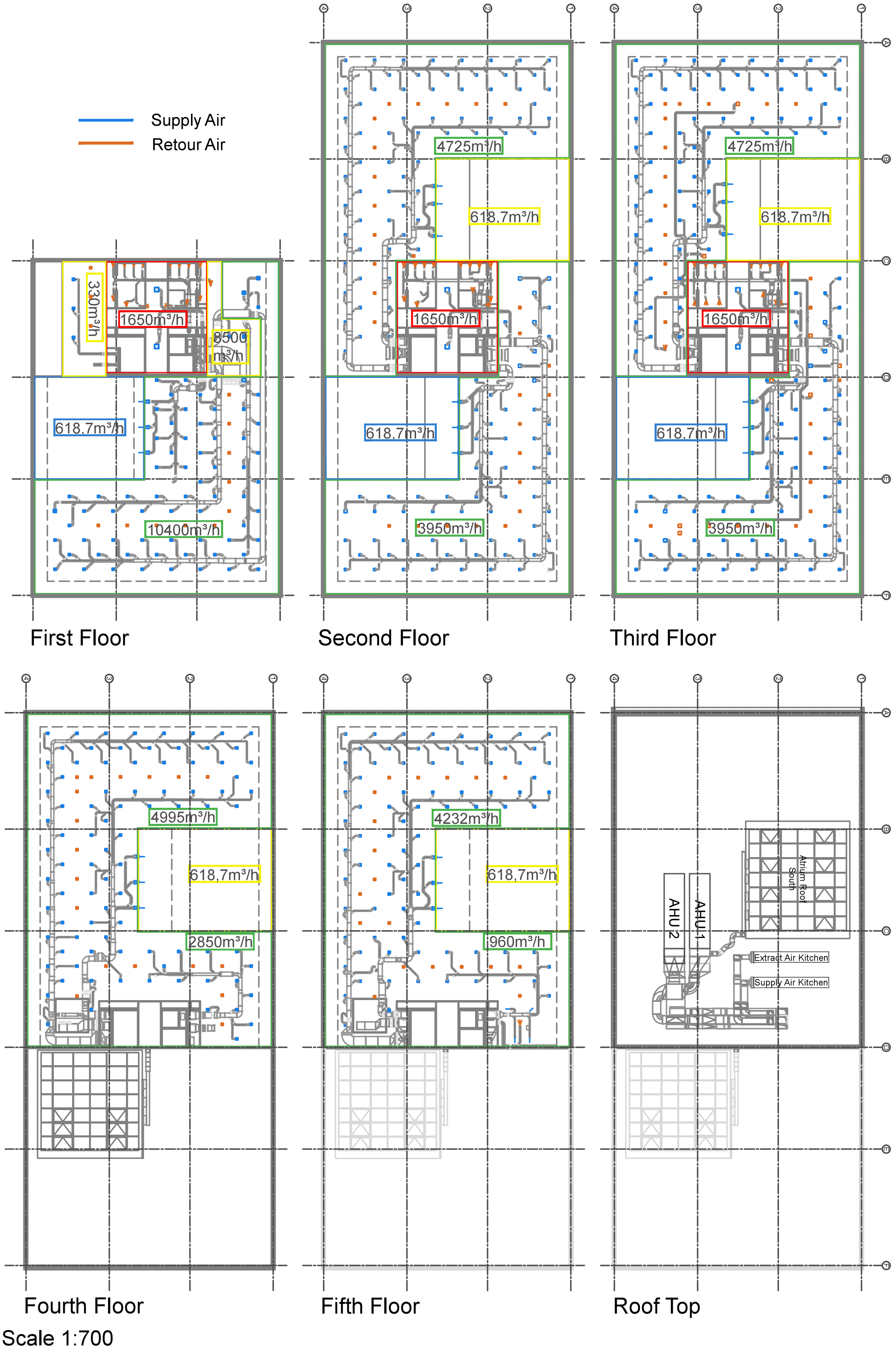


Fig. a2.13: Ventilation Ziggo office building.

A.2.4. Radiators

Following the system principle for the radiator group is given (figure a2.14).

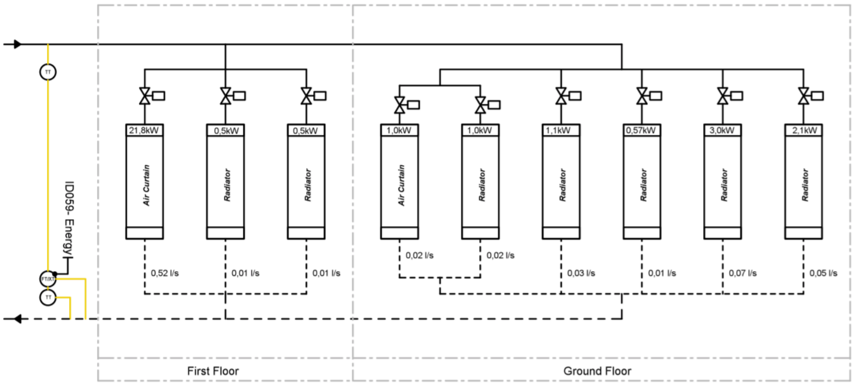


Fig. a2.14: Principles AHUs heating and cooling coil (IDs according Appendix A.3.1).

A.2.5. Heat Pump

A Daiken HP is installed. It can operate in heating or cooling mode. Furthermore, it can operate in partial load by controlling the compressor linear between 25%-100%. Two minutes before HP control is enabled the condenser and evaporator valve are opened. Minimal outgoing temperature at the evaporator (cold) side is 4,5°C. Minimal outgoing temperature at the condenser (warm) side is 20°C. Per hour a maximum of 6 HP start/stops can occur.

During heating mode condenser outlet temperature set point is determined by the central heating set point. Maximum outgoing condenser temperature is 55°C. With a peak electricity demand of 53,1kW, maximum heating power is 247kW. Simultaneously max 192kW of cold is produced at the evaporator.

During cooling mode evaporator outlet temperature set point is determined by the difference between the initial outgoing temperature and central cooling set point. With a peak electricity demand of 42,9kW, maximum cooling power is 247kW. Simultaneously max 291kW of heat is produces at the condenser. Following the system principle of the HP is given (see figure a2.15).

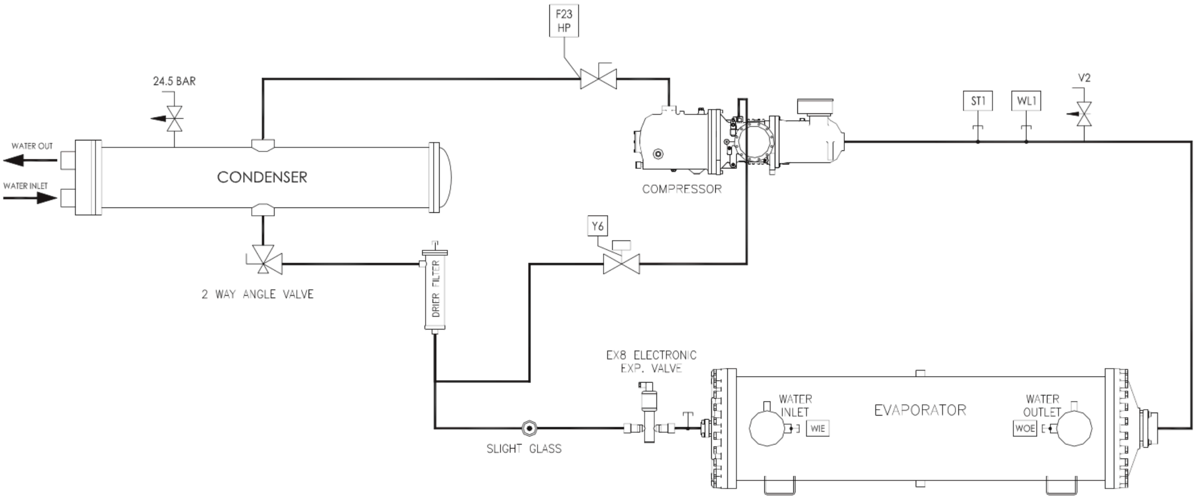


Fig. a2.15: Heat pump system principle.

A.2.6. Buffer Tanks

If HVAC thermal demand depends on the HP - especially relevant for heating mode - supply comes with a gap of 2 minutes. Two stratified thermal buffers are installed to overcome the gap: one hot and one cold of respectively 1750 and 1500 liter. Following the geometry of both buffers is given (see figure a2.16).

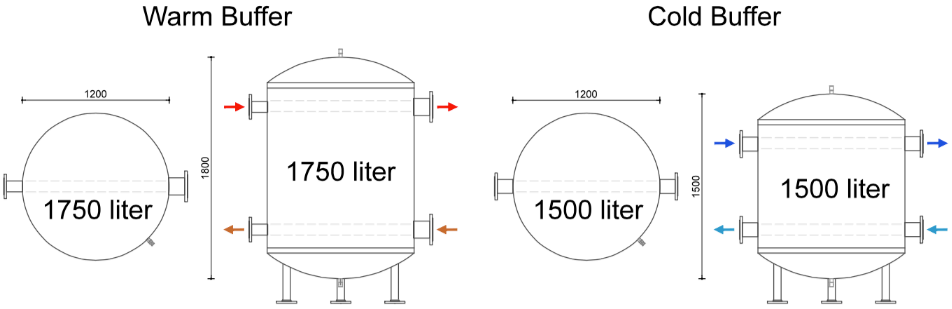


Fig. a2.16: Dimensions thermal buffers.

A.2.7. Gas Fired Boiler

A Remeha gas-fired boiler is installed as backup for the central heating system. Goal of the PP is to use the boiler as less as possible. The boiler is activated if HP in heating or cooling mode isn't sufficient to supply the required heat.

Set point of the boiler is defined by the delta between the measured and preferred central heating supply temperature. The control is released if heating has a thermal demand, and supply temperature for 10 minutes is < 1K than the set point temperature. For a water temperature of 40°C the boiler efficiency is 108%. Maximum energy supply of the boiler is 283kW. Following the boiler dimensions are given (see figure a2.17).

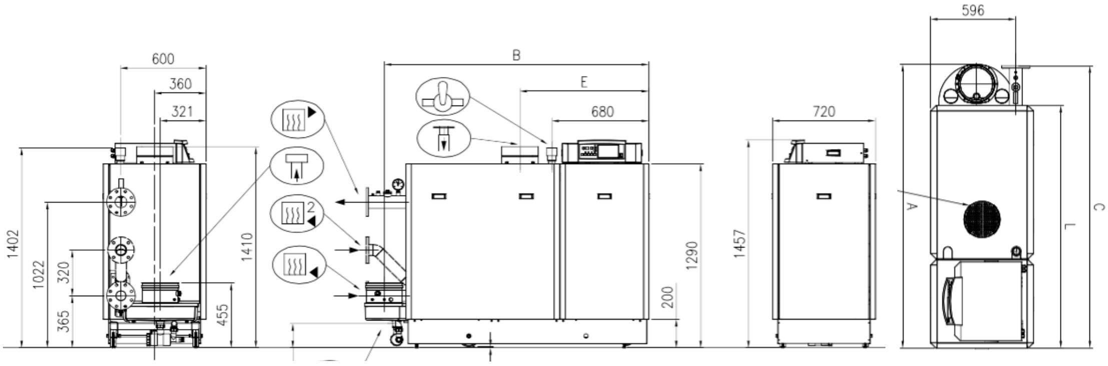


Fig. a2.17: Dimensions gas fired boiler.

A.2.8. Heat Exchanger

First, the properties of the PP-HEX are given. Second, the properties of the HEX for extra cold regeneration are given.

PP-HEX

A countercurrent flat plate HEX is placed to exchange thermal energy between the PP and ATES installation. It contains stainless steel (ALLOY 316) plates of 0,4mm thick and a heating surface area of 102,5m^2. Following dimensions of the HEX are given (see figure a.2.18).

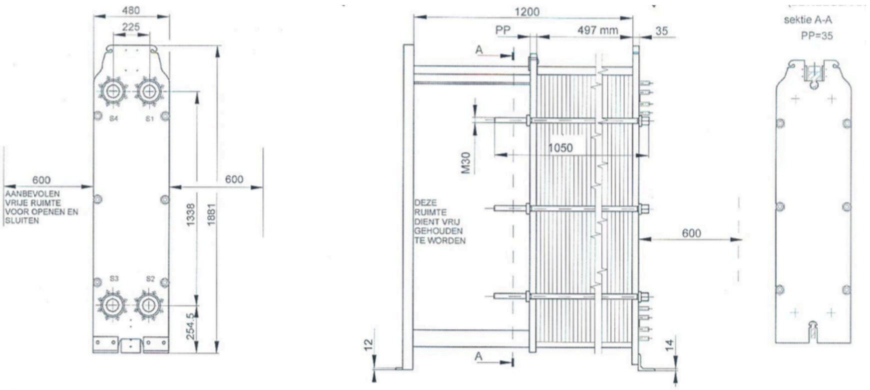


Fig. a2.18: Dimensions PP-HEX.

Regeneration-HEX

A countercurrent flat plate HEX is placed to exchange thermal energy between the water of the nearby canal and ATES groundwater. It contains stainless steel (ALLOY 316) plates of 0,4mm thick and a heating surface area of 23,5m^2. Following the dimensions of the HEX are given (see figure a.2.19).

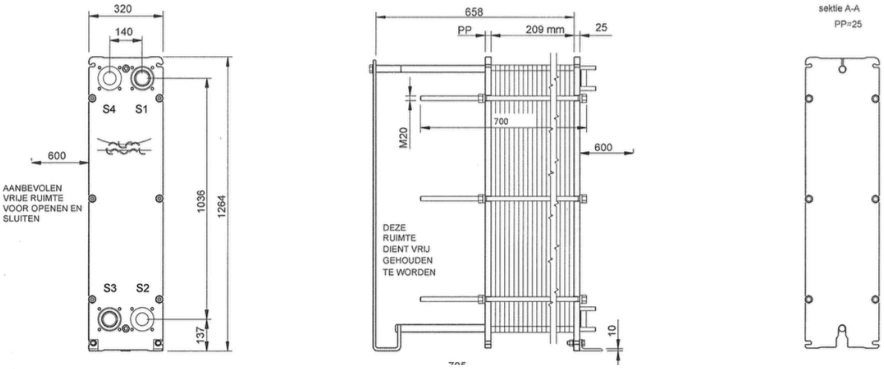


Fig. a2.19: Dimensions regeneration-HEX.

A.2.9. ATES Installation

First, the aquifer properties are described. Second, the well pump specifications are described. Third, the extra regeneration facility for the cold well is described.

Aquifers

Both aquifer filters have a height of 29m and a diameter of 0.2m. The cold well filter is placed between 40-69m. The warm well filter is placed between 41-70m. From center to center the wells are placed at a distance of 172m from each other. Ground structure of both wells is buildup from clay (0-6m), sand (6-11,5m), clay (11,5-20m) and sand (20-72m).

According Dutch legislation (art. 6.4 Waterwet [26]) and the license granted, groundwater conditions need to satisfy the following requirements:

- Average annual injection temperature may not be < 5^{o}C and > 20^{o}C;
- Average injection temperature over a month may not be > 25^{o}C;
- Per year a maximum of 600.000m^3 groundwater may be replaced;
- Per hour the maximum groundwater replacement may be 100m^3
- Within 5 year average thermal unbalance may not be > 25%.

Well Pump

Both wells are equipped with a similar Lowara underwater pump. In case of maximum heating demand the warm well pump has a limited pumping rate of 33m^3/h, plus 6m^3/h for regeneration. Maximum cooling demand for the cold well pump comes with a limited pumping rate of 33m^3/h. Pump specifications are:

- Max flow: 39 m^3/h;
- Nominal flow: 33 m^3/h;
- Minimal flow: 6,5m^3/h;
- Shaft power: 6,8 kW
- Electric power: 7,5 kW

Regeneration

Extra regeneration capacity can be manually enabled for the cold well. By a HEX thermal energy between the groundwater and nearby canal can be exchanged (see figure 2.19 for details HEX). Maximum energy supply of the warm well equals a pump operation of 33m^3/h. Maximum warm well pump capacity is 39m^3/h. Consequently a debit of 6m^3/h is always available to enable extra cold charging. Activation of extra regeneration is enabled manually.

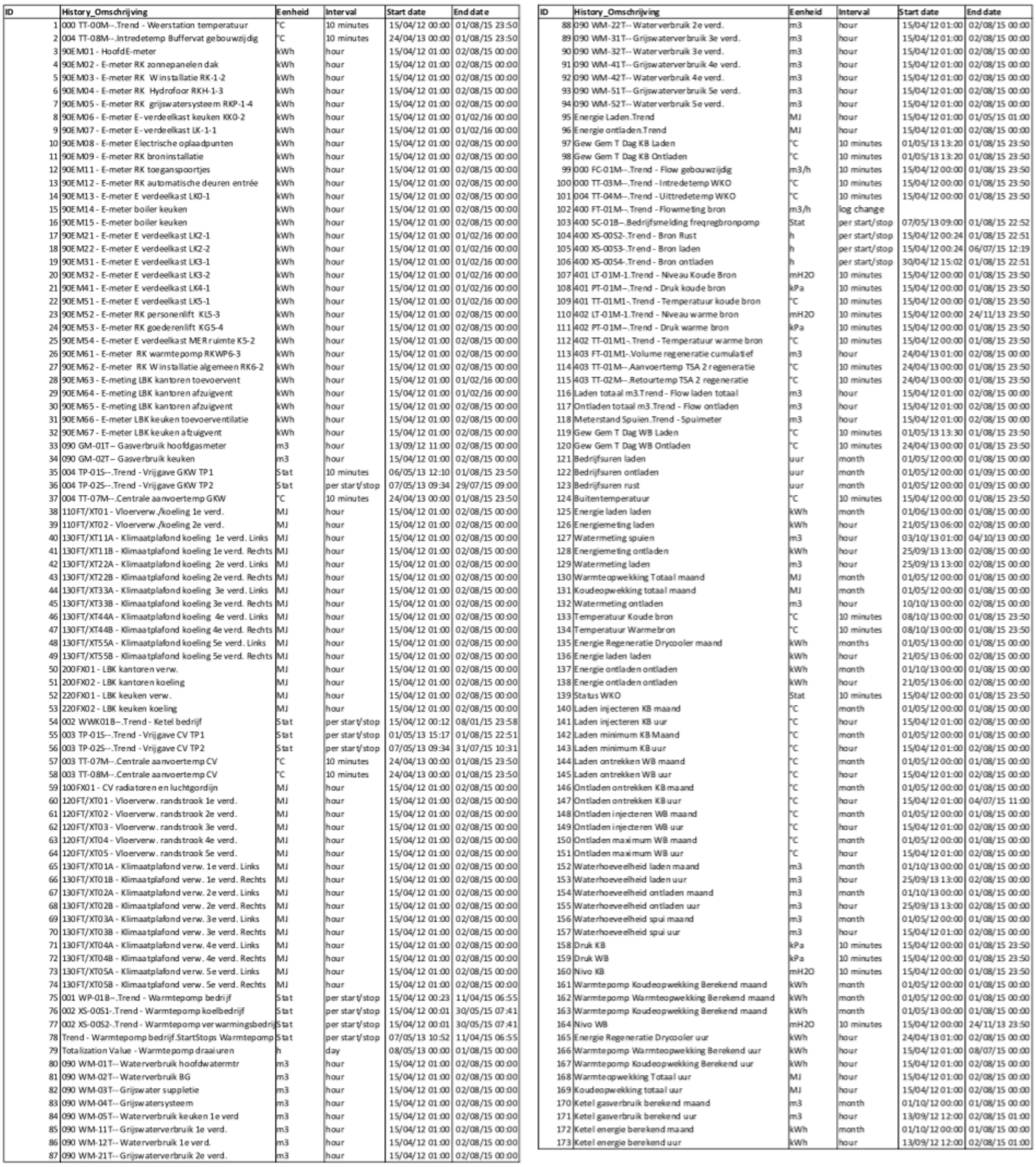
B. Appendix – Exploitation Data

B.1. Data Acquisition

B.1.1. Data Telecontrol

Department Telecontrol of Wolter & Dros provided a historical BMS dataset of 173 variables. Time length of each variable is between 15/04/2012 – 01/02/2016. Table b1.1 gives on overview of the acquired dataset.

Table b1.1: Data provided Telecontrol.



ID	History_Omschrijving	Eenheid	Interval	Start date	End date
1	000 TT-00M--.Trend - Weerstation temperatuur	°C	10 minutes	15/04/12 00:00	01/08/15 23:50
2	004 TT-08M--.Intredetemp Buffervat gebouwzijdig	°C	10 minutes	24/04/13 00:00	01/08/15 23:50
3	90EM01 - HoofdE-meter	kWh	hour	15/04/12 01:00	02/08/15 00:00
4	90EM02 - E-meter RK zonnepanelen dak	kWh	hour	15/04/12 01:00	02/08/15 00:00
5	90EM03 - E-meter RK W installatie RK-1-2	kWh	hour	15/04/12 01:00	02/08/15 00:00
6	90EM04 - E-meter RK Hydrofoor RKH-1-3	kWh	hour	15/04/12 01:00	02/08/15 00:00
7	90EM05 - E-meter RK grijswatersysteem RKP-1-4	kWh	hour	15/04/12 01:00	02/08/15 00:00
8	90EM06 - E-meter E-verdeelkast keuken KK0-2	kWh	hour	15/04/12 01:00	01/02/16 00:00
9	90EM07 - E-meter E-verdeelkast LK-1-1	kWh	hour	15/04/12 01:00	01/02/16 00:00
10	90EM08 - E-meter Electrische oplaadpunten	kWh	hour	15/04/12 01:00	02/08/15 00:00
11	90EM09 - E-meter RK broninstallatie	kWh	hour	15/04/12 01:00	02/08/15 00:00
12	90EM11 - E-meter RK toeganspoortjes	kWh	hour	15/04/12 01:00	02/08/15 00:00
13	90EM12 - E-meter RK automatische deuren entrée	kWh	hour	15/04/12 01:00	02/08/15 00:00
14	90EM13 - E-meter E verdeelkast LK0-1	kWh	hour	15/04/12 01:00	02/08/15 00:00
15	90EM14 - E-meter boiler keuken	kWh	hour	15/04/12 01:00	02/08/15 00:00
16	90EM15 - E-meter boiler keuken	kWh	hour	15/04/12 01:00	02/08/15 00:00
17	90EM21 - E-meter E verdeelkast LK2-1	kWh	hour	15/04/12 01:00	01/02/16 00:00
18	90EM22 - E-meter E verdeelkast LK2-2	kWh	hour	15/04/12 01:00	01/02/16 00:00
19	90EM31 - E-meter E verdeelkast LK3-1	kWh	hour	15/04/12 01:00	01/02/16 00:00
20	90EM32 - E-meter E verdeelkast LK3-2	kWh	hour	15/04/12 01:00	01/02/16 00:00
21	90EM41 - E-meter E verdeelkast LK4-1	kWh	hour	15/04/12 01:00	01/02/16 00:00
22	90EM51 - E-meter E verdeelkast LK5-1	kWh	hour	15/04/12 01:00	01/02/16 00:00
23	90EM52 - E-meter RK personenlift KL5-3	kWh	hour	15/04/12 01:00	02/08/15 00:00
24	90EM53 - E-meter RK goederenlift KG5-4	kWh	hour	15/04/12 01:00	02/08/15 00:00
25	90EM54 - E-meter E verdeelkast MER ruimte K5-2	kWh	hour	15/04/12 01:00	02/08/15 00:00
26	90EM61 - E-meter RK warmtepomp RKWP6-3	kWh	hour	15/04/12 01:00	02/08/15 00:00
27	90EM62 - E-meter RK W installatie algemeen RK6-2	kWh	hour	15/04/12 01:00	02/08/15 00:00
28	90EM63 - E-meting LBK kantoren toevoervent	kWh	hour	15/04/12 01:00	01/02/16 00:00
29	90EM64 - E-meting LBK kantoren afzuigvent	kWh	hour	15/04/12 01:00	01/02/16 00:00
30	90EM65 - E-meting LBK kantoren afzuigvent	kWh	hour	15/04/12 01:00	02/08/15 00:00
31	90EM66 - E-meter LBK keuken toevoerventilatie	kWh	hour	15/04/12 01:00	02/08/15 00:00
32	90EM67 - E-meter LBK keuken afzuigvent	kWh	hour	15/04/12 01:00	02/08/15 00:00
33	090 GM-01T-- Gasverbruik hoofdgasmeter	m3	hour	13/09/12 11:00	02/08/15 00:00
34	090 GM-02T-- Gasverbruik keuken	m3	hour	15/04/12 01:00	02/08/15 00:00
35	004 TP-01S--.Trend - Vrijgave GKW TP1	Stat	10 minutes	06/05/13 12:10	01/08/15 23:50
36	004 TP-02S--.Trend - Vrijgave GKW TP2	Stat	per start/stop	07/05/13 09:34	29/07/15 09:00
37	004 TT-07M--.Centrale aanvoertemp GKW	°C	10 minutes	24/04/13 00:00	01/08/15 23:50
38	110FT/XT01 - Vloerverw./koeling 1e verd.	MJ	hour	15/04/12 01:00	02/08/15 00:00
39	110FT/XT02 - Vloerverw./koeling 2e verd.	MJ	hour	15/04/12 01:00	02/08/15 00:00
40	130FT/XT11A - Klimaatplafond koeling 1e verd. Links	MJ	hour	15/04/12 01:00	02/08/15 00:00
41	130FT/XT11B - Klimaatplafond koeling 1e verd. Rechts	MJ	hour	15/04/12 01:00	02/08/15 00:00
42	130FT/XT22A - Klimaatplafond koeling 2e verd. Links	MJ	hour	15/04/12 01:00	02/08/15 00:00
43	130FT/XT22B - Klimaatplafond koeling 2e verd. Rechts	MJ	hour	15/04/12 01:00	02/08/15 00:00
44	130FT/XT33A - Klimaatplafond koeling 3e verd. Links	MJ	hour	15/04/12 01:00	02/08/15 00:00
45	130FT/XT33B - Klimaatplafond koeling 3e verd. Rechts	MJ	hour	15/04/12 01:00	02/08/15 00:00
46	130FT/XT44A - Klimaatplafond koeling 4e verd. Links	MJ	hour	15/04/12 01:00	02/08/15 00:00
47	130FT/XT44B - Klimaatplafond koeling 4e verd. Rechts	MJ	hour	15/04/12 01:00	02/08/15 00:00
48	130FT/XT55A - Klimaatplafond koeling 5e verd. Links	MJ	hour	15/04/12 01:00	02/08/15 00:00
49	130FT/XT55B - Klimaatplafond koeling 5e verd. Rechts	MJ	hour	15/04/12 01:00	02/08/15 00:00
50	200FX01 - LBK kantoren verw.	MJ	hour	15/04/12 01:00	02/08/15 00:00
51	200FX02 - LBK kantoren koeling	MJ	hour	15/04/12 01:00	02/08/15 00:00
52	220FX01 - LBK keuken verw.	MJ	hour	15/04/12 01:00	02/08/15 00:00
53	220FX02 - LBK keuken koeling	MJ	hour	15/04/12 01:00	02/08/15 00:00
54	002 WWK01B--.Trend - Ketel bedrijf	Stat	per start/stop	15/04/12 00:12	08/01/15 23:58
55	003 TP-01S--.Trend - Vrijgave CV TP1	Stat	per start/stop	01/05/13 15:17	01/08/15 22:51
56	003 TP-02S--.Trend - Vrijgave CV TP2	Stat	per start/stop	07/05/13 09:34	31/07/15 10:31
57	003 TT-07M--.Centrale aanvoertemp CV	°C	10 minutes	24/04/13 00:00	01/08/15 23:50
58	003 TT-08M--.Centrale aanvoertemp CV	°C	10 minutes	24/04/13 00:00	01/08/15 23:50
59	100FX01 - CV radiatoren en luchtgordijn	MJ	hour	15/04/12 01:00	02/08/15 00:00
60	120FT/XT01 - Vloerverw. randstrook 1e verd.	MJ	hour	15/04/12 01:00	02/08/15 00:00
61	120FT/XT02 - Vloerverw. randstrook 2e verd.	MJ	hour	15/04/12 01:00	02/08/15 00:00
62	120FT/XT03 - Vloerverw. randstrook 3e verd.	MJ	hour	15/04/12 01:00	02/08/15 00:00
63	120FT/XT04 - Vloerverw. randstrook 4e verd.	MJ	hour	15/04/12 01:00	02/08/15 00:00
64	120FT/XT05 - Vloerverw. randstrook 5e verd.	MJ	hour	15/04/12 01:00	02/08/15 00:00
65	130FT/XT01A - Klimaatplafond verw. 1e verd. Links	MJ	hour	15/04/12 01:00	02/08/15 00:00
66	130FT/XT01B - Klimaatplafond verw. 1e verd. Rechts	MJ	hour	15/04/12 01:00	02/08/15 00:00
67	130FT/XT02A - Klimaatplafond verw. 2e verd. Links	MJ	hour	15/04/12 01:00	02/08/15 00:00
68	130FT/XT02B - Klimaatplafond verw. 2e verd. Rechts	MJ	hour	15/04/12 01:00	02/08/15 00:00
69	130FT/XT03A - Klimaatplafond verw. 3e verd. Links	MJ	hour	15/04/12 01:00	02/08/15 00:00
70	130FT/XT03B - Klimaatplafond verw. 3e verd. Rechts	MJ	hour	15/04/12 01:00	02/08/15 00:00
71	130FT/XT04A - Klimaatplafond verw. 4e verd. Links	MJ	hour	15/04/12 01:00	02/08/15 00:00
72	130FT/XT04B - Klimaatplafond verw. 4e verd. Rechts	MJ	hour	15/04/12 01:00	02/08/15 00:00
73	130FT/XT05A - Klimaatplafond verw. 5e verd. Links	MJ	hour	15/04/12 01:00	02/08/15 00:00
74	130FT/XT05B - Klimaatplafond verw. 5e verd. Rechts	MJ	hour	15/04/12 01:00	02/08/15 00:00
75	001 WP-01B--.Trend - Warmtepomp bedrijf	Stat	per start/stop	15/04/12 00:23	11/04/15 06:55
76	002 XS-00S1-.Trend - Warmtepomp koelbedrijf	Stat	per start/stop	15/04/12 00:01	30/05/15 07:41
77	002 XS-00S2-.Trend - Warmtepomp verwarmingsbedrij	Stat	per start/stop	15/04/12 00:01	30/05/15 07:41
78	Trend - Warmtepomp bedrijf.StartStops Warmtepomp	Stat	per start/stop	07/05/13 10:52	11/04/15 06:55
79	Totalization Value - Warmtepomp draaiuren	h	day	08/05/13 00:00	01/08/15 00:00
80	090 WM-01T--Waterverbruik hoofdwatermtr	m3	hour	15/04/12 01:00	02/08/15 00:00
81	090 WM-02T--Waterverbruik BG	m3	hour	15/04/12 01:00	02/08/15 00:00
82	090 WM-03T--Grijswater suppletie	m3	hour	15/04/12 01:00	02/08/15 00:00
83	090 WM-04T--Grijswatersysteem	m3	hour	15/04/12 01:00	02/08/15 00:00
84	090 WM-05T--Waterverbruik keuken 1e verd	m3	hour	15/04/12 01:00	02/08/15 00:00
85	090 WM-11T--Grijswaterverbruik 1e verd.	m3	hour	15/04/12 01:00	02/08/15 00:00
86	090 WM-12T--Waterverbruik 1e verd.	m3	hour	15/04/12 01:00	02/08/15 00:00
87	090 WM-21T--Grijswaterverbruik 2e verd.	m3	hour	15/04/12 01:00	02/08/15 00:00
88	090 WM-22T--Waterverbruik 2e verd.	m3	hour	15/04/12 01:00	02/08/15 00:00
89	090 WM-31T--Grijswaterverbruik 3e verd.	m3	hour	15/04/12 01:00	02/08/15 00:00
90	090 WM-32T--Waterverbruik 3e verd.	m3	hour	15/04/12 01:00	02/08/15 00:00
91	090 WM-41T--Grijswaterverbruik 4e verd.	m3	hour	15/04/12 01:00	02/08/15 00:00
92	090 WM-42T--Waterverbruik 4e verd.	m3	hour	15/04/12 01:00	02/08/15 00:00
93	090 WM-51T--Grijswaterverbruik 5e verd.	m3	hour	15/04/12 01:00	02/08/15 00:00
94	090 WM-52T--Waterverbruik 5e verd.	m3	hour	15/04/12 01:00	02/08/15 00:00
95	Energie Laden.Trend	MJ	hour	15/04/12 01:00	01/05/15 01:00
96	Energie ontladen.Trend	MJ	hour	15/04/12 01:00	02/08/15 00:00
97	Gew Gem T Dag KB Laden	°C	10 minutes	01/05/13 13:20	01/08/15 23:50
98	Gew Gem T Dag KB Ontladen	°C	10 minutes	01/05/13 13:20	01/08/15 23:50
99	000 FC-01M--.Trend - Flow gebouwzijdig	m3/h	10 minutes	15/04/12 00:00	01/08/15 23:50
100	000 TT-03M--.Trend - Intredetemp WKO	°C	10 minutes	15/04/12 00:00	01/08/15 23:50
101	004 TT-04M--.Trend - Uittredetemp WKO	°C	10 minutes	15/04/12 00:00	01/08/15 23:50
102	400 FT-01M--.Trend - Flowmeting bron	m3/h	log change		
103	400 SC-01B--.Bedrijfsmelding freqregbronpomp	Stat	per start/stop	07/05/13 09:00	01/08/15 22:52
104	400 XS-00S2-.Trend - Bron Rust	h	per start/stop	15/04/12 00:24	01/08/15 22:51
105	400 XS-00S3-.Trend - Bron laden	h	per start/stop	15/04/12 00:24	06/07/15 12:19
106	400 XS-00S4-.Trend - Bron ontladen	h	per start/stop	30/04/12 15:02	01/08/15 22:51
107	401 LT-01M-1.Trend - Niveau Koude Bron	mH2O	10 minutes	15/04/12 00:00	01/08/15 23:50
108	401 PT-01M--.Trend - Druk koude bron	kPa	10 minutes	15/04/12 00:00	01/08/15 23:50
109	401 TT-01M1-.Trend - Temperatuur koude bron	°C	10 minutes	15/04/12 00:00	01/08/15 23:50
110	402 LT-01M-1.Trend - Niveau warme bron	mH2O	10 minutes	15/04/12 00:00	24/11/13 23:50
111	402 PT-01M--.Trend - Druk warme bron	kPa	10 minutes	15/04/12 00:00	01/08/15 23:50
112	402 TT-01M1-.Trend - Temperatuur warme bron	°C	10 minutes	15/04/12 00:00	01/08/15 23:50
113	403 FT-01M1-.Volume regeneratie cumulatief	m3	hour	24/04/13 01:00	02/08/15 00:00
114	403 TT-01M--.Aanvoertemp TSA 2 regeneratie	°C	10 minutes	24/04/13 00:00	01/08/15 23:50
115	403 TT-02M--.Retourtemp TSA 2 regeneratie	°C	10 minutes	24/04/13 00:00	01/08/15 23:50
116	Laden totaal m3.Trend - Flow laden totaal	m3	hour	15/04/12 01:00	02/08/15 00:00
117	Ontladen totaal m3.Trend - Flow ontladen	m3	hour	15/04/12 01:00	02/08/15 00:00
118	Meterstand Spuien.Trend - Spuimeter	m3	hour	15/04/12 01:00	02/08/15 00:00
119	Gew Gem T Dag WB Laden	°C	10 minutes	01/05/13 13:30	01/08/15 23:50
120	Gew Gem T Dag WB Ontladen	°C	10 minutes	24/04/13 00:00	01/08/15 23:50
121	Bedrijfsuren laden	uur	month	01/05/12 00:00	01/08/15 00:00
122	Bedrijfsuren ontladen	uur	month	01/05/12 00:00	01/09/15 00:00
123	Bedrijfsuren rust	uur	month	01/05/12 00:00	01/09/15 00:00
124	Buitentemperatuur	°C	10 minutes	15/04/12 00:00	01/08/15 23:50
125	Energie laden laden	kWh	month	01/06/13 00:00	01/08/15 00:00
126	Energiemeting laden	kWh	hour	21/05/13 06:00	02/08/15 00:00
127	Watermeting spuien	m3	hour	03/10/13 01:00	04/10/13 00:00
128	Energiemeting ontladen	kWh	hour	25/09/13 13:00	02/08/15 00:00
129	Watermeting laden	m3	hour	25/09/13 13:00	02/08/15 00:00
130	Warmteopwekking Totaal maand	MJ	month	01/05/12 00:00	01/08/15 00:00
131	Koudeopwekking totaal maand	MJ	month	01/05/12 00:00	01/08/15 00:00
132	Watermeting ontladen	m3	hour	10/10/13 00:00	02/08/15 00:00
133	Temperatuur Koude bron	°C	10 minutes	08/10/13 00:00	01/08/15 23:50
134	Temperatuur Warmebron	°C	10 minutes	08/10/13 00:00	01/08/15 23:50
135	Energie Regeneratie Drycooler maand	kWh	months	01/05/13 00:00	01/08/15 00:00
136	Energie laden laden	kWh	hour	21/05/13 06:00	02/08/15 00:00
137	Energie ontladen ontladen	kWh	month	01/10/13 00:00	01/08/15 00:00
138	Energie ontladen ontladen	kWh	hour	21/05/13 06:00	02/08/15 00:00
139	Status WKO	Stat	10 minutes	15/04/12 00:00	01/08/15 23:50
140	Laden injecteren KB maand	°C	month	01/05/12 00:00	01/08/15 00:00
141	Laden injecteren KB uur	°C	hour	15/04/12 01:00	02/08/15 00:00
142	Laden minimum KB Maand	°C	month	01/05/12 00:00	01/08/15 00:00
143	Laden minimum KB uur	°C	hour	15/04/12 01:00	02/08/15 00:00
144	Laden ontrekken WB maand	°C	month	01/05/12 00:00	01/08/15 00:00
145	Laden ontrekken WB uur	°C	hour	15/04/12 01:00	02/08/15 00:00
146	Ontladen ontrekken KB maand	°C	month	01/05/12 00:00	01/08/15 00:00
147	Ontladen ontrekken KB uur	°C	hour	15/04/12 01:00	04/07/15 11:00
148	Ontladen injecteren WB maand	°C	month	01/05/12 00:00	01/08/15 00:00
149	Ontladen injecteren WB uur	°C	hour	15/04/12 01:00	02/08/15 00:00
150	Ontladen maximum WB maand	°C	month	01/05/12 00:00	01/08/15 00:00
151	Ontladen maximum WB uur	°C	hour	15/04/12 01:00	02/08/15 00:00
152	Waterhoeveelheid laden maand	m3	month	01/10/13 00:00	01/08/15 00:00
153	Waterhoeveelheid laden uur	m3	hour	25/09/13 13:00	02/08/15 00:00
154	Waterhoeveelheid ontladen maand	m3	month	01/10/13 00:00	01/08/15 00:00
155	Waterhoeveelheid ontladen uur	m3	hour	25/09/13 13:00	02/08/15 00:00
156	Waterhoeveelheid spui maand	m3	month	01/05/12 00:00	01/08/15 00:00
157	Waterhoeveelheid spui uur	m3	hour	15/04/12 01:00	02/08/15 00:00
158	Druk KB	kPa	10 minutes	15/04/12 00:00	01/08/15 23:50
159	Druk WB	kPa	10 minutes	15/04/12 00:00	01/08/15 23:50
160	Nivo KB	mH2O	10 minutes	15/04/12 00:00	01/08/15 23:50
161	Warmtepomp Koudeopwekking Berekend maand	kWh	month	01/05/12 00:00	01/08/15 00:00
162	Warmtepomp Warmteopwekking Berekend maand	kWh	month	01/05/12 00:00	01/08/15 00:00
163	Warmtepomp Koudeopwekking Berekend maand	kWh	month	01/05/13 00:00	01/08/15 00:00
164	Nivo WB	mH2O	10 minutes	15/04/12 00:00	24/11/13 23:50
165	Energie Regeneratie Drycooler uur	kWh	hour	24/04/13 01:00	02/08/15 00:00
166	Warmtepomp Warmteopwekking Berekend uur	kWh	hour	15/04/12 01:00	08/07/15 00:00
167	Warmtepomp Koudeopwekking Berekend uur	kWh	hour	15/04/12 01:00	02/08/15 00:00
168	Warmteopwekking Totaal uur	MJ	hour	15/04/12 01:00	02/08/15 00:00
169	Koudeopwekking totaal uur	MJ	hour	15/04/12 01:00	02/08/15 00:00
170	Ketel gasverbruik berekend maand	m3	month	01/10/12 00:00	01/08/15 00:00
171	Ketel gasverbruik berekend uur	m3	hour	13/09/12 12:00	02/08/15 01:00
172	Ketel energie berekend maand	kWh	month	01/10/12 00:00	01/08/15 00:00
173	Ketel energie berekend uur	kWh	hour	13/09/12 12:00	02/08/15 01:00

B.1.2. BMS Indoor Conditions

From the BMS Ti and CO_2 concentration are logged between 3/11/2015 – 01/02/2016. Conditions are measured and logged every 10 minutes. Table b1.2 shows information concerning the BMS data. Figure a1.1 illustrates the location of each BMS sensor ID.

Table b1.2: Overview BMS logged data.

Description	Metasys ID	Entity	Interval	Logged row length
First Floor				
Room 1.1 - air temperature	01BTC23 TT-11M--	^oC	10 min.	12960
Room 1.1 - CO_2 concentration	CO2 1VD	ppm	10 min.	12960
Room 1.1 - air temperature	01ATC27TT-11M--	^oC	10 min.	12960
Second Floor				
Room 2.1 - air temperature	02ATC23 TT-11M--	^oC	10 min.	12960
Room 2.1 - CO_2 concentration	CO2 2VD links	ppm	10 min.	12960
Room 2.2 - air temperature	02BTC27 TT-11M--	^oC	10 min.	12960
Room 2.2 - CO_2 concentration	CO2 2VD rechts	ppm	10 min.	12960
Third Floor				
Room 3.1 - air temperature	03ATC23 TT-11M--	^oC	10 min.	12960
Room 3.1 - CO_2 concentration	CO2 3VD links	ppm	10 min.	12960
Room 3.2 - air temperature	03BTC29 TT-11M--	^oC	10 min.	12960
Room 3.2 - CO_2 concentration	CO2 3VD rechts	ppm	10 min.	12960
Fourth Floor				
Room 4.1 - air temperature	04ATC23 TT-11M--	^oC	10 min.	12960
Room 4.1 - CO_2 concentration	CO2 4VD links	ppm	10 min.	12960
Room 4.1 - air temperature	04BTC33 TT-11M--	^oC	10 min.	12960
Room 4.1 - CO_2 concentration	CO2 4VD rechts	ppm	10 min.	12960
Fifth Floor				
Room 5.1 - air temperature	05ATC23 TT-11M--	^oC	10 min.	12960
Room 5.1 - CO_2 concentration	CO2 5VD links	ppm	10 min.	12960
Room 5.1 - air temperature	05BTC33 TT-11M--	^oC	10 min.	12960
Room 5.1 - CO_2 concentration	CO2 5VD rechts	ppm	10 min.	12960

B.1.3. TU/e Indoor Conditions

Between 14/10/15 – 1/02/2016 a North and South orientated TU/e data logger measured the indoor air temperature, CO_2 concentration and relative humidity. Figure b1.1 shows the positions of both loggers on the second floor. Table b1.3 gives the data properties. Figure a1.1 illustrates the location of the data loggers.

Table b1.3: Overview logged data TU/e equipment.

Description	Entity	Interval	Logged row length
Second Floor			
Room 2.1 – air temperature	^oC	10 min.	15776
Room 2.2 – Relative Humidity	%	10 min.	15776
Room 2.1 - CO_2 concentration	ppm	10 min.	15776
Room 2.2 – air temperature	^oC	10 min.	15776
Room 2.2 - Relative Humidity	%	10 min.	15776
Room 2.2 – CO_2 concentration	ppm	10 min.	15776

Fig. b1.1: Data loggers on the second floor. Left: room 2.1, Right: room 2.2.

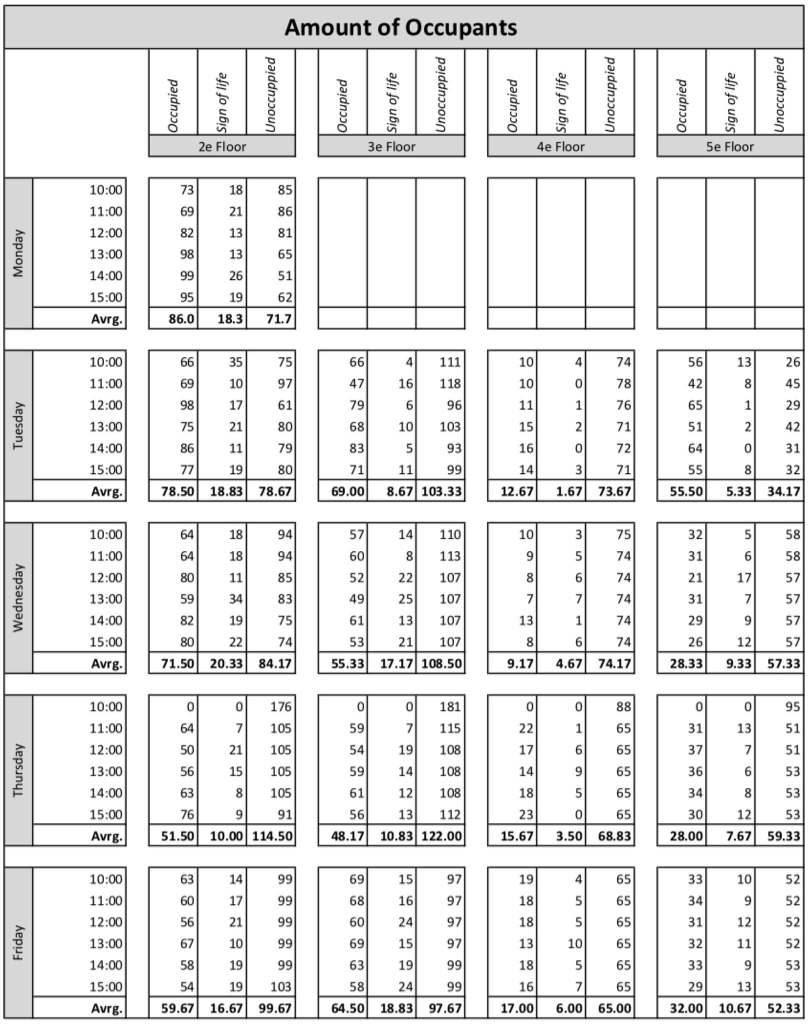
B.1.4. Occupant Data

Ziggo Facility manager Melle Schippers performed occupancy counts. In 2013, two incidental counts where performed (see table b1.4). In 2015, a more extensive occupancy counting was performed (see table b1.5).

Table b1.4: Daily occupancy counts.

Room	Seats	Occupied	Unoccupied
Occupancy rate | Monday - 05/08/2013 at 13:30			
2.1 - Office garden South	99	43	56
2.2 - Office garden North	77	46	31
3.1 - Office garden South	99	22	77
3.2 - Office garden North	82	35	47
4.1 - Office garden	88	25	63
5.1 - Office garden	95	40	55
Total	**540**	**211**	**329**
Occupancy rate | Friday - 27/09/2013 at 10:45			
2.1 - Office garden South	9	46	53
2.2 - Office garden North	77	52	25
3.1 - Office garden South	99	7	92
3.2 - Office garden North	82	49	33
4.1 - Office garden	88	25	63
5.1 - Office garden	95	44	51
Total	**540**	**223**	**317**

Table b1.5: Occupancy counts 12/01/2015 till 16/01/2015.



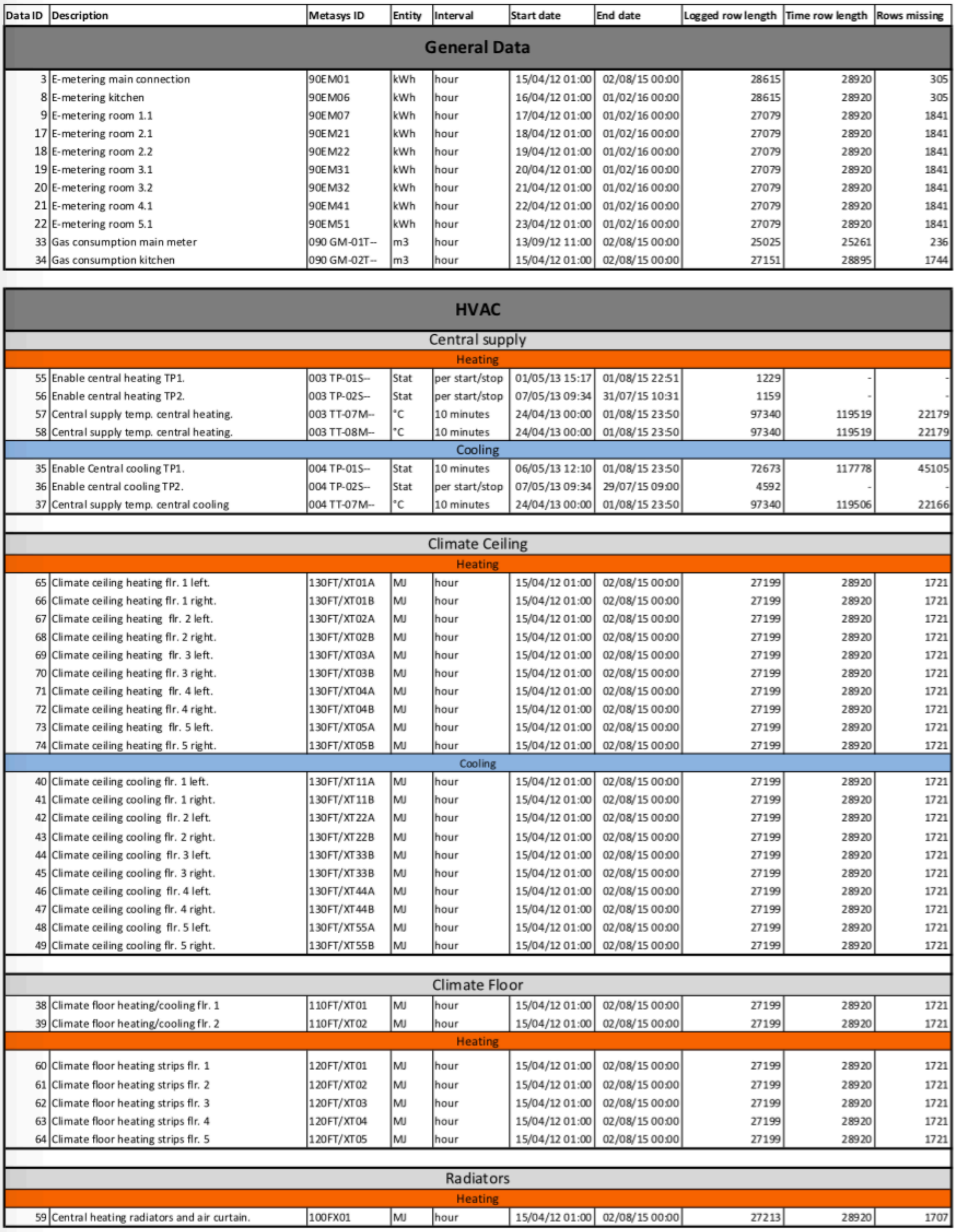
Amount of Occupants		2e Floor			3e Floor			4e Floor			5e Floor		
		Occupied	Sign of life	Unoccupied	Occupied	Sign of life	Unoccupied	Occupied	Sign of life	Unoccupied	Occupied	Sign of life	Unoccupied
Monday	10:00	73	18	85									
	11:00	69	21	86									
	12:00	82	13	81									
	13:00	98	13	65									
	14:00	99	26	51									
	15:00	95	19	62									
	Avrg.	**86.0**	**18.3**	**71.7**									
Tuesday	10:00	66	35	75	66	4	111	10	4	74	56	13	26
	11:00	69	10	97	47	16	118	10	0	78	42	8	45
	12:00	98	17	61	79	6	96	11	1	76	65	1	29
	13:00	75	21	80	68	10	103	15	2	71	51	2	42
	14:00	86	11	79	83	5	93	16	0	72	64	0	31
	15:00	77	19	80	71	11	99	14	3	71	55	8	32
	Avrg.	**78.50**	**18.83**	**78.67**	**69.00**	**8.67**	**103.33**	**12.67**	**1.67**	**73.67**	**55.50**	**5.33**	**34.17**
Wednesday	10:00	64	18	94	57	14	110	10	3	75	32	5	58
	11:00	64	18	94	60	8	113	9	5	74	31	6	58
	12:00	80	11	85	52	22	107	8	6	74	21	17	57
	13:00	59	34	83	49	25	107	7	7	74	31	7	57
	14:00	82	19	75	61	13	107	13	1	74	29	9	57
	15:00	80	22	74	53	21	107	8	6	74	26	12	57
	Avrg.	**71.50**	**20.33**	**84.17**	**55.33**	**17.17**	**108.50**	**9.17**	**4.67**	**74.17**	**28.33**	**9.33**	**57.33**
Thursday	10:00	0	0	176	0	0	181	0	0	88	0	0	95
	11:00	64	7	105	59	7	115	22	1	65	31	13	51
	12:00	50	21	105	54	19	108	17	6	65	37	7	51
	13:00	56	15	105	59	14	108	14	9	65	36	6	53
	14:00	63	8	105	61	12	108	18	5	65	34	8	53
	15:00	76	9	91	56	13	112	23	0	65	30	12	53
	Avrg.	**51.50**	**10.00**	**114.50**	**48.17**	**10.83**	**122.00**	**15.67**	**3.50**	**68.83**	**28.00**	**7.67**	**59.33**
Friday	10:00	63	14	99	69	15	97	19	4	65	33	10	52
	11:00	60	17	99	68	16	97	18	5	65	34	9	52
	12:00	56	21	99	60	24	97	18	5	65	31	12	52
	13:00	67	10	99	69	15	97	13	10	65	32	11	52
	14:00	58	19	99	63	19	99	18	5	65	33	9	53
	15:00	54	19	103	58	24	99	16	7	65	29	13	53
	Avrg.	**59.67**	**16.67**	**99.67**	**64.50**	**18.83**	**97.67**	**17.00**	**6.00**	**65.00**	**32.00**	**10.67**	**52.33**

B.2. Data Normalization

B.2.1. Data Telecontrol

Regarding this research table b1.1 gives the 104 relevant variables.

Table b2.1 (1/2): Overview relevant data provided by Telecontrol.



Data ID	Description	Metasys ID	Entity	Interval	Start date	End date	Logged row length	Time row length	Rows missing
General Data									
3	E-metering main connection	90EM01	kWh	hour	15/04/12 01:00	02/08/15 00:00	28615	28920	305
8	E-metering kitchen	90EM06	kWh	hour	16/04/12 01:00	01/02/16 00:00	28615	28920	305
9	E-metering room 1.1	90EM07	kWh	hour	17/04/12 01:00	01/02/16 00:00	27079	28920	1841
17	E-metering room 2.1	90EM21	kWh	hour	18/04/12 01:00	01/02/16 00:00	27079	28920	1841
18	E-metering room 2.2	90EM22	kWh	hour	19/04/12 01:00	01/02/16 00:00	27079	28920	1841
19	E-metering room 3.1	90EM31	kWh	hour	20/04/12 01:00	01/02/16 00:00	27079	28920	1841
20	E-metering room 3.2	90EM32	kWh	hour	21/04/12 01:00	01/02/16 00:00	27079	28920	1841
21	E-metering room 4.1	90EM41	kWh	hour	22/04/12 01:00	01/02/16 00:00	27079	28920	1841
22	E-metering room 5.1	90EM51	kWh	hour	23/04/12 01:00	01/02/16 00:00	27079	28920	1841
33	Gas consumption main meter	090 GM-01T--	m3	hour	13/09/12 11:00	02/08/15 00:00	25025	25261	236
34	Gas consumption kitchen	090 GM-02T--	m3	hour	15/04/12 01:00	02/08/15 00:00	27151	28895	1744
HVAC									
Central supply									
Heating									
55	Enable central heating TP1.	003 TP-01S--	Stat	per start/stop	01/05/13 15:17	01/08/15 22:51	1229	-	-
56	Enable central heating TP2.	003 TP-02S--	Stat	per start/stop	07/05/13 09:34	31/07/15 10:31	1159	-	-
57	Central supply temp. central heating.	003 TT-07M--	°C	10 minutes	24/04/13 00:00	01/08/15 23:50	97340	119519	22179
58	Central supply temp. central heating.	003 TT-08M--	°C	10 minutes	24/04/13 00:00	01/08/15 23:50	97340	119519	22179
Cooling									
35	Enable Central cooling TP1.	004 TP-01S--	Stat	10 minutes	06/05/13 12:10	01/08/15 23:50	72673	117778	45105
36	Enable central cooling TP2.	004 TP-02S--	Stat	per start/stop	07/05/13 09:34	29/07/15 09:00	4592	-	-
37	Central supply temp. central cooling	004 TT-07M--	°C	10 minutes	24/04/13 00:00	01/08/15 23:50	97340	119506	22166
Climate Ceiling									
Heating									
65	Climate ceiling heating flr. 1 left.	130FT/XT01A	MJ	hour	15/04/12 01:00	02/08/15 00:00	27199	28920	1721
66	Climate ceiling heating flr. 1 right.	130FT/XT01B	MJ	hour	15/04/12 01:00	02/08/15 00:00	27199	28920	1721
67	Climate ceiling heating flr. 2 left.	130FT/XT02A	MJ	hour	15/04/12 01:00	02/08/15 00:00	27199	28920	1721
68	Climate ceiling heating flr. 2 right.	130FT/XT02B	MJ	hour	15/04/12 01:00	02/08/15 00:00	27199	28920	1721
69	Climate ceiling heating flr. 3 left.	130FT/XT03A	MJ	hour	15/04/12 01:00	02/08/15 00:00	27199	28920	1721
70	Climate ceiling heating flr. 3 right.	130FT/XT03B	MJ	hour	15/04/12 01:00	02/08/15 00:00	27199	28920	1721
71	Climate ceiling heating flr. 4 left.	130FT/XT04A	MJ	hour	15/04/12 01:00	02/08/15 00:00	27199	28920	1721
72	Climate ceiling heating flr. 4 right.	130FT/XT04B	MJ	hour	15/04/12 01:00	02/08/15 00:00	27199	28920	1721
73	Climate ceiling heating flr. 5 left.	130FT/XT05A	MJ	hour	15/04/12 01:00	02/08/15 00:00	27199	28920	1721
74	Climate ceiling heating flr. 5 right.	130FT/XT05B	MJ	hour	15/04/12 01:00	02/08/15 00:00	27199	28920	1721
Cooling									
40	Climate ceiling cooling flr. 1 left.	130FT/XT11A	MJ	hour	15/04/12 01:00	02/08/15 00:00	27199	28920	1721
41	Climate ceiling cooling flr. 1 right.	130FT/XT11B	MJ	hour	15/04/12 01:00	02/08/15 00:00	27199	28920	1721
42	Climate ceiling cooling flr. 2 left.	130FT/XT22A	MJ	hour	15/04/12 01:00	02/08/15 00:00	27199	28920	1721
43	Climate ceiling cooling flr. 2 right.	130FT/XT22B	MJ	hour	15/04/12 01:00	02/08/15 00:00	27199	28920	1721
44	Climate ceiling cooling flr. 3 left.	130FT/XT33B	MJ	hour	15/04/12 01:00	02/08/15 00:00	27199	28920	1721
45	Climate ceiling cooling flr. 3 right.	130FT/XT33B	MJ	hour	15/04/12 01:00	02/08/15 00:00	27199	28920	1721
46	Climate ceiling cooling flr. 4 left.	130FT/XT44A	MJ	hour	15/04/12 01:00	02/08/15 00:00	27199	28920	1721
47	Climate ceiling cooling flr. 4 right.	130FT/XT44B	MJ	hour	15/04/12 01:00	02/08/15 00:00	27199	28920	1721
48	Climate ceiling cooling flr. 5 left.	130FT/XT55A	MJ	hour	15/04/12 01:00	02/08/15 00:00	27199	28920	1721
49	Climate ceiling cooling flr. 5 right.	130FT/XT55B	MJ	hour	15/04/12 01:00	02/08/15 00:00	27199	28920	1721
Climate Floor									
38	Climate floor heating/cooling flr. 1	110FT/XT01	MJ	hour	15/04/12 01:00	02/08/15 00:00	27199	28920	1721
39	Climate floor heating/cooling flr. 2	110FT/XT02	MJ	hour	15/04/12 01:00	02/08/15 00:00	27199	28920	1721
Heating									
60	Climate floor heating strips flr. 1	120FT/XT01	MJ	hour	15/04/12 01:00	02/08/15 00:00	27199	28920	1721
61	Climate floor heating strips flr. 2	120FT/XT02	MJ	hour	15/04/12 01:00	02/08/15 00:00	27199	28920	1721
62	Climate floor heating strips flr. 3	120FT/XT03	MJ	hour	15/04/12 01:00	02/08/15 00:00	27199	28920	1721
63	Climate floor heating strips flr. 4	120FT/XT04	MJ	hour	15/04/12 01:00	02/08/15 00:00	27199	28920	1721
64	Climate floor heating strips flr. 5	120FT/XT05	MJ	hour	15/04/12 01:00	02/08/15 00:00	27199	28920	1721
Radiators									
Heating									
59	Central heating radiators and air curtain.	100FX01	MJ	hour	15/04/12 01:00	02/08/15 00:00	27213	28920	1707

Table b2.1 (2/2): Overview relevant data provided by Telecontrol.

Data ID	Description	Metasys ID	Entity	Interval	Start date	End date	Logged row length	Time row length	Rows missing
HVAC									
Air Handeling Unit									
Heating									
50	AHU office heating	200FX01	MJ	hour	15/04/12 01:00	02/08/15 00:00	27213	28920	1707
52	AHU kitchen heating	220FX01	MJ	hour	15/04/12 01:00	02/08/15 00:00	27213	28920	1707
Cooling									
51	AHU office cooling	200FX02	MJ	hour	15/04/12 01:00	02/08/15 00:00	27213	28920	1707
53	AHU kitchen cooling	220FX02	MJ	hour	15/04/12 01:00	02/08/15 00:00	27213	28920	1707
Electricity									
28	E-metering AHU office supply.	90EM63	kWh	hour	15/04/12 01:00	01/02/16 00:00	27093	28920	1827
29	E-metering AHU offices extraction.	90EM64	kWh	hour	15/04/12 01:00	01/02/16 00:00	27093	28920	1827
30	E-metering AHU offices extraction.	90EM65	kWh	hour	15/04/12 01:00	02/08/15 00:00	27093	28920	1827
31	E-metering AHU kitchen supply.	90EM66	kWh	hour	15/04/12 01:00	02/08/15 00:00	27093	28920	1827
32	E-metering AHU kitchen extraction.	90EM67	kWh	hour	15/04/12 01:00	02/08/15 00:00	27093	28920	1827
Power Plant									
Heat exchanger 1									
99	Flow building side.	000 FC-01M--	m3/h	10 minutes	15/04/12 00:00	01/08/15 23:50	168690	173375	4685
100	Incoming temp. building side.	000 TT-03M--	°C	10 minutes	15/04/12 00:00	01/08/15 23:50	170487	173375	2888
101	Outgoing temp. building side.	004 TT-04M--	°C	10 minutes	15/04/12 00:00	01/08/15 23:50	170487	173375	2888
102	Flow metering heat/cold source.	400 FT-01M--	m3/h	log change	09/08/12 07:40	08/01/15 23:59	1537262	-	-
Heat Pump									
75	Heat pump in operation.	001 WP-01B--	Stat	per start/stop	15/04/12 00:23	11/04/15 06:55	39042	-	-
78	Heat pump in operation.	-	Stat	per start/stop	07/05/13 10:52	11/04/15 06:55	20531	-	-
79	Heat pump operation hours	-	h	day	08/05/13 00:00	01/08/15 00:00	662	815	153
Heating									
77	Heat pump heating operation.	002 XS-00S2-	Stat	per start/stop	15/04/12 00:01	30/05/15 07:41	2924	-	-
162	Heat pump heat generation calculated.	-	kWh	month	01/05/12 00:00	01/08/15 00:00	40	40	0
166	Heat pump heat generation calculated.	-	kWh	hour	15/04/12 01:00	08/07/15 00:00	27813	28319	28279
Cooling									
76	Heat pump cooling operation.	002 XS-00S1-	Stat	per start/stop	15/04/12 00:01	30/05/15 07:41	2925	-	-
161	Heat pump cold generation calculated.	-	kWh	month	01/05/12 00:00	01/08/15 00:00	40	40	-
163	Heat pump cold generation calculated.	-	kWh	month	01/05/13 00:00	01/08/15 00:00	25	40	15
167	Heat pump cold generation calculated.	-	kWh	hour	15/04/12 01:00	02/08/15 00:00	28629	28920	291
Electricity									
26	E-meterering Heat pump.	90EM61	kWh	hour	15/04/12 01:00	02/08/15 00:00	28629	28920	291
Gas Fired Boiler									
54	Boiler in operation.	002 WWK01B--	Stat	per start/stop	15/04/12 00:12	08/01/15 23:58	201777	-	-
170	Boiler gas consumption calculated.	-	m3	month	01/10/12 00:00	01/08/15 00:00	34	34	0
171	Boiler gas consumperion calculated.	-	m3	hour	13/09/12 12:00	02/08/15 01:00	25025	25261	236
172	Boiler energy calculated.	-	kWh	month	01/10/12 00:00	01/08/15 00:00	34	34	0
173	Boiler energy calculated.	-	kWh	hour	13/09/12 12:00	02/08/15 01:00	25025	25261	236
ATES									
11	E-Metering well installation	90EM09	kWh	hour	15/04/12 01:00	02/08/15 00:00	28615	28920	305
103	Operation signal freq. contrl. wellpump	400 SC-01B--	Stat	per start/stop	07/05/13 09:00	01/08/15 22:52	10082	-	-
104	Trend well pause	400 XS-00S2-	Stat	per start/stop	15/04/12 00:24	01/08/15 22:51	17905	-	-
105	Trend well charging	400 XS-00S3-	Stat	per start/stop	15/04/12 00:24	06/07/15 12:19	13178	-	-
106	Trend well discharging	400 XS-00S4-	Stat	per start/stop	30/04/12 15:02	01/08/15 22:51	4688	-	-
Warm Well									
119	Weighted avrg. temp. day heat source charging.	-	°C	10 minutes	01/05/13 13:30	01/08/15 23:50	96251	118430	22179
120	Weighted avrg. temp. day heat source discharging.	-	°C	10 minutes	24/04/13 00:00	01/08/15 23:50	97340	119519	22179
110	Water level heat source.	402 LT-01M-1	mH2O	10 minutes	15/04/12 00:00	24/11/13 23:50	70126	84672	14546
111	Pressure heat source.	402 PT-01M--	kPa	10 minutes	15/04/12 00:00	01/08/15 23:50	170489	173375	2886
112	Temp. heat source.	402 TT-01M1-	°C	10 minutes	15/04/12 00:00	01/08/15 23:50	170489	173375	2886
134	Temp. heat source.	-	°C	10 minutes	08/10/13 00:00	01/08/15 23:50	94029	95471	1442
148	Discharging injecting heat source.	-	°C	month	01/05/12 00:00	01/08/15 00:00	40	40	0
149	Discharging injecting heat source.	-	°C	hour	15/04/12 01:00	02/08/15 00:00	28463	28895	432
Cold Well									
97	Weighted avrg. temp. day cold source chaging.	-	°C	10 minutes	01/05/13 13:20	01/08/15 23:50	96252	118431	22179
98	Weighted avrg. temp. day cold source discharging.	-	°C	10 minutes	01/05/13 13:20	01/08/15 23:50	72553	118431	45878
107	Water level cold source.	401 LT-01M-1	mH2O	10 minutes	15/04/12 00:00	01/08/15 23:50	170489	173375	2886
108	Pressure cold source.	401 PT-01M--	kPa	10 minutes	15/04/12 00:00	01/08/15 23:50	170489	173375	2886
109	Temp. cold source.	401 TT-01M1-	°C	10 minutes	15/04/12 00:00	01/08/15 23:50	170489	173375	2886
133	Temp. cold source	-	°C	10 minutes	08/10/13 00:00	01/08/15 23:50	94029	95471	1442
140	Charging injecting cold source.	-	°C	month	01/05/12 00:00	01/08/15 00:00	40	40	0
141	Charging injecting cold source.	-	°C	hour	15/04/12 01:00	02/08/15 00:00	28463	28895	432
Heat exchanger 2									
113	Volume meter regeneration cmulatively	403 FT-01M1-	m3	hour	24/04/13 01:00	02/08/15 00:00	16222	19919	3697
114	Supply temp. HEX2 regeneration primary.	403 TT-01M--	°C	10 minutes	24/04/13 00:00	01/08/15 23:50	97341	119519	22178
115	Return temp. HEX2 regeneration primary.	403 TT-02M--	°C	10 minutes	24/04/13 00:00	01/08/15 23:50	97341	119519	22178

B.2.2. Telecontrol Algorithm

```
%% Load Data

% Time Vectors
load B_TimeVec;
load B_TimeVecT;

%% Ziggo Data - Label
load B_ZIGGOCData.mat;

%% Creating Dataset time vectors

x1 = ID{'(enter numbers)'};

year = x1(:,1); month = x1(:,2); day = x1(:,3); hour = x1(:,4);...
    minute = x1(:,5);

    x1t = datenum(year,month,day,hour,minute);

%% Comparing Vectors to real time vectors
% Using the function 'ismember' Ziggo data set is compared to a complete
% time vector in order to identify data gaps. In case of similarity
% output  = 1. If not output =0.

[Time_Error1 Error_Value1] = ismember(int.min10,x1t,'rows');

%% Creating good Matrix lengths
% Enter amount of label variables. Enter length of time interval
%(1 minute = 2103841, 10 minutes = 210385, hour = 35065, day = 1461, month
% = 48)

Amount = x; int_lenght = 210385;

Error_ValueX = [Error_Value1];

ID_X = [x1(:,7)];

A = zeros(int_lenght,Amount);

for x = 1:size(Error_ValueX(:,1));
    for y = 1:Amount;
            if Error_ValueX(x,y) == 0
                A(x,y) = NaN;
            else
                A(x,y) = ID_X(Error_ValueX(x),y);
            end
    end
end

% Enter Label type
ID{'(enter numbers)'}= [int.min10 A  Time_Error1];

% Adjust (time interval) regarding the set that is treated
save Ziggo_data_(time inteval) ID{‘(enter numbers)’;
```

B.3. Data Reliability

Research is performed on examining the reliability of office HVAC related data [30,31]. The examined datasets where mainly extracted from BMS's. The datasets included energy calculations and physical measurements. It's concluded that uncertainty regarding the reliability of HVAC datasets can be related to the following [31]:

1. Quality of measurement: depending on sensor hardware specifications.
2. Quality of installation: e.g. location of sensor.
3. Measurement interval: dynamics of the measured variable.
4. Measurement processing: method of logging data.
5. Interval of analysis: relation variable dynamics, measurement interval and processing.
6. Missing/incomplete content: data gaps and/or missing variable measurement(s).

According the points above the reliability of the acquired Telecontrol- and indoor conditions data is examined. First, the reliability of the Telecontrol dataset is discussed. Second, reliability of the indoor conditions dataset is discussed.

B.3.1. Telecontrol

Regarding flow and temperature measurements performed at the ATES, accuracy of equipment is known. Table b3.1 gives the measurement characteristics that need to be considered.

Table b3.1: Specifications measurement equipment dataset Telecontrol.

Manufacture	Measuring range	Accuracy	Appliance	ID Telecontrol
Zenner WSI-K-100 (2x)	0,5 to 250 m^3/h	±2%	- Outgoing flow HEX PP side - Flow between wells (ATES side)	- ID099 - ID102
RTD Thermometer omnigrad TST90 (4x)	-50 to 200°C	±0,04°C	- In- outgoing temp. HEX PP side - In-outgoing temp. HEX ATES side	- ID100, ID101 - ID109, ID112

Flow and temperature measurements are used to calculate thermal energy flows. The accuracy of thermal energy calculations can be determined by the information of table b3.1. For thermal energy to the wells and the following relative fault needs to be considered (1):

$$\frac{\Delta f}{f} = \frac{\Delta T_1 + \Delta T_2}{T_1 - T_2} + \frac{\Delta V}{V} = \frac{0{,}04 + 0{,}04}{15 - 7} + \frac{0{,}66}{33} = 3\%$$

**Relative fault according peak demand design conditions: charging cold well*

The reliability of the Telecontrol dataset is examined on data characteristics. By taking samples the data is examined regarding the points previously discussed. An example of a testing process is provided at the next page. A summary is given regarding data characteristic that bring along uncertainty:

- Most variables contain data gaps (see Appendix B.1.1, table b1.1 last column) (6)
- No insight in equations representing calculated variables (6).
- ATES regeneration data insufficient to reproduce calculation (see example next page) (4,6).
- HVAC thermal energy data log is performed per 10MJ (3,4).
- No physical HVAC- and indoor conditions data is logged (6).
- Variables contain different time intervals (3,5).
- Varying intervals of logging electricity measurements (4,5).
- Insufficient data to define HP partial load operations (5,6).
- No central heating and cooling system flows and pressures logged (6).
- ATES well injection temperatures give constant values (1,6)

Telecontrol Example

As peviourslly discussed, the Telecontrol dataset contains several uncertainties. Following an example is given (see figure b3.1). Figure b3.1 shows for A: Hourly ATES calculation preformed within the BMS (ID094 & ID095), B: time gaps of ID094 & ID095, C: reviewed energy calculation based on flow and temperature measurements (ID102, ID109 & ID112), D: time gaps of related variables in C, E: monthly summation of both energy calculations. Variables in A and B represent hourly data. Variables in C and D represent minute data.

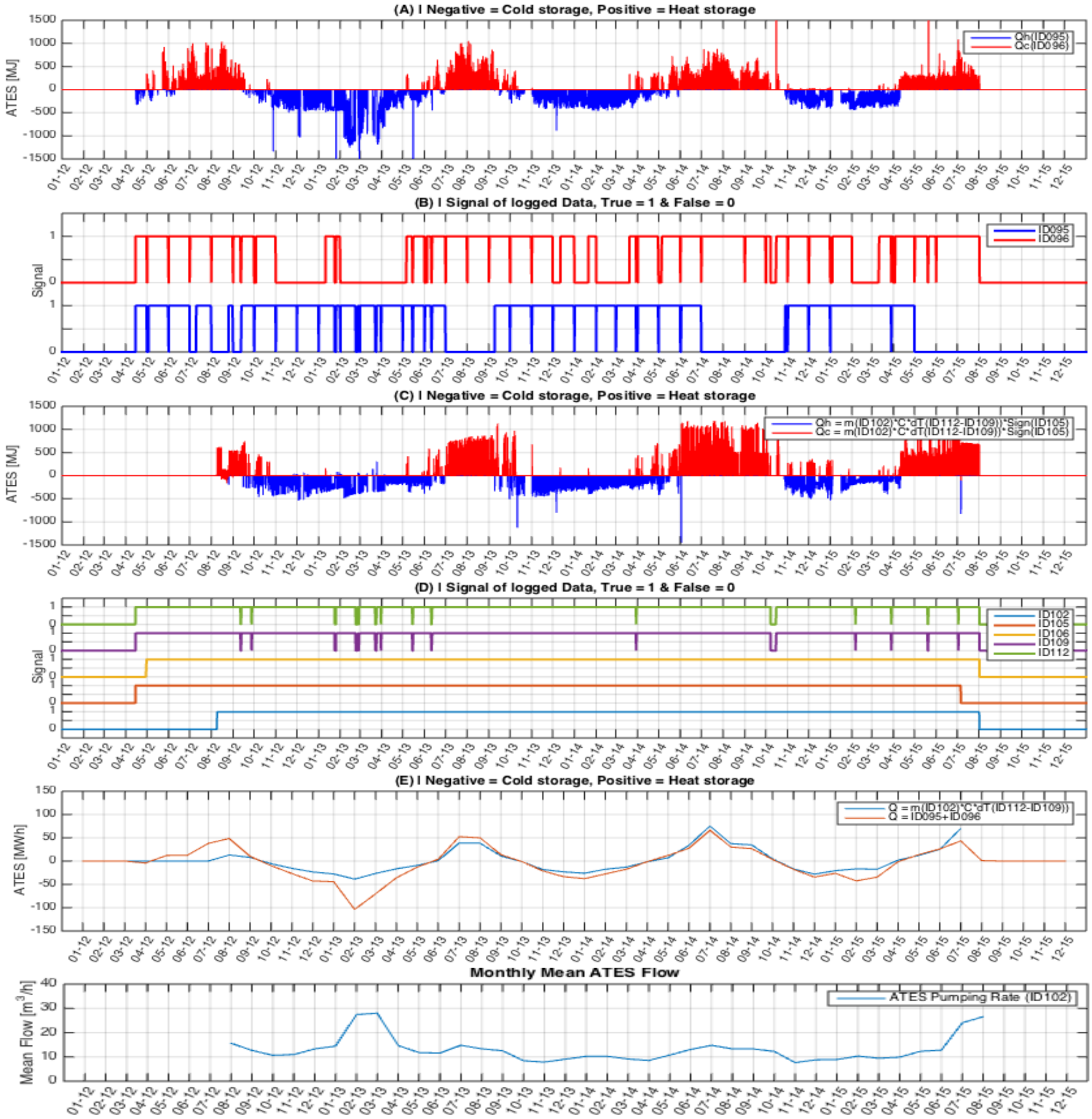


Fig. b3.1: Comparison between BMS- and reviewed ATES calculation.

Between 09-12 and 05-13, monthly ATES in E deviate significantly. Between 02-13 and 04-13 ATES of A is ±2 times larger compared to C. F gives that median pumping rate is 30m^3/h with a range up to 39m^3/h. Unfortunately regeneration data (ID113-115) is insufficient to check this observation. From GW flow data (ID012) it's concluded regeneration was active. Furthermore, well injection temperatures for ID109 and ID112 are constant values. This declares the differences in E.

Comparing the time gaps in B and D, it's shown that B has significantly more false (=0) values. Furthermore, when comparing the time gaps in B with the value in A its been noticed that after a time gap the value in A can be 2 times higher. It's concluded that if a log is missed it is summed with the following data log. Consequently this needs to be considered if hourly analysis of ID95-96 is performed.

B.3.2. Indoor Conditions

Indoor conditions data is gathered through BMS- and TU/e transmitters. Specifications regarding the BMS CO_2 measurements are known (see table 3.2). Specifications regarding Ti measurements are unknown. TU/e transmitters include three sensors. Specifications regarding temperature, CO_2 and relative humidity (RH) are known (see table b3.2).

Table b3.2: Specifications Ziggo and TU/e measurement equipment.

Manufacture	**Measuring range**	**Accuracy**	**Appliance**
	Ziggo Transmitter		
CD-Wxx-00-0 Series Wall Mount CO2 Transmitter	- CO_2: 0 to 5000ppm - Temp: unknown	- ±40ppm - Unknown	All rooms
	TU/e Transmitter		
Eltek GD-47 T/RV/CO2 transmitter	- temp.: -10 to 50 °C - RH: 0 to 95% - CO_2: 0 to 5000ppm	- 0,1°C - ±2% - ±40ppm	- Room 2.1 (South) - Room 2.2 (North)

To calibrate the BMS measurements, TU/e data loggers where placed at the second floor. TU/e transmitters are placed near the used Ziggo temperature sensor (see Appendix A.1, figures a1.1). Subsequently BMS and TU/e measurements are compared (see figure b3.2).

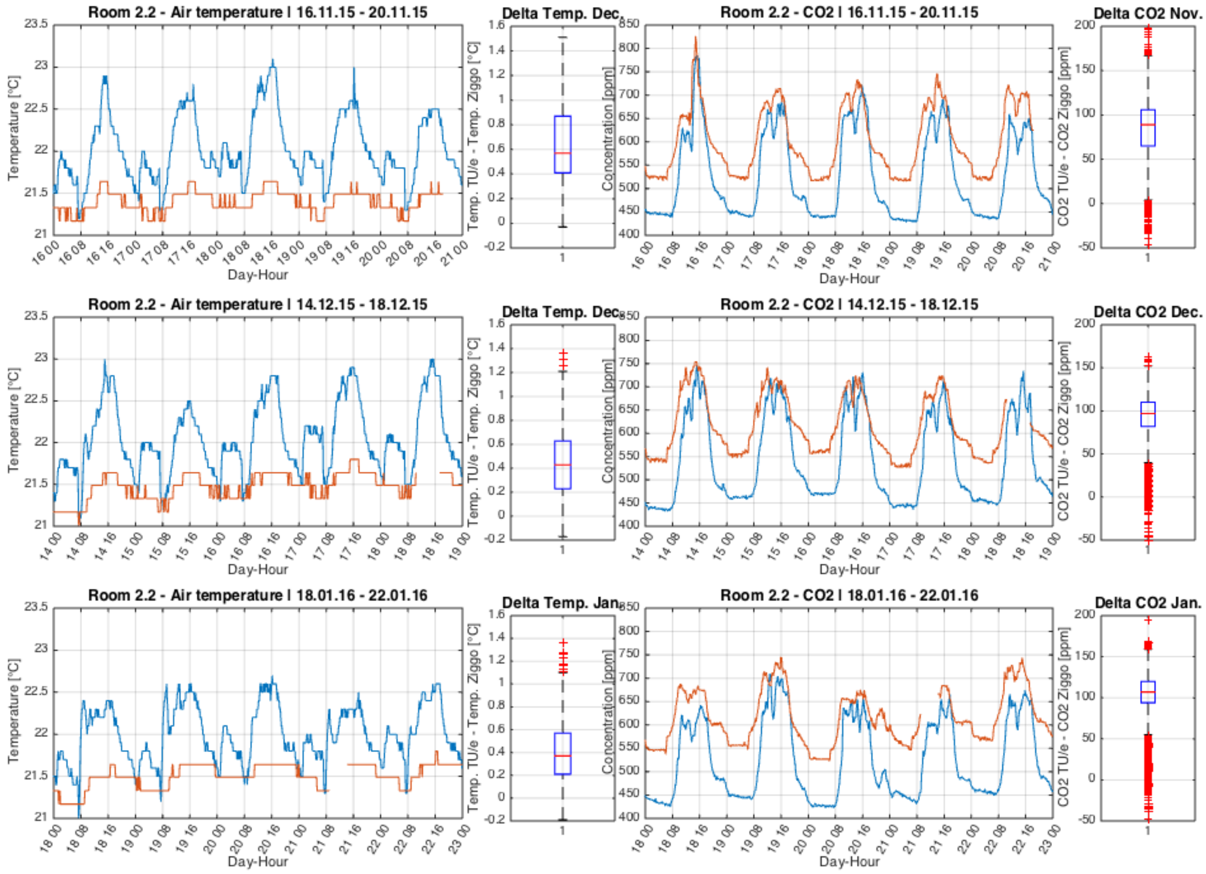


Fig. b3.2: Comparison temperature and CO_2 level.

Figure b3.2 gives Ti and CO_2 in room 2.2 for a Monday to Friday period in November-, December 2015 and January 2016. Due to a sensor error at room 2.1 (constant value of 22°C), temperature boxplots are only based on the dataset of room 2.2. CO_2 boxplots are based on the dataset of room 2.1 and 2.2.

Ti measurements show similar trends. However, comparison gives that results can deviate up to 1,5°C. Average deviation is around 0,5°C. The CO_2 measurements show similarity for higher values. For lower values a difference of ±100ppm is shown. In regard to the outdoor concentration (375-450 [38]) and the TU/e data loggers it's highly likely the minimal measured values of the Ziggo transmitters are reliable.

C. Appendix – Performance Analysis

C.1. Energy Consumption

C.1.1. Electricity

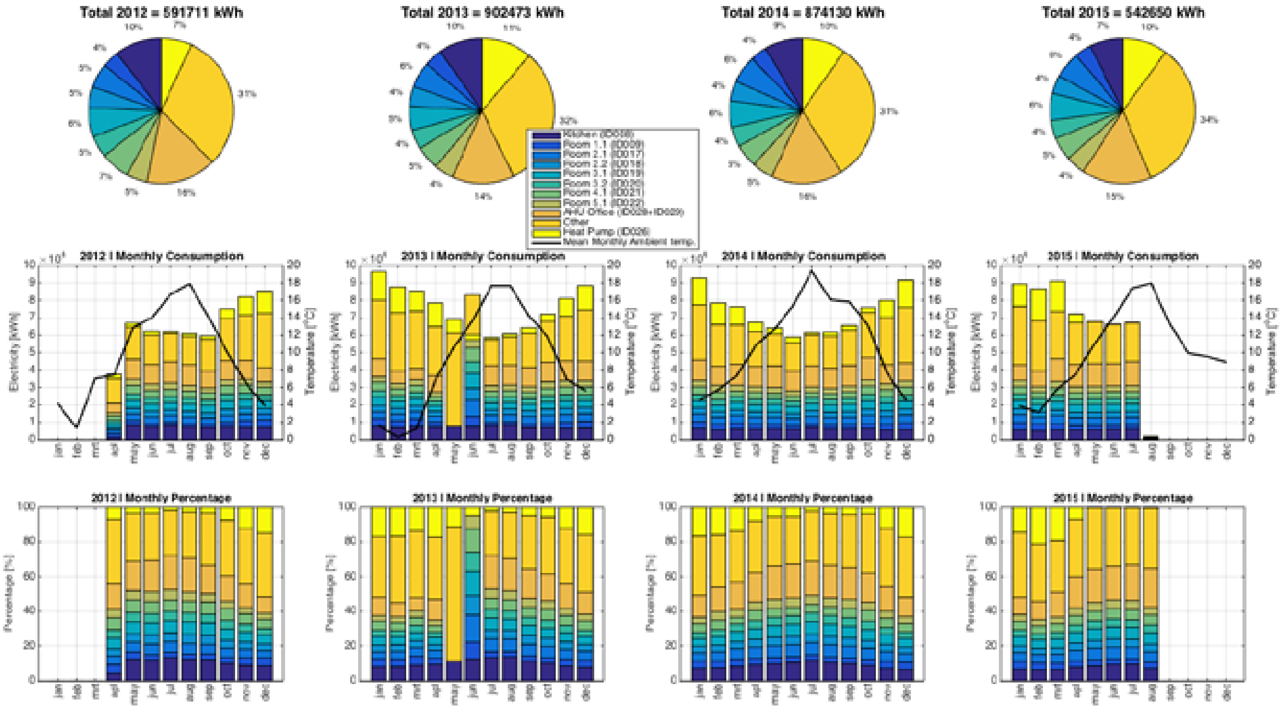


Fig. c1.1: Electricity consumption between 15/04/2012 - 02/08/15.

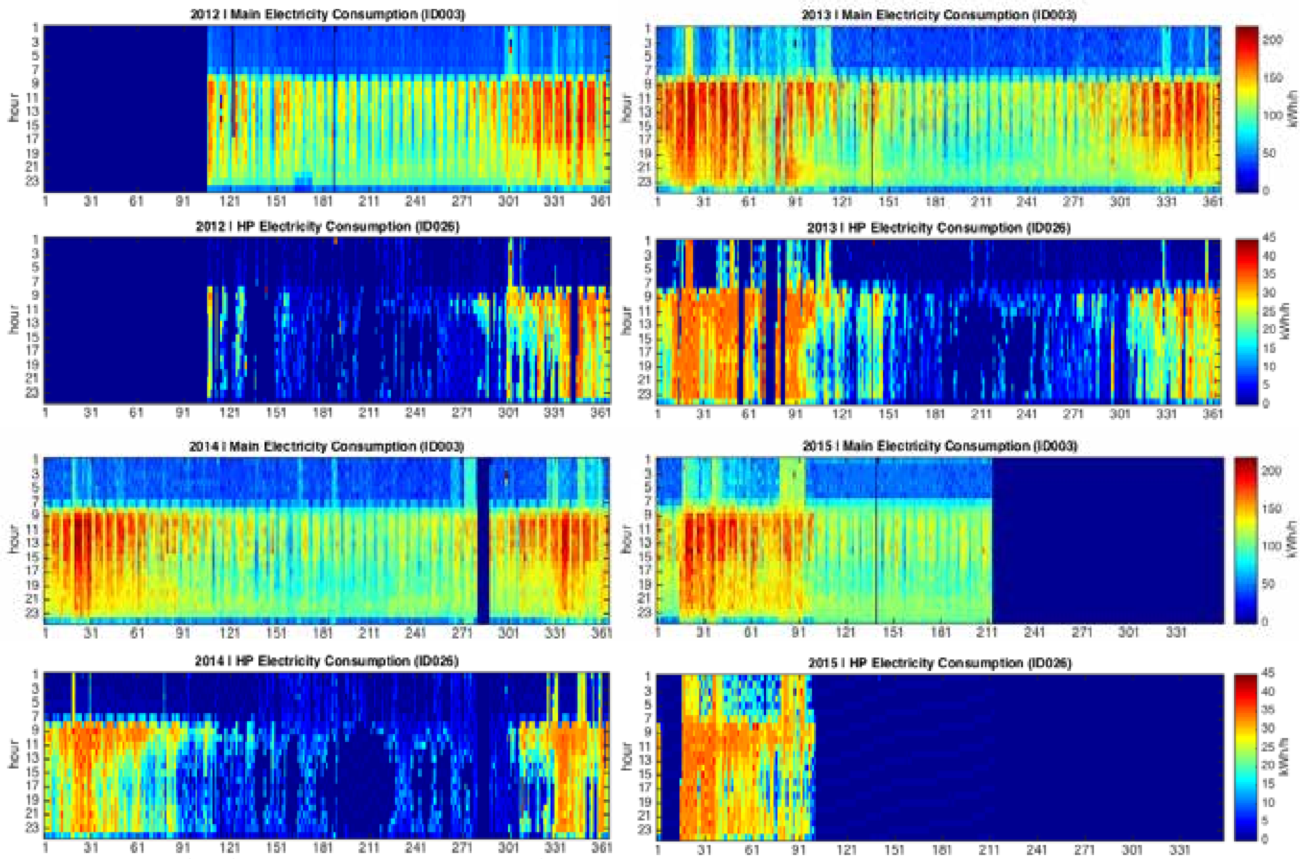


Fig. c1.2: Carpet plot electricity consumption main and HP.

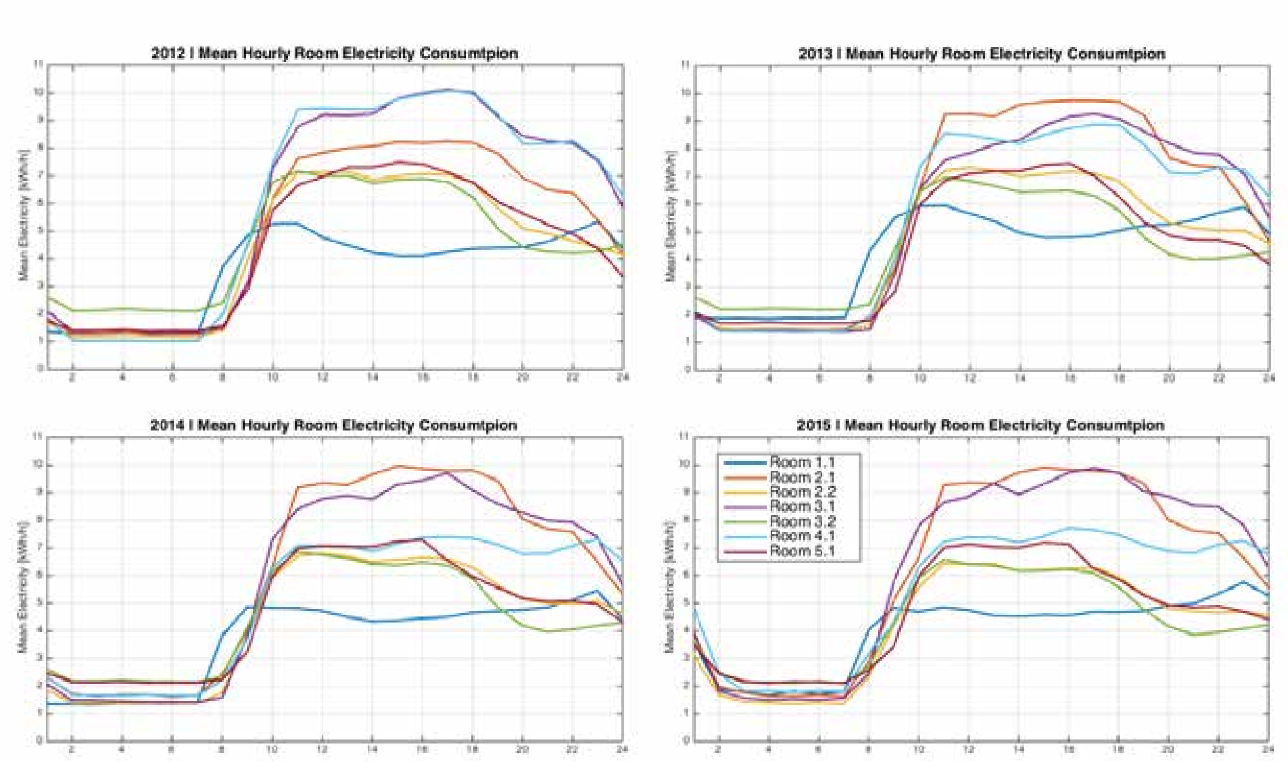


Fig. c1.3: Hourly mean room electricity consumption.

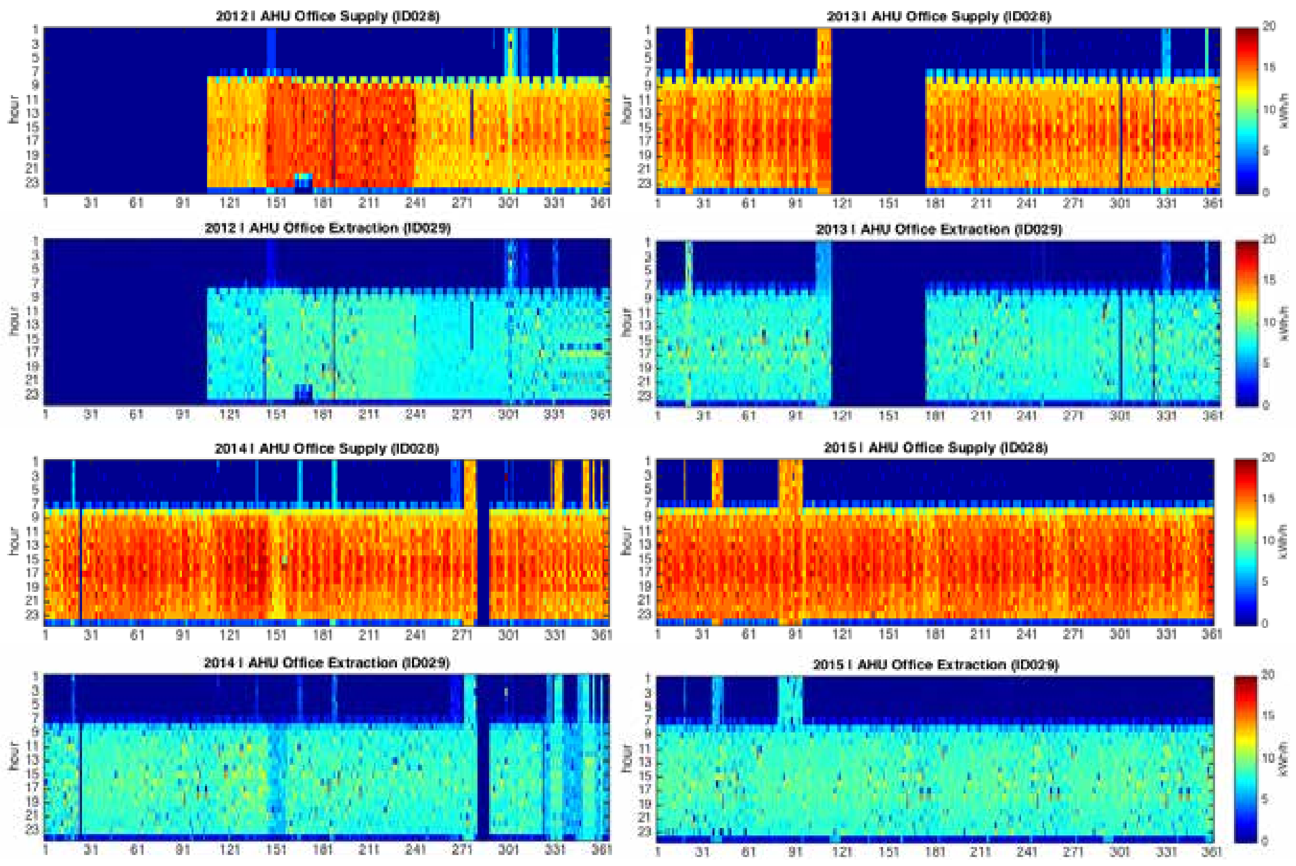


Fig. c1.4: Carpet plot office AHU electricity consumption between 15/04/2012 - 31/12/15.

C.1.2. Gas

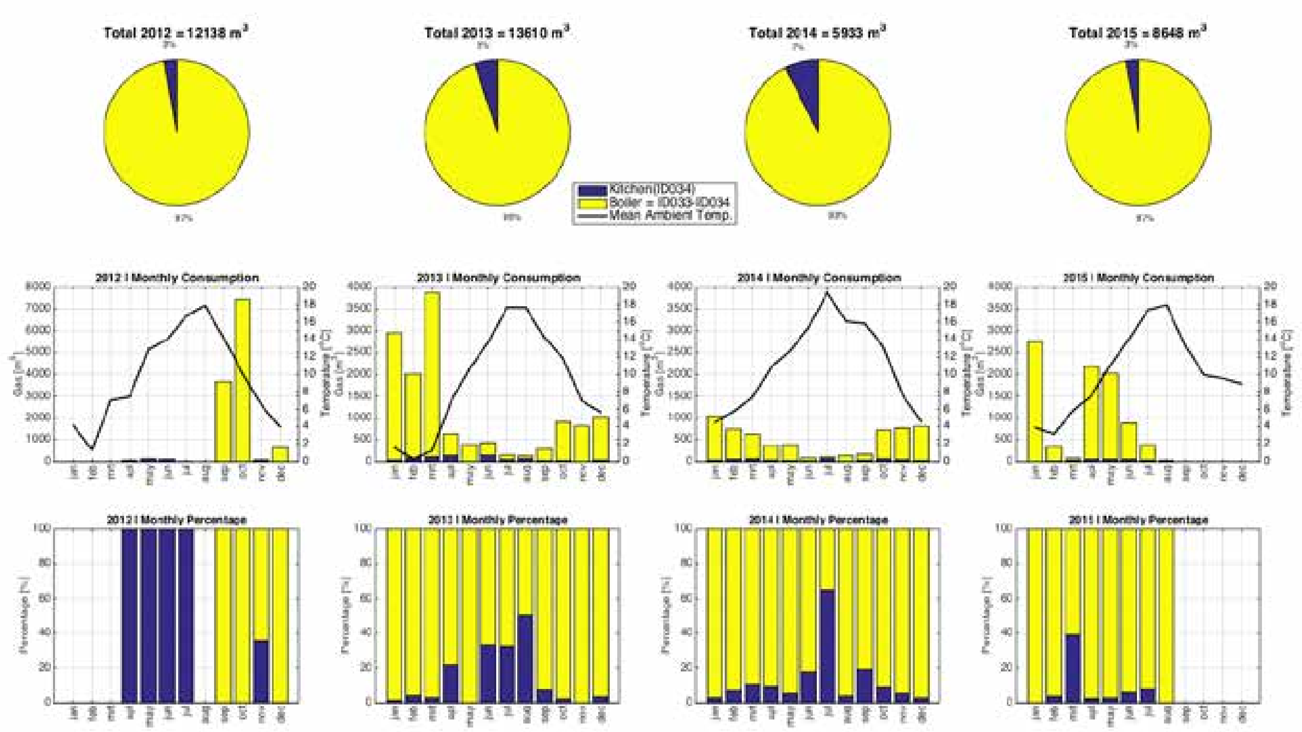


Fig. c1.4: Gas consumption.

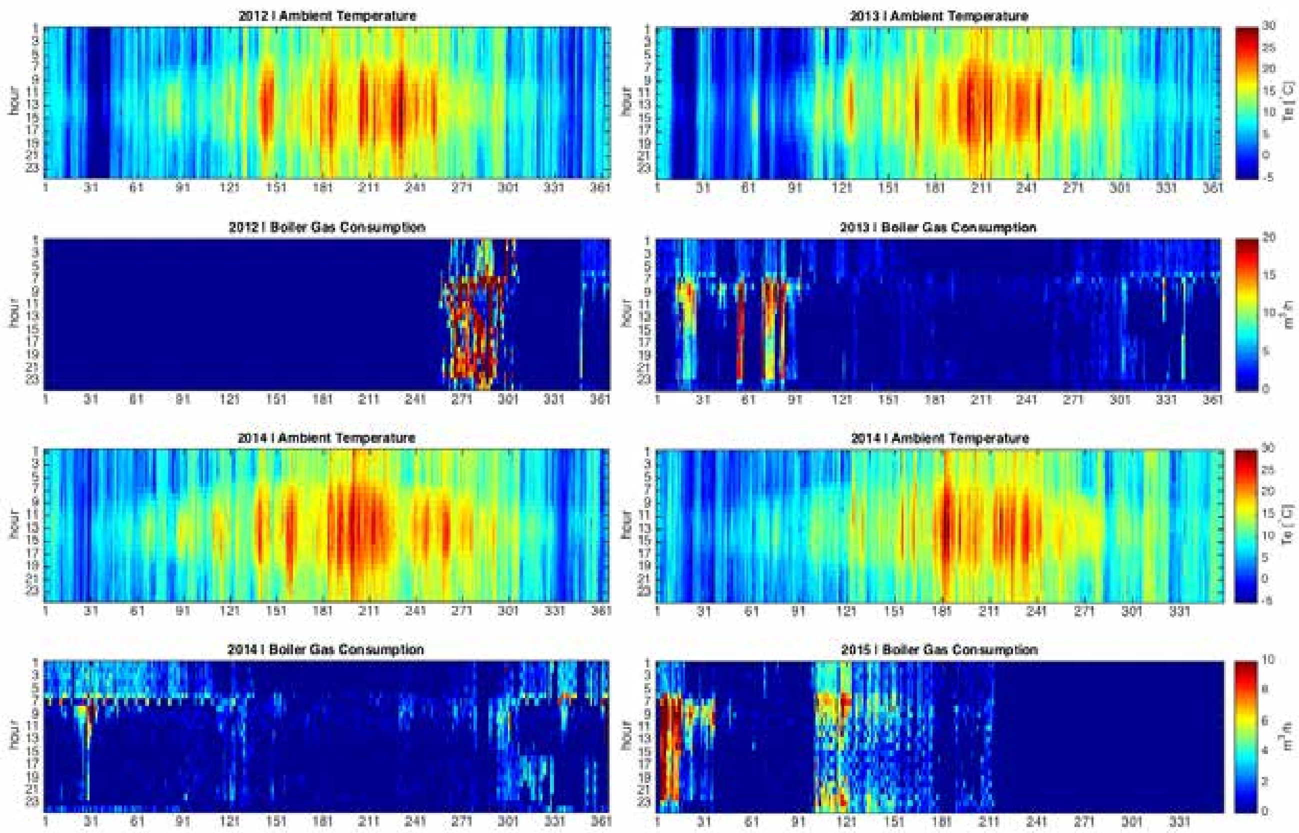


Fig. c1.5: Carpet plot boiler gas consumption.

C.2. ATES Analysis

C.2.1. Groundwater conditions

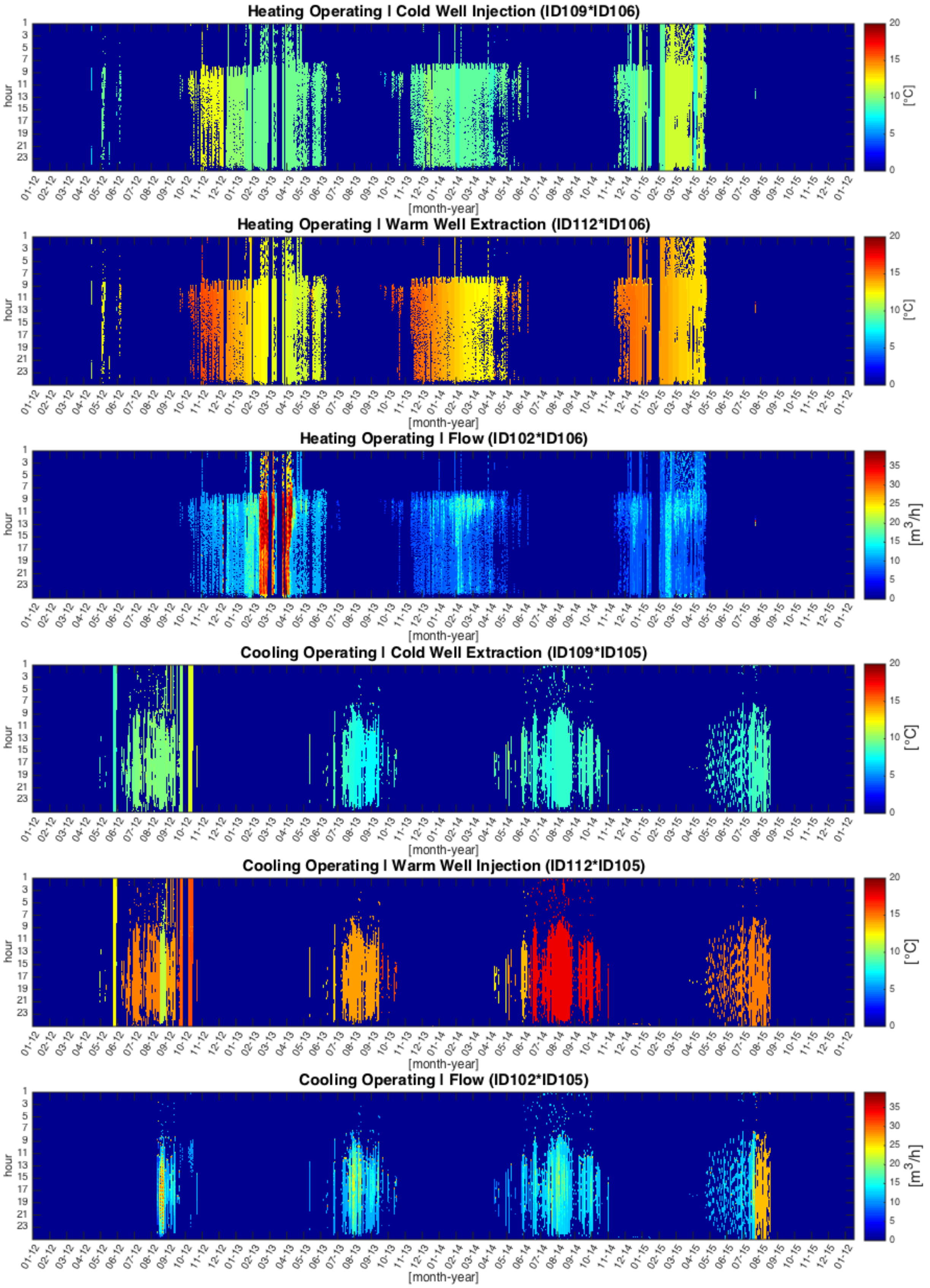


Fig. c2.1: Carpet plot groundwater conditions (warm well = ID112, cold well = ID109, flow = ID102, operation cold pump = ID105, operation warm pump = ID106).

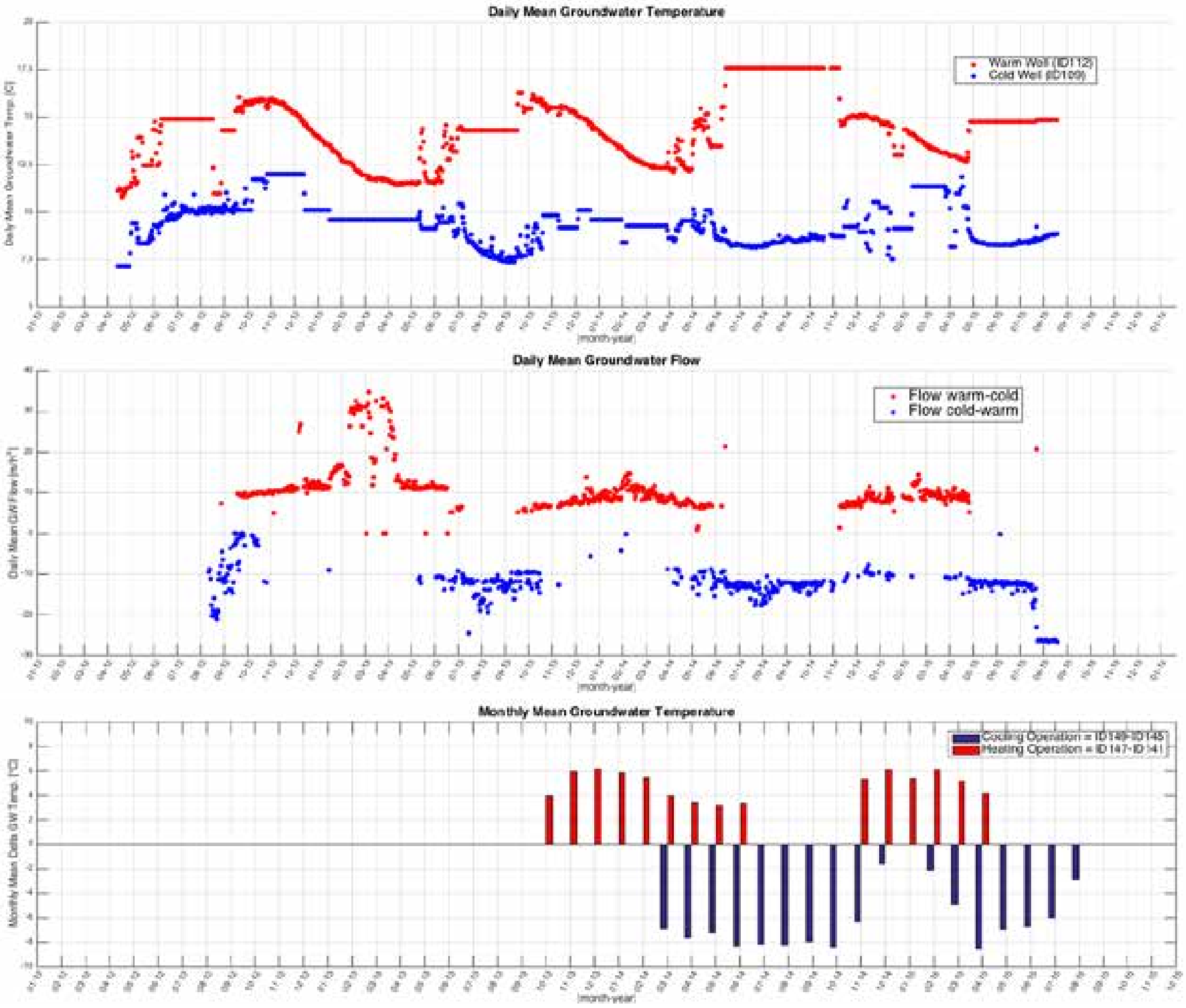


Fig. c2.2: Daily mean- groundwater temperature & flow + montlhy mean delta temperature.

C.2.2. ATES State of Charge

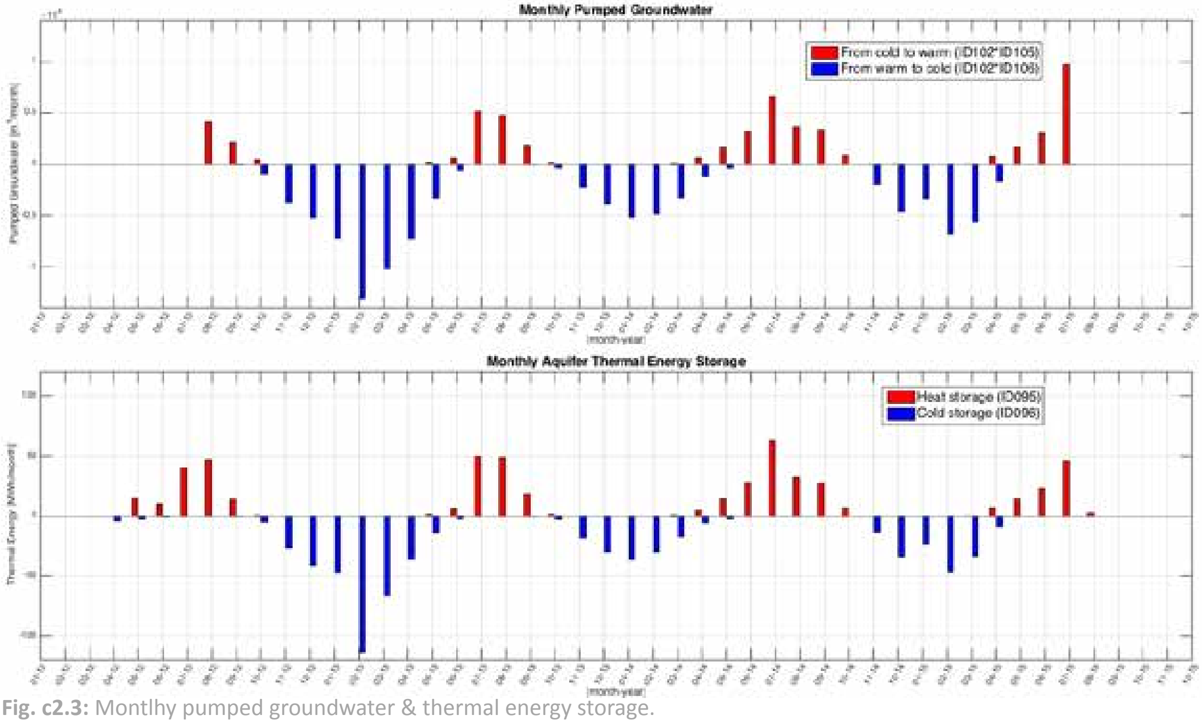


Fig. c2.3: Montlhy pumped groundwater & thermal energy storage.

C.3. HVAC Analysis

C.3.1. Indoor Conditions

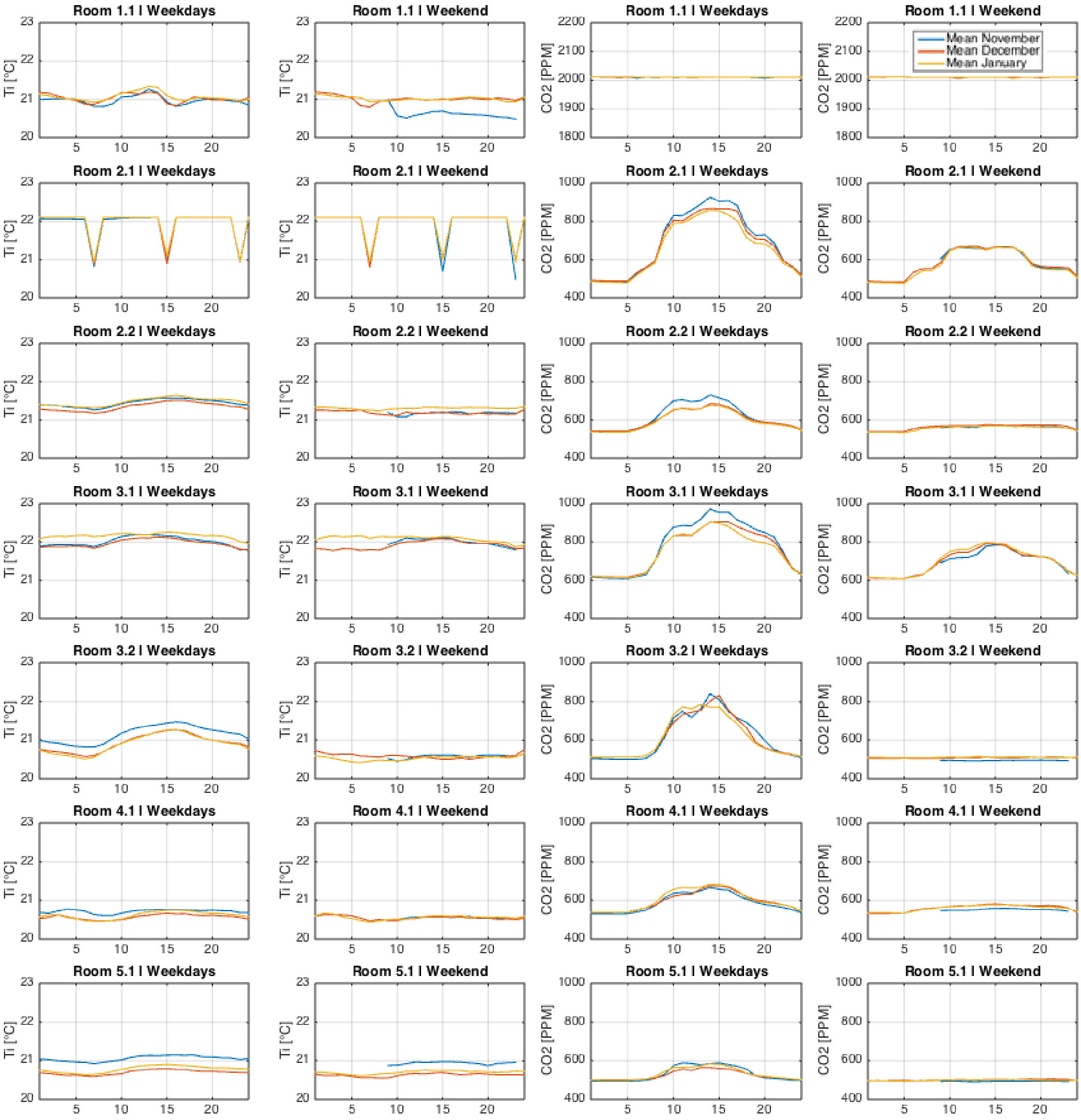


Fig. c3.1: Per room, hourly mean indoor conditions.

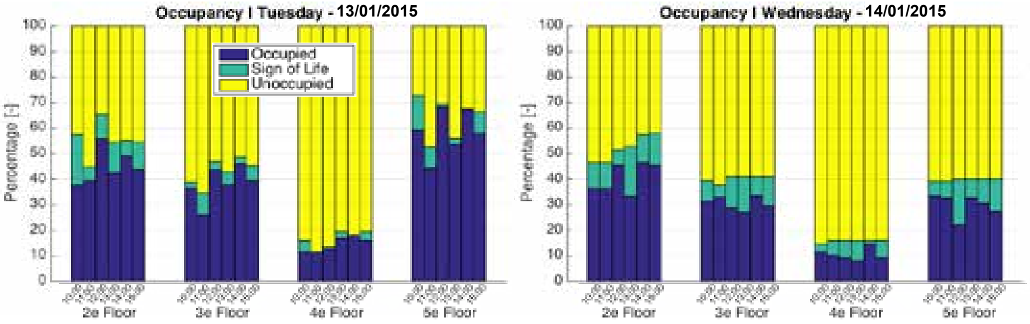


Fig. c3.2: 2015 building occupancy percentage per floor according data Appendix B.1.4, table b1.5 (1/2).

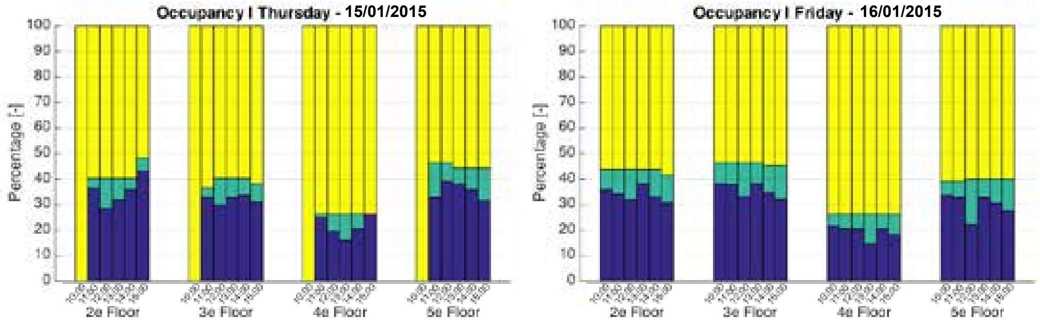


Fig. c3.2: 2015 building occupancy percentage per floor according data Appendix B.1.4, table b1.5 (2/2).

C.3.2. HVAC Thermal Load

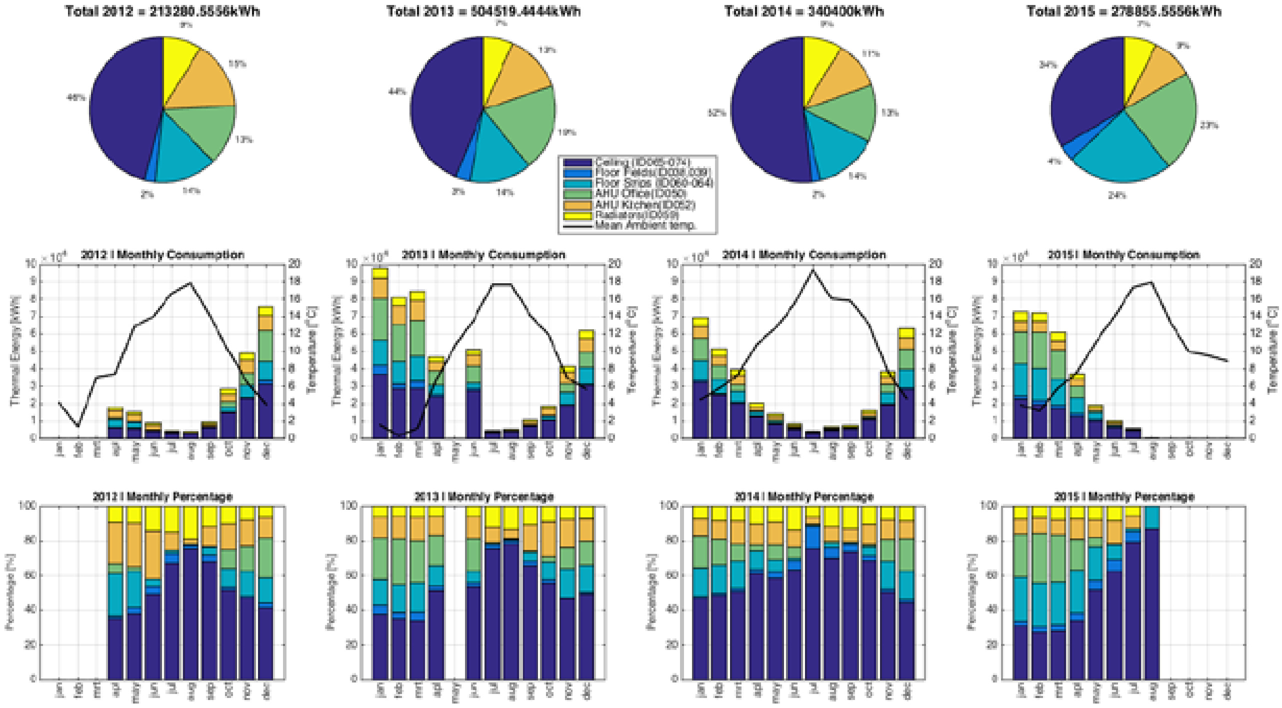


Fig. c3.3: Heating thermal energy load

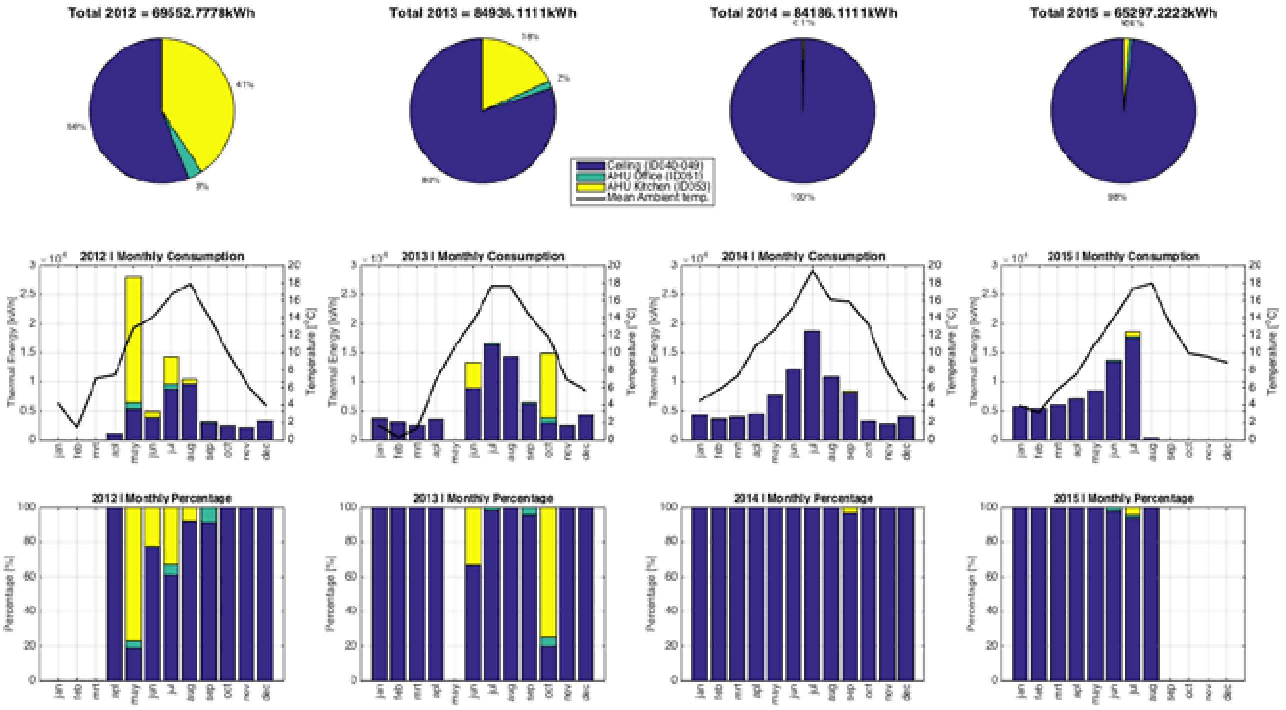


Fig. c3.4: Cooling thermal energy load

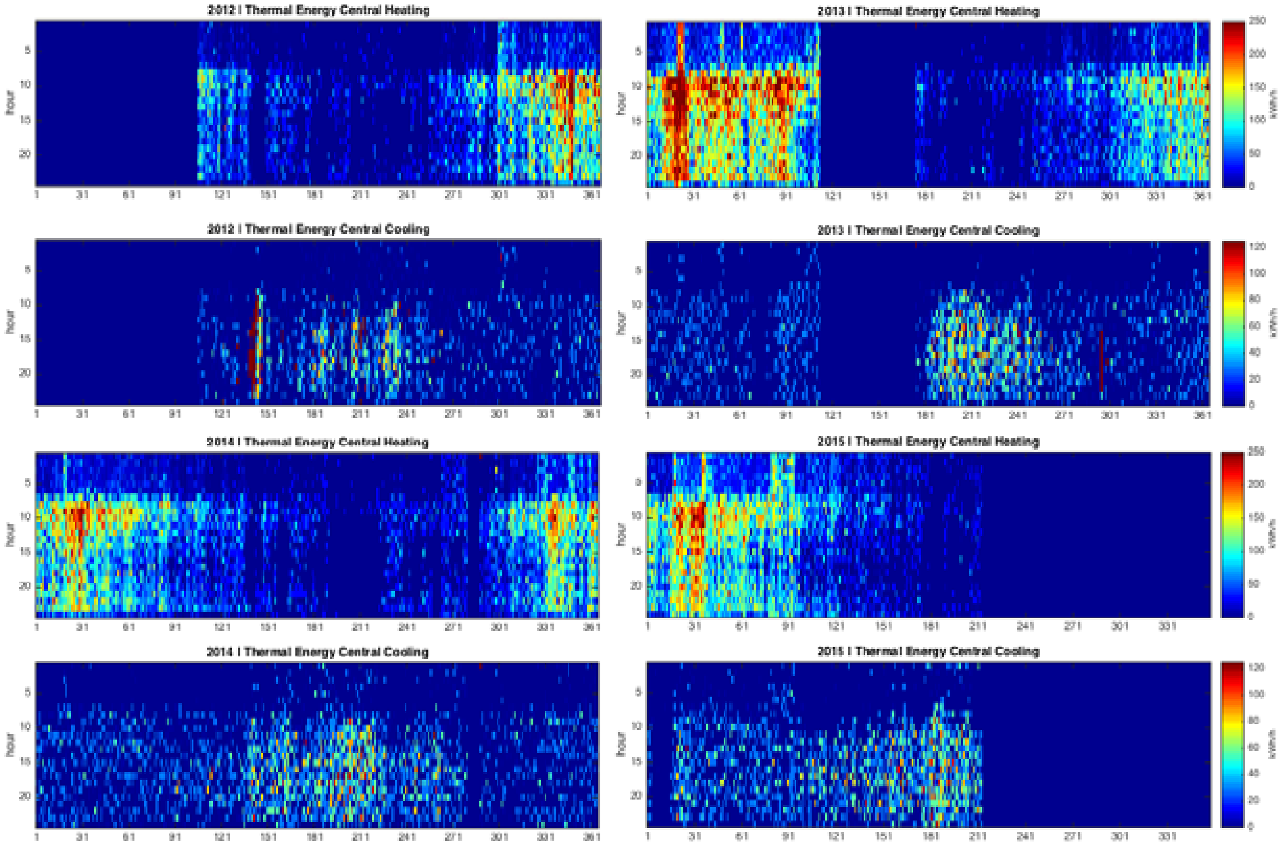


Fig. c3.5: Carpet plot total HVAC thermal energy load.

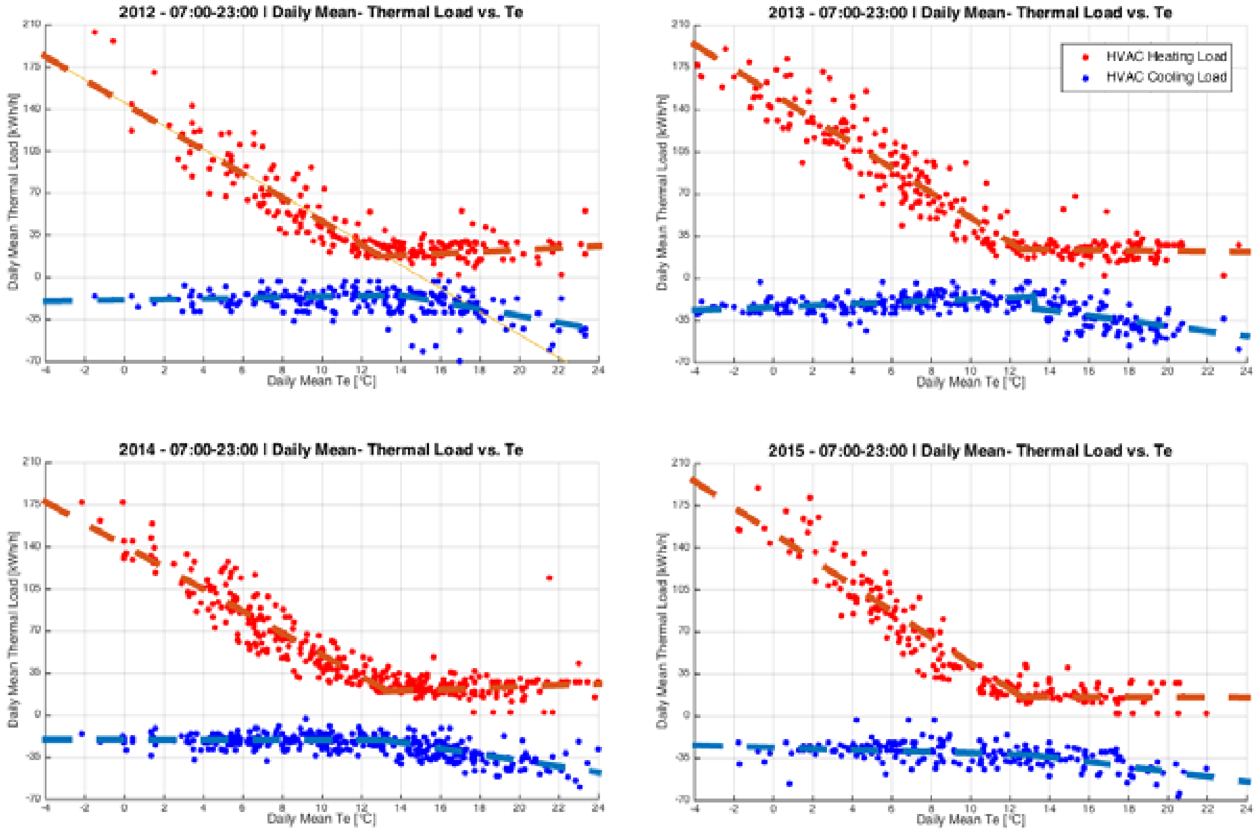


Fig. c3.6: Daily mean HVAC thermal energy load vs. mean Te (kitchen AHU excluded).

D. Appendix – Modeling

D.1. Benchmark

To compare and rate how accurate the models can reproduce a variable, a number of criteria are used. For the models consecutively Mean Squared Error (MSE), Mean Absolute Error (MAE) and goodness of fit (FIT) is calculated by respectively equation D.1, D.2 and D.3.

$$MAE = \frac{1}{N}\sum_{k=1}^{N} |Q_{n\,real} - Q_{n\,simulated}| \qquad \text{(D.1)}$$

$$MSE = \frac{1}{N}\sum_{k=1}^{N} (Q_{n\,real} - Q_{n\,simulated})^2 \qquad \text{(D.2)}$$

$$FIT = 100\,.\,(1 - \frac{norm(T_{n\,real} - T_{n\,simulated})}{norm\,(T_{n\,real} - T_{n\,simulated})} \qquad \text{(D.3)}$$

The MAE expresses the overall mean error over the simulated period. The MSE is used to give more weight to values, making it a good function to express the amount. Goodness of fit expresses the percentage of the simulated data points that are equal to the measured data.

D.1.1. Office AHU Benchmark

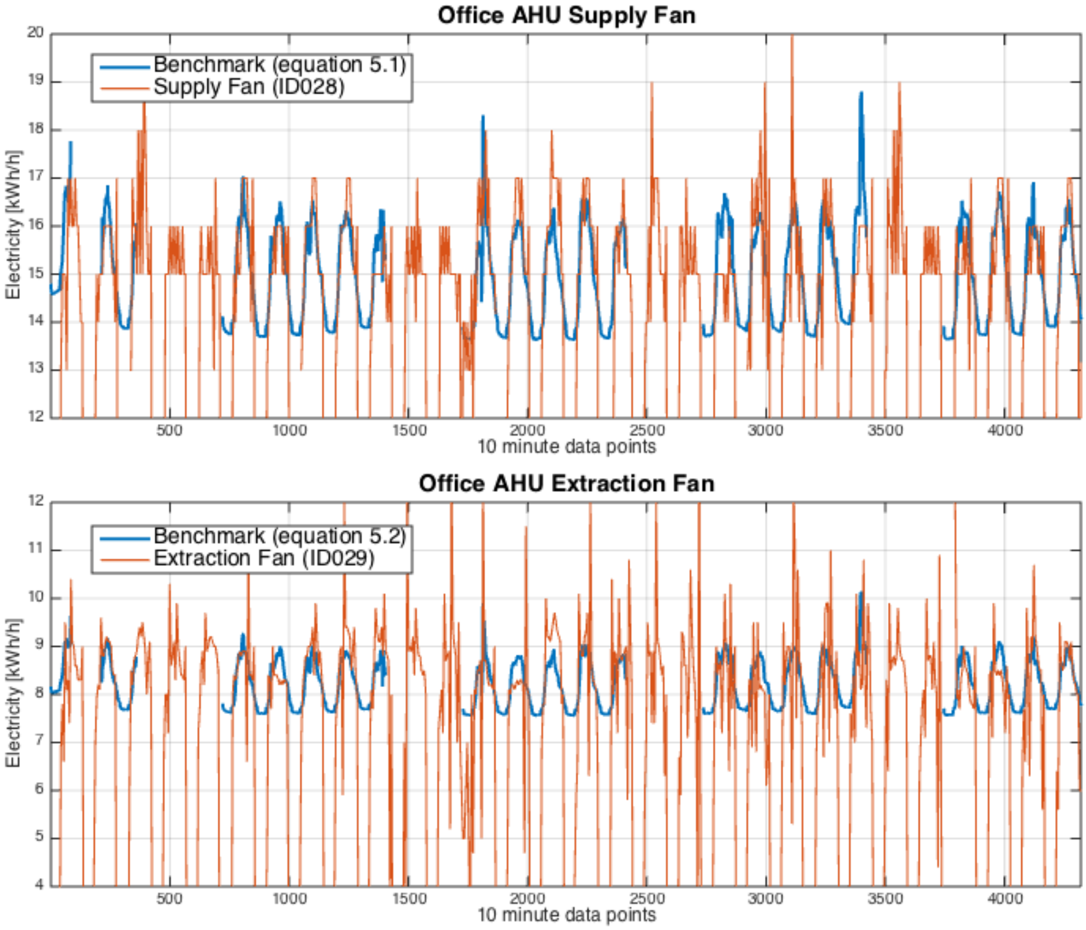
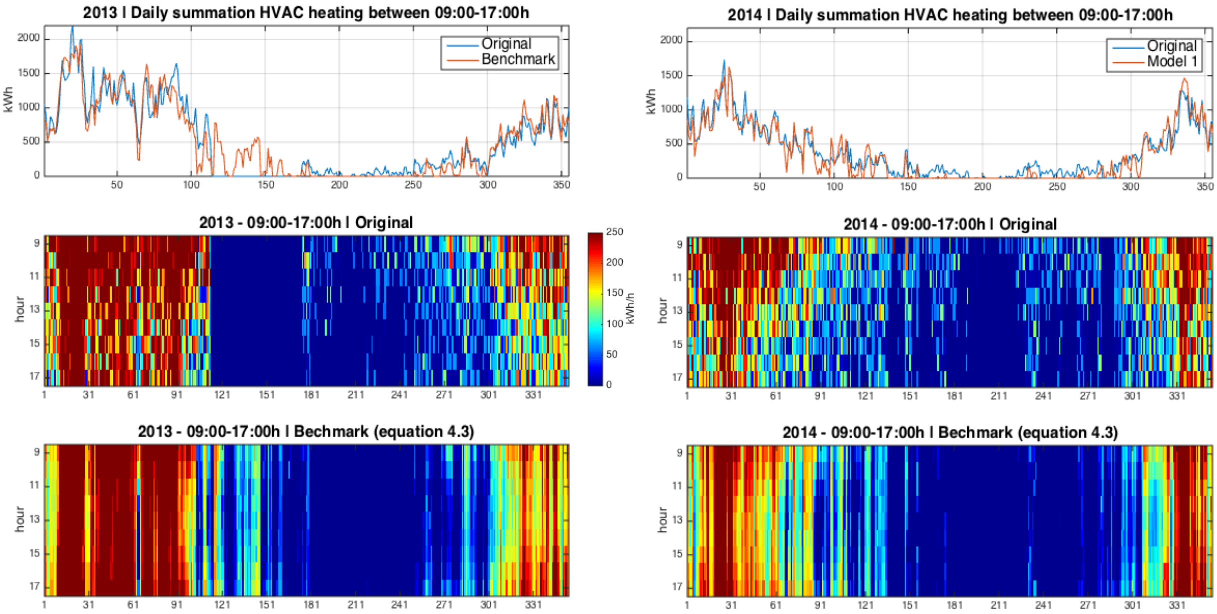


Fig. d1.1: Simulated and empirical fan electricity (gaps in benchmark are related to data gaps in CO_2 concentration).

D.1.2. HVAC Thermal Energy Benchmark


2013 I Daily summation HVAC heating between 09:00-17:00h

2014 I Daily summation HVAC heating between 09:00-17:00h

2013 - 09:00-17:00h I Original

2014 - 09:00-17:00h I Original

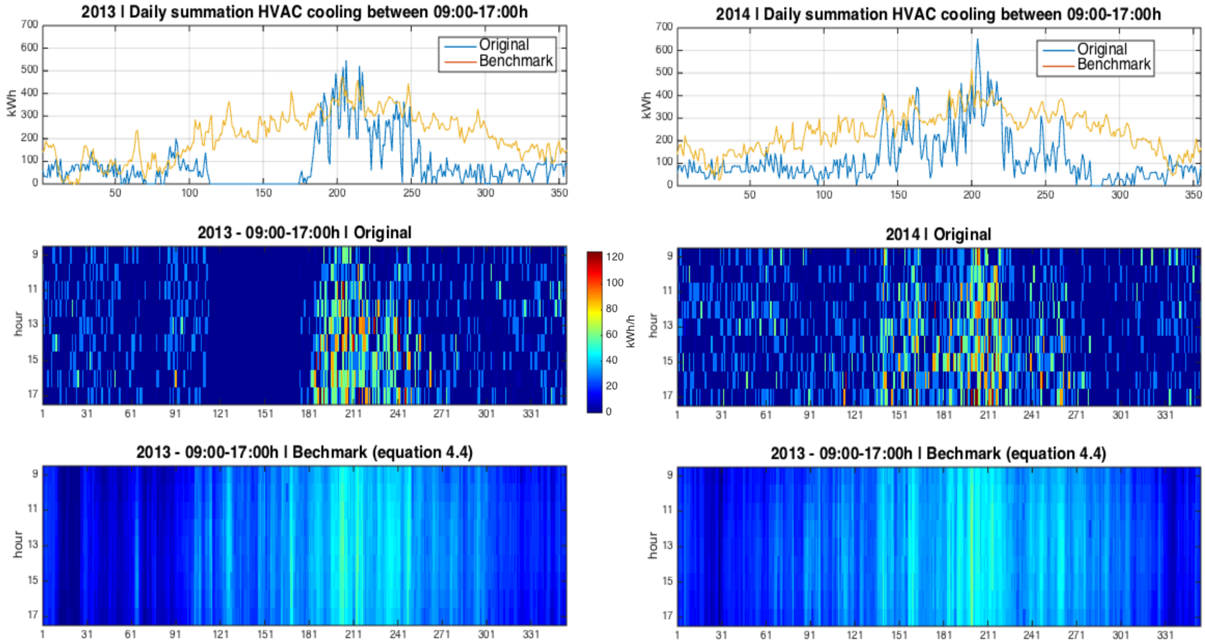
2013 - 09:00-17:00h I Bechmark (equation 4.3)

2014 - 09:00-17:00h I Bechmark (equation 4.3)

Fig. d1.2: 2013 and 2014 simulation results thermal heating model.

Table d1.2: Simulation results thermal heating model.

	2012	2013	2014	2015
Equation 4.3 - MAE	28.55	32.55	28.61	28.59
Equation 4.3 - MSE	1350.57	1707.51	1314.94	1238.43
Equation 4.3 - FIT	29.31	32.55	27.79	35.41


2013 I Daily summation HVAC cooling between 09:00-17:00h

2014 I Daily summation HVAC cooling between 09:00-17:00h

2013 - 09:00-17:00h I Original

2014 I Original

2013 - 09:00-17:00h I Bechmark (equation 4.4)

2013 - 09:00-17:00h I Bechmark (equation 4.4)

Fig. d1.3: 2013 and 2014 simulation results thermal cooling model.

Table d1.3: Simulation results thermal cooling model.

	2012	2013	2014	2015
Equation 4.4 - MAE	19.45	17.89	16.75	18.99
Equation 4.4 - MSE	753.69	548.60	465.28	732.49
Equation 4.4 - FIT	0.35	4.58	5.40	5.80

D.2. Design Model

D.2.1. Occupancy Profile

An occupancy profile is built in consideration of the results in figure c1.3, c3.1 and c3.2. Office room occupancy counts during weekdays give 216 people. Together with room 1.1 (restaurant), peak building occupancy for simulation is set on 250. Following the occupancy profile for a typical week is given (see figure d2.1).

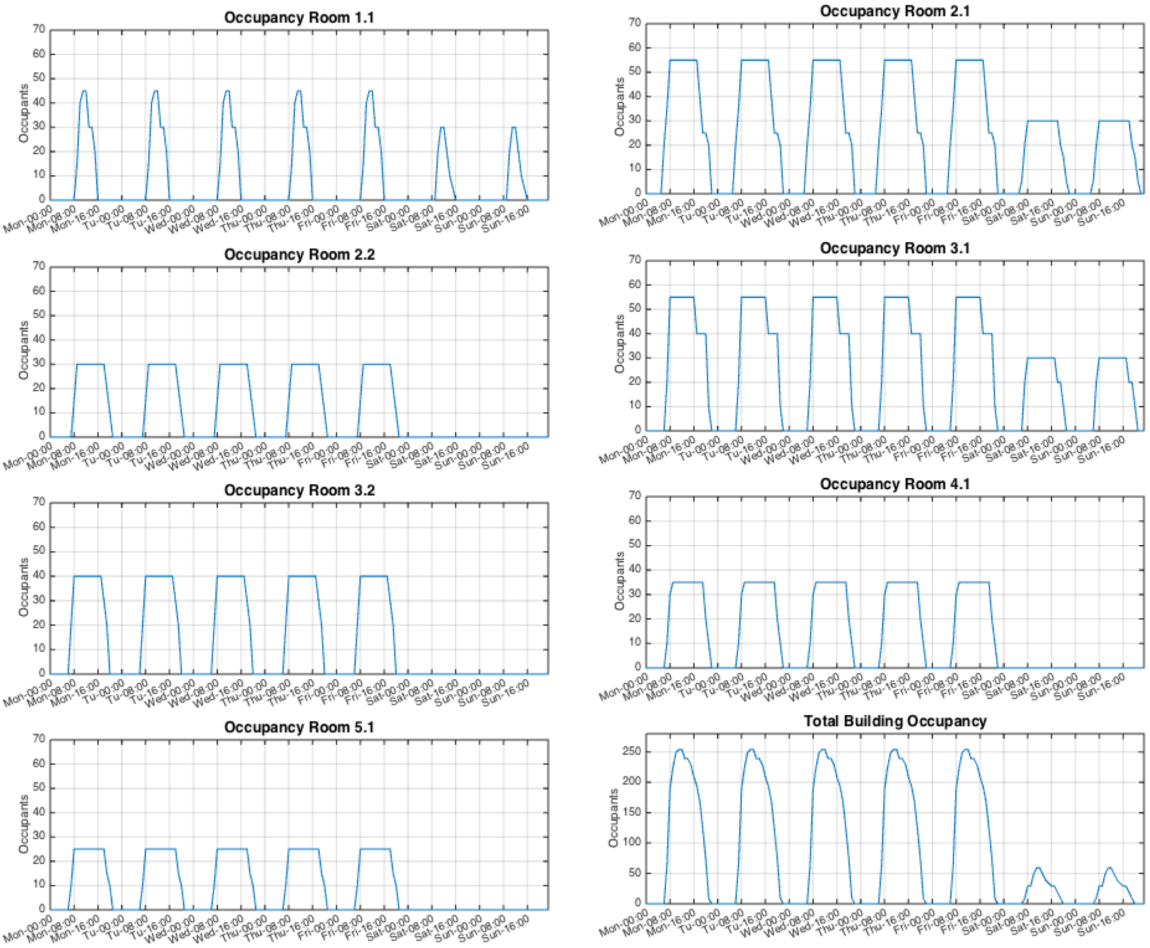


Figure d2.1: Building occupancy used for simulation.

D.2.2. Ventilation Specifications

Room ventilation properties are determined according design specifications (see Appendix A.2.3). Ventilation is shut down incase CO_2 concentration < 600ppm. Office AHU fan electricity analysis gives total ventilation is 48.000m^3/h. Max ventilation is 51.500 m^3/h. 10.800m^3/h is constant. Consequently ventilation rate used for validation is determined. Following the specifications for rooms with VAV are given (see table d2.1).

Table d2.1: model specifications for ventilation.

	Room Volume	Max Ventilation at 1200ppm	Min Ventilation at 700ppm	Ventilation Validation
Room 1.1	2000m^3	10400m^3/h	2080m^3/h	9500m^3/h
Room 2.1	2100m^3	4725m^3/h	945m^3/h	4310m^3/h
Room 2.2	2100m^3	3950m^3/h	790m^3/h	3600m^3/h
Room 3.1	2100m^3	4725m^3/h	945m^3/h	4310m^3/h
Room 3.2	2100m^3	3950m^3/h	790m^3/h	3600m^3/h
Room 4.1	2730m^3	7845m^3/h	1570m^3/h	7170m^3/h
Room 5.1	2730m^3	5190m^3/h	1030m^3/h	4735m^3/h

D.3. Simulation Results

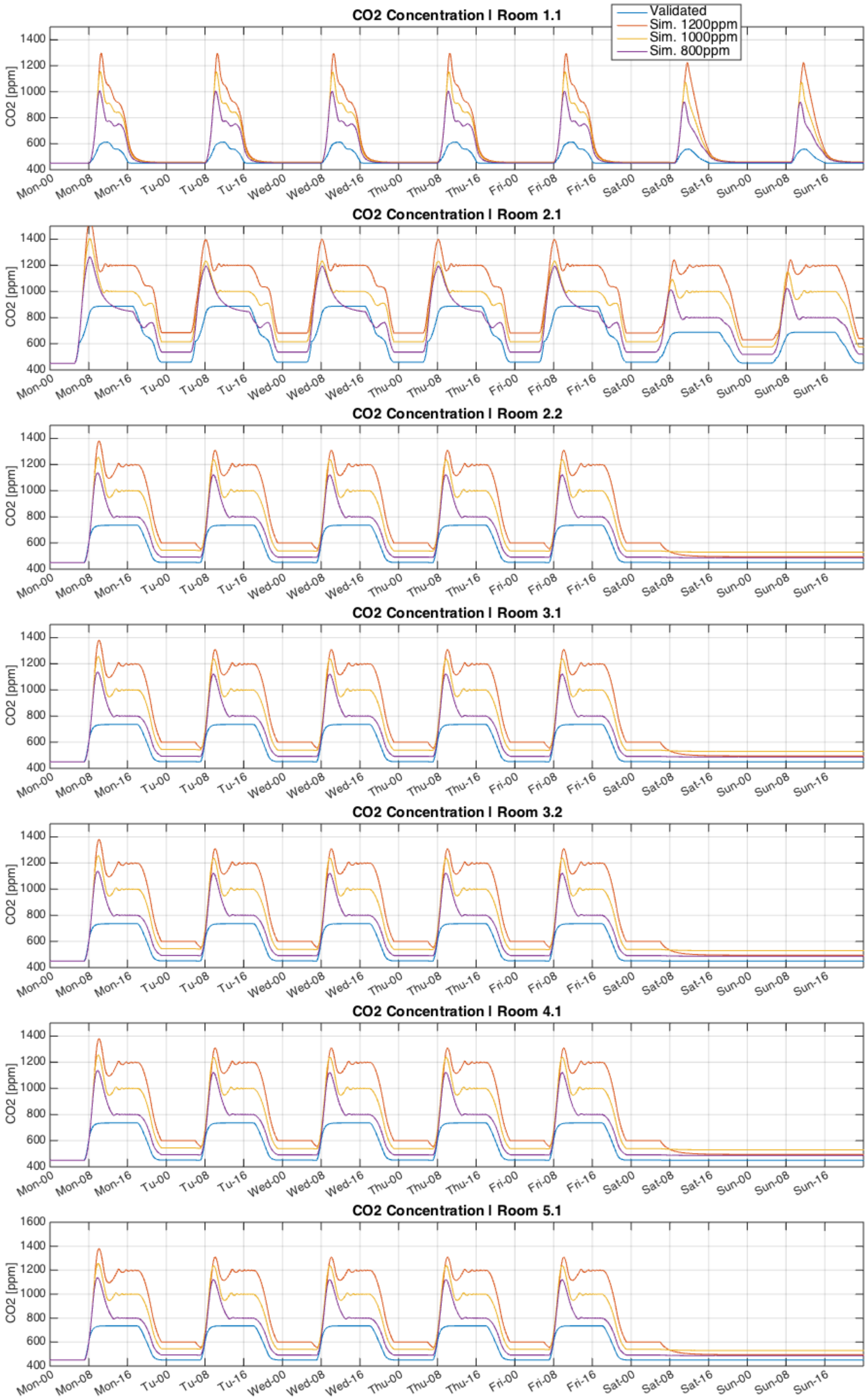


Table d3.1: Simulated CO_2 concentration per room.