Sworn statement

I hereby declare that I am the sole author of this thesis and have written it without the help of third parties. Ideas and quotations from other sources that I used directly or indirectly are marked. This thesis has not yet been presented to an examination office and has not yet been published.

Eidesstattliche Erklärung

Hiermit versichere ich an Eides statt, die vorligende Arbeit selbständig und ohne Hilfe Dritter angefertigt zu haben. Gedanken und Zitate, die ich aus fremden Quellen direkt oder indirekt übernommen habe, sind als solche kenntlich gemacht. Diese Arbeit hat in gleicher oder ähnlicher Form noch keiner Prüfungsbehörde worgelegen und wurde bisher nicht veröffentlicht.

Berlin, August the 2nd, 2017

Pau Castro Valls

Abstract

Absorption chiller cooling is a recent technology based on a source of heat coming from hot water as driving energy. This hot water can come from renewable sources such as solar heating or from district heating networks as a by-product of combined heat and power plants (CHP). This technology reduces notably the electrical consumption in comparison with traditional compression cooling technologies. These benefits usually have their counterpart, which is a larger investment.

This thesis describes some of the test sites that TU Berlin is currently operating in Germany and Jordan and describes some of the advanced control strategies that have been designed to regulate the operation of certain components of the system. Further in this work, specific values of system components consumption are analysed in order to explain the behaviour of the system under different operation conditions when some strategies are active or not.

The thesis shows that when advanced control strategies are active in the sites and no abnormal operation conditions are given, the specific electrical consumption of the components involved in the strategies is significantly reduced, helping the absorption cooling plant to be more energy efficient.

Kurzfassung

Die Kühlung mit einer Absorptionskälteanlage ist mittlerweile eine gängige Technologie, bei der die Energie von heißem Wasser die treibende Kraft darstellt. Das heiße Wasser kann aus erneuerbaren Energiequellen kommen, wie beispielsweise Solarheizung oder aus Fernwärmenetzen als Nebenprodukt von Kraft-Wärme-Kopplungen (CHP). Im Vergleich zu herkömmlichen Kompressorkältemaschinen wird durch diese Technologie der Stromverbrauch deutlich reduziert. Nachteilig sind hingegen die höheren Investitionskosten.

Diese Arbeit beschreibt einige der Teststellen, an denen die TU Berlin in Deutschland und Jordanien arbeitet und befasst sich mit einigen Regelungsmaßnahmen, die entwickelt wurden um die Betrieb von bestimmten Komponenten im System zu regeln. Weiterhin werden in dieser Arbeit spezifische Werte des Systemkomponentenverbrauchs analysiert um das Verhalten des Systems unter verschiedenen Betriebskonditionen zu erklären, wenn manche der Maßnahmen aktiv oder inaktiv sind.

Die These zeigt, dass, wenn fortgeschrittene Kontrollstrategien in den Standorten aktiv

sind und keine anormalen Betriebsbedingungen gegeben sind, der spezifische elektrische Verbrauch der an den Strategien beteiligten Komponenten deutlich reduziert wird, was dazu beiträgt, dass die Absorptionskühlanlage energieeffizienter ist.

Structure of this Thesis

The structure of this Thesis is divided in two parts. In the first part, the current state of the art of the absorption chiller technology will be briefly explained, so the working principles of an absorption chiller. The different sites considered for the study will be described, as the variables taken into account for each site. In this first part, also the agents that are going to be analysed will be specified and the control strategies will be explained.

The second part will consist in the data handling and the energetical evaluation for the sites, the different strategies, the results obtained and the conclusions reached in this thesis.

Contents

Part I. Overview of the absorption chiller technology, field test sites and approach to the energetical analysis

In this part, the current state of the art of the absorption chiller technology will be briefly explained, so the working principles of an absorption chiller. The different sites considered for the study will be described, as the variables taken into account for each site. In this first part, also the agents that are going to be analysed will be specified and the control strategies will be explained.

1. Introduction

1.1. FAkS project

This thesis is written in the framework of the *Feldtest Absorptionskälteanlagen für KWKK Systeme* project (FAkS). This project is developed jointly with partners in the field of machine and energy plant technology of the TUB and cooperation partners (Stadtwerke, Unternehmen) and consists in the installation of laboratory-optimized absorption chillers in field tests at various locations in Germany and Jordan, operation and optimization of the absorption refrigeration plants.

This project is funded by the BMWi, the Federal Ministry of Economy and Energy *(Bundesministerium für Wirtschaft und Energie).*

1.2. Motivation

In a world where more energy is demanded in cooling seasons for air conditioning or cooling purposes, there is an urgent need to keep providing the demanded cooling capacity but at lower energy costs.

This reduction of the energy costs can be carried away by absorption cooling technology. This is a recent technology that allows to reduce load peaks in the electricity network due the fact that does not use electrically driven compressors. This technology also takes advantage of heating water provided by combined heat and power plants. In low heat demand during summer operation, this heat can be used as driving heat for the absorption chiller cooling plants in order to face the high cooling demand. (Petersen et al. 2013)

Is interesting to see which challenges will have to face this new technology along with traditional compression cooling technologies in a future with a scenario of rising demand of cooling power and depletion of resources to produce energy to satisfy this demand.

Another motivation for this thesis is to dive in this new cooling technology and get to know its working principles and the operating characteristics of absorption chiller cooling plants.

Finally, a personal motivation is the fact that the thesis involves the handling and analysis of real data from the operating field tests in the framework of the FAkS project.

1.3. Objective

The main goal of this Work is the study and analysis of the behaviour of the absorption chillers and their related actors in different configurations depending on the site and operating under different control strategies.

To achieve this main goal, the appropriate variables from every site will have to be selected and handled in order to get the information wanted. In addition, the different strategy operating modes will have to be identified and the time frame where to analyse the data will have to be selected depending on when those different modes are active.

1.4. Scope

The scope of this Work is the analysis of the absorption chillers and their close related devices. Further parts of the site installations such as heating networks or chilled water distribution networks will remain out of the study.

The period considered for the analysis comprises the years 2016 and 2017 until beginning of July, nevertheless the time frames of operation analysed will comprise few days or hours.

2. State of the Art of the absorption chiller technology

Absorption chiller cooling plants are a solution to the previously presented fact that more electrical energy will be needed so satisfy the cooling demand of buildings in summer periods, and a way to reduce those load peaks is needed. Absorption chiller technology can be that solution, since its energy source is heat instead of electricity, and does not incorporate compression coolers, which are responsible for most of the electrical consumption of a traditional compression cooling device.

The driving heat for an absorption chiller can be provided by the district hot water network, which is a by-product of combined heat and power plants (CHP). In some countries, where CHP plants are not used, solar thermal heating devices can be implemented, if the climatology is favourable.

2.1. Absorption chiller working principle

Absorption chillers are closed thermal systems that use a liquid interface to transfer heat between three different water circuits. This liquid interface is in most of the cases a solution of lithium bromide, known as working pair H_2O – LiBr.

Four parts or chambers compose the absorption chiller itself: the evaporator (E), the absorber (A), the desorber (D) and the condenser (C).

Evaporator

In the evaporator enters the chilled water at room temperature and exits at the temperature demanded by the client, if possible depending on other factors of the system. Through a heat exchanger, chilled water is cooled down, while refrigerant water is evaporated and headed to the absorber.

Absorber

In the absorber, refrigerant steam coming from the evaporator condenses and gives heat to the cooling water. In addition, the concentrated LiBr solution is sprayed over the heat exchanger and collected on the bottom of the absorber, which mixed with the condensed refrigerant water leads to a less concentrated LiBr solution. This less concentrated solution is pumped to the desorber.

Desorber

In the desorber, hot water coming from the heating network or thermal solar systems is driven through an exchanger, while the solution coming from the absorber is sprayed over this exchanger. Part of this solution is evaporated, resulting in steam and a concentrated solution in liquid state collected on the bottom of the desorber. This steam is headed to the condenser.

Condenser

In the condenser, this steam coming from the desorber is condensed while giving heat to the cooling water, which flows through an exchanger. The condensed steam is the refrigerant water, pumped back to the evaporator. (Paitazoglou 2015) (Srikhirin & Aphornratana 2001)

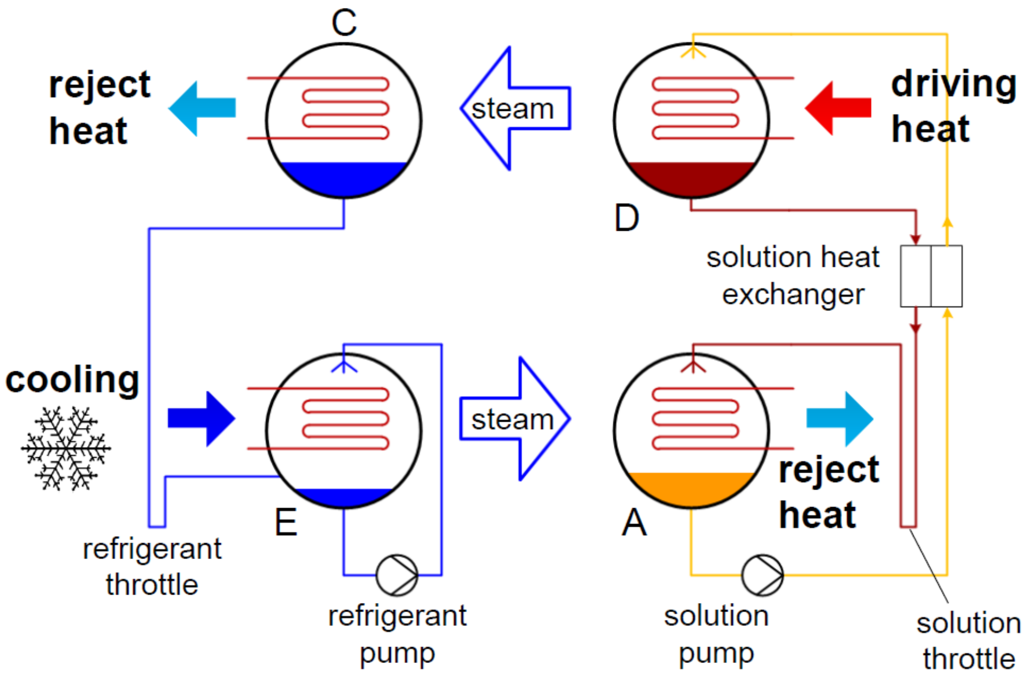


Figure 2.1. Working principle of the absorption chiller. (Paitazoglou 2015)

2.2. Hydraulic integration of an absorption chiller cooling plant

The hydraulic integration of the absorption chiller in its most basic form is the one shown in **¡Error! No se encuentra el origen de la referencia.**. Some of the measurement units are standard and common in all chiller rigs and configurations. Every absorption chiller system is formed by, at least, three different external circuits: hot water circuit, with an index of 2 and shown in red, cooling water circuit, with an index of 1 and shown in green, and the chilled water circuit, with an index of 0 and shown in blue. For safety reasons, the hot and cooling water circuits are equipped with one control valve each.

Hot water circuit

The hot water circuit is the chiller energy source and supplies the desorber of driving heat coming from district heating water network or a thermal solar system. A three-way valve is responsible for controlling the hot water temperature at the desorber inlet and for protecting the chiller from excessively high hot water temperatures. The driving capacity $\dot{Q}_{2Dc,1}$ is determined by a heat flow meter reading the temperatures before and after the desorber and the hot water flow rate.

Cooling water circuit

The cooling water circuit supplies the absorber and the condenser with water from a heat sink such as a reject heat device. In the basic configuration, the absorber and the condenser are supplied with cooling water in series: first the absorber and then the condenser. A three-way valve is responsible for setting a specific cooling water temperature at the absorber inlet and for protecting the chiller from non-desirable cooling water temperatures. The reject heat capacity is determined by a heat flow meter reading the temperatures before and after the absorber and condenser and the cooling water flow rate.

Chilled water circuit

A pump supplies the evaporator with water to be chilled. The flow rate of chilled water is set to a design flow rate at commissioning. The set value for the chilled water outlet is achieved by controlling hot and cooling water inlet temperatures simultaneously. The cooling capacity $\dot{Q}_{0Eh,1}$ is determined by a heat flow meter reading the temperatures before and after the evaporator and the chilled water flow rate. (Albers & Paitazoglou 2014)

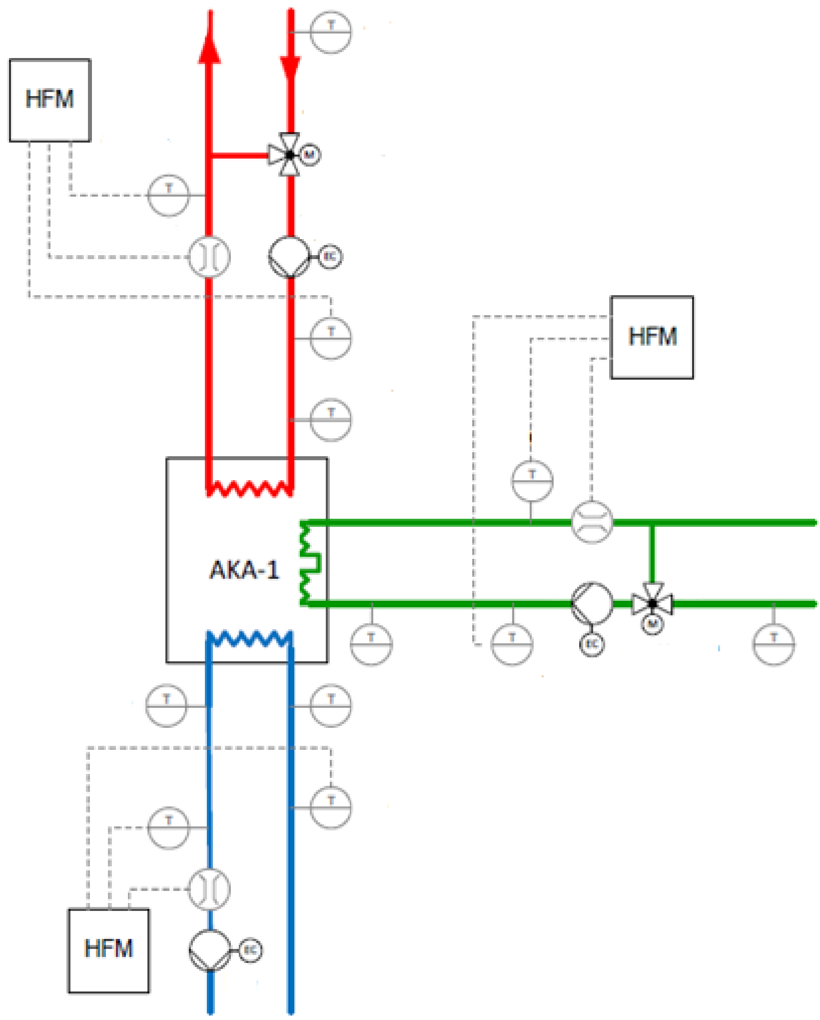


Figure 2.2. Basic scheme of the hydraulic integration of an absorption chiller. (Albers & Paitazoglou 2014)

2.3. Absorption chiller load control

The operation of the absorption chiller and related devices in absorption cooling plants is controlled by a superior controller that communicates to a CE-Controller placed in the absorption chiller.

The CE-Controller is responsible for controlling the absorption chiller's cooling capacity and has three objectives: supply of the demanded cooling capacity, maintain the demanded chilled water outlet temperature, and ensuring the demanded hot water outlet temperature. The controller achieves these three objectives simultaneously by adjusting the inlet hot water temperature at the desorber $t_{2Di,1}$and the inlet cooling water temperature at the absorber $t_{1Ai,1}$ through the control valves in the hot and cooling water circuits.

Hot water control

The hot water inlet temperature at the desorber $t_{2Di,1}$ is adjusted by the three-way valve in the hot water circuit. In the case of hot water inlet temperature at the desorber exceeding the maximum permitted temperature, the three-way valve allows colder hot water from the return line to flow through the bypass in order to lower the temperature at the desorber inlet for safety reasons.

In the case of a too low temperature of the hot water inlet, the CE-Controller adapts the set value for the cooling water temperature at the inlet if the absorber in order to keep providing the demanded cooling capacity, if possible, with a higher energy cost of the cooling devices in the cooling water circuit.

Cooling water control

The cooling water inlet temperature at the absorber $t_{1Ai,1}$ is set by the three-way valve in the cooling water circuit. In cased of a lower temperature at the inlet of the absorber than the minimum permitted, the valve will allow warm cooling water from the condenser outlet to flow through the bypass and mix with cold cooling water at the inlet of the absorber in order to warm it up.

In the case that cooling water demanded temperature at the inlet of the absorber cannot be achieved, the CE-Controller readapts the set value of the hot water inlet temperature in order to keep providing the demanded cooling capacity. The cost of this is that the set value for the absorber outlet temperature cannot be maintained.

Chilled water control

The CE-Controller calculates the cooling load through the next equation, based on the set value for chilled water outlet temperature $t_{0Eo,1,set}$, the chilled water inlet temperature $t_{0Ei,1}$ and the chilled water flow rate $\dot{V}_{0Eh,1}$.

$$\dot{Q}_{0Em,1,set} = \dot{V}_{0Eh,1} \cdot \rho \cdot Cp \cdot (t_{0Ei,1} - t_{0Eo,1,set})$$

The satisfaction of the cooling load is achieved by the continuous control of hot and cooling water temperatures $t_{2Di,1}$ and $t_{1Ai,1}$. (Albers & Paitazoglou 2014)

3. Description of the sites

This thesis will analyse six sites that implement absorption chillers in their cooling plants, developed by the TU Berlin. These six sites have different environment conditions, different configurations and components that will be evaluated and compared. In this chapter, these sites will be described and the variables taken into account for each site will be listed and explained. The hydraulic schemes of all sites can be found in Appendix A. Hydraulic schemes of the sites.

There are two types of absorption chillers, the Bumblebee type (Hummel) with a nominal cooling power of 160 kW and the Bee type (Biene) with a nominal cooling power of 50 kW. (Paitazoglou 2015)

For the variables analysed in data points, there is a nomenclature that is going to be described in the following table:

Subscript	Meaning
0	Chilled water circuit
1	Cooling water circuit
2	Hot water circuit
A	Absorber
C	Condenser
c	Cold
Cons	Consumer
D	Desorber
E	Evaporator
E	Energy consumption
h	Hot
i	Inlet
L	Power consumption
o	Outlet
Prod	Producer
Q	Heat
set	Set value
t	Temperature
V	Volume flow

Table 3.1. Nomenclature of the subscripts in the data points

3.1. KFWK Kassel

This site uses one single absorption chiller Bumblebee type along with a single compression chiller. The driving heat source is district heating from a CHP plant.

It has the particularity that can use a mixture of hot district water and return district water as driving hot water for the desorber. Another singularity of this site is that the cooling water is taken from a river (free source) and does not need a dry cooler, which means energy consumption for cooling down this water.

The elements that are going to be included in the analysis are the chilled water circuits of the absorption and compression chillers and the whole cooling water circuit.

The elements that are going to be excluded from the analysis are the whole hot water circuit and the storage tank in the chilled water line before the consumer's end. The Table 3.2 shows the variables that had been taken into account to carry out the analysis of the site:

Variable	Units	Description
		Cooling water circuit
V_1Qx_1	m^3/h	Volume flow of cooling water in the AKA cooling circuit
V_1Qx_1_set	m^3/h	Set volume flow of cooling water in the AKA cooling circuit
E_1Pm_1	kWh	Electrical energy consumption of the AKA cooling water pump
L_1Pm_1	kW	Electrical power consumption of the AKA cooling water pump
t_1Ai_1	° C	Inlet temperature of the absorber
t_1Co_1	° C	Outlet temperature of the condenser
Q_1Qx_1	kW	Reject heat capacity of the AKA
		Chilled water circuit
V_0Ex_1	m^3/h	Volume flow of chilled water provided by the AKA
V_0Ex_1_set	m^3/h	Set volume flow of chilled water provided by the AKA
V_0Vx	m^3/h	Consumer's network chilled water volume flow
Q_0Vx	kW	Cooling capacity provided to the consumer
E_0Pm_1	kWh	Energy consumption of the AKA chilled water pump
L_0Pm_1	kW	Power consumption of the AKA chilled water pump
Q_0Ex_1	kW	Cooling capacity of the AKA
Q_0Ex_K1	kW	Cooling capacity of the KKA
L_RRm_K1	kW	Electrical power consumption of the KKA
L_AAm_1	kW	Electrical power consumption of the AKA
		Other variables
t_7Ki_M	° C	Ambient temperature

Table 3.2. List of variables considered for the analysis of KFWK site

3.2. ESTW Essen WSG

This site uses one single absorption chiller Bee type along with a single compression chiller and a free heat exchanger between cooling water circuit and chilled water circuit. This heat exchanger is used to provide the demanded temperature of chilled water when the cooling water temperature is low enough to allow this (winter season). This way, both absorption and compression chillers do not have to be operative, with the energy saving that this implies. The driving heat source is district heating from a CHP plant.

There is a dry cooler for the absorption chiller and free heat exchanger common cooling circuit, and another dry cooler for the compression chiller independent cooling circuit.

The boundaries of the analysis of this site include the cooling water circuit of the absorption chiller and the free heat exchanger, the compression chiller and its cooling system as a whole and the chilled water circuits of the compression chiller and absorption chiller / free heat exchanger until the consumers' distribution network.

The excluded elements are the mixing chilled water tank and the chilled water distribution network to the consumers. The Table 3.3 shows the variables taken for the analysis of this site:

Variable	Units	Description
		Cooling water circuit
V_1Qx_1	m^3/h	Volume flow of cooling water in the AKA cooling circuit
V_1Qx_1_set	m^3/h	Set volume flow of cooling water in the AKA cooling circuit
E_1Pm_1	kWh	Electrical energy consumption of the AKA cooling water pump
t_1Ai_1	°C	Inlet temperature of the absorber
t_1Co_1	°C	Outlet temperature of the condenser
Q_1Qx_1	kW	Reject heat capacity of the AKA
t_1Ko_1	°C	Temperature of the cooling water at the outlet of the dry cooler
t_1Ko_1_set	°C	Set temperature of the cooling water at the outlet of the dry cooler
E_7Km_K	kWh	Electrical energy consumption of the cooling fans RKW-1
Modbus_V_1Qx_1_dyn_ActStrategy	bit	Value that indicates either if any control strategy is applied to the operation of the cooling water pump or not
Modbus_V_1Qx_1_dyn_strategy	bit	Value that indicates which control strategy is applied to the operation of the cooling water pump
Modbus_t_1Ko_1_dyn_ActStrategy	bit	Value that indicates either if any control strategy is applied to the operation of the dry cooler or not
Modbus_t_1Ko_1_dyn_strategy	bit	Value that indicates which control strategy is applied to the operation of the dry cooler
		Chilled water circuit
V_0Ex_1	m^3/h	Volume flow of chilled water provided by the AKA
V_0Ex_1_set	m^3/h	Set volume flow of chilled water provided by the AKA

V_0Mx_Prod	m^3/h	Consumer's network chilled water volume flow
Q_0Mx_Prod	kW	Cooling capacity provided to the consumer
E_0Pm_1	kWh	Electrical energy consumption of the AKA chilled water pump
Q_0Ex_1	kW	Cooling capacity of the AKA
Q_0Hx_H1	kW	Cooling capacity of the free heat exchanger
Q_0Ex_KKA1	kW	Cooling capacity of the KKA
E_RRm_KKA1	kWh	Electrical energy consumption of the KKA
E_AAm_1	kWh	Energy consumption of the AKA
Modbus_V_0Ex_1 _dyn_ActStrategy	bit	Value that indicates either if any control strategy is applied to the operation of the chilled water pump or not
Modbus_V_0Ex_1 _dyn_strategy	bit	Value that indicates which control strategy is applied to the operation of the chilled water pump
	Other variables	
t_7Ki_M	°C	Ambient temperature

Table 3.3. List of variables considered for the analysis of ESTW site

3.3. LVRZ Leverkusen

This site uses one single absorption chiller Bee type along with a single compression chiller and a free heat exchanger between cooling water circuit and chilled water circuit, as the case of ESTW site. The driving heat source is district heating from a CHP plant.

The absorption chiller and free heat exchanger use one common cooling water circuit and dry cooler, while the compression chiller uses its own independent cooling circuit. The particularity of this site is that none of the three chilled water circuits (absorption, compression chillers and free heat exchanger) has its own pump. Neither there is a common pump for all three chilled water circuits. In this case, there are two parallel pumps placed in the consumers' chilled water distribution network.

The elements included in the analysis are the cooling water circuit of the absorption chiller and the free heat exchanger, the compression chiller and its cooling system as a whole and the three chilled water circuits until the consumers' distribution network.

Will be excluded from the analysis the hot water circuit and the consumers' chilled water distribution network. The Table 3.4 shows the variables taken for the analysis of this site:

Variable	Unit s	Description
	Cooling water circuit	

V_1Qx_1	m^3/h	Volume flow of cooling water in the AKA cooling circuit
V_1Qx_1_set	m^3/h	Set volume flow of cooling water in the AKA cooling circuit
E_1Pm_1	kWh	Electrical energy consumption of the cooling pump
t_1Ai_1	° C	Inlet temperature of the absorber
t_1Co_1	° C	Outlet temperature of the condenser
Q_1Qx_1	kW	Reject heat capacity of the AKA
t_1Ko_1	° C	Temperature of cooling water after the dry cooler
t_1Ko_1_set	° C	Set temperature of cooling water after the dry cooler
E_7Km_K	kWh	Energy consumption of the dry cooler
Modbus_V_1Qx_1 _dyn_ActStrategy	bit	Value that indicates either if any control strategy is applied to the operation of the cooling water pump or not
Modbus_V_1Qx_1 _dyn_strategy	bit	Value that indicates which control strategy is applied to the operation of the cooling water pump
Modbus_t_1Ko_1 _dyn_ActStrategy	bit	Value that indicates either if any control strategy is applied to the operation of the dry cooler or not
Modbus_t_1Ko_1 _dyn_strategy	bit	Value that indicates which control strategy is applied to the operation of the dry cooler
	Chilled water circuit	
V_0Ex_1	m^3/h	Volume flow of chilled water provided by the AKA
V_0Ex_1_set	m^3/h	Set volume flow of chilled water provided by the AKA
V_0Mx_Prod	m^3/h	Consumer’s network chilled water volume flow
Q_0Mx_Prod	kW	Cooling capacity provided to the consumer
E_0Pm_N	kWh	Electrical energy consumption of the global chilled water pump
Q_0Ex_1	kW	Cooling capacity of the AKA
Q_0Hx_H1	kW	Cooling capacity of the free heat exchanger
Q_0Ex_KKA1	kW	Cooling capacity of the KKA
E_6Rm_KKA1	kWh	Electrical energy consumption of the KKA
E_AAm_1	kWh	Electrical energy consumption of the AKA
	Other variables	
t_7Ki_M	° C	Ambient temperature

Table 3.4. List of variables considered for the analysis of LVRZ site

3.4. HENK Hannover

This site uses one single absorption chiller Bumblebee type along with a single compression chiller and another absorption chiller York type. The driving heat source is district heating from a CHP plant.

The absorption chiller uses its own cooling circuit with dry cooler, while the compression and York absorption chillers use another cooling circuit with two dry coolers. This site does not have a free heat exchanger between cooling and chilled water circuits.

The elements included in the analysis are the absorption chiller cooling circuit, the compression chiller, the York type chiller and the chilled water circuit of the absorption chiller.

The elements excluded are the hot water circuit, the compression and York chiller chilled water circuits, the cooling circuit for the compression and York chillers and the chilled water storage tank before the customers' end. The Table 3.5 shows the variables taken for the analysis of this site:

Variable	Units	Description
		Cooling water circuit
V_1Qh_1	m^3/h	Volume flow of cooling water in the AKA cooling circuit
V_1Qh_1_set	m^3/h	Set volume flow of cooling water in the AKA cooling circuit
E_1Pm_1	kWh	Energy consumption of the cooling pump
Q_1Qx_1	kW	Reject heat capacity of the AKA
t_1Ko_1	° C	Temperature of cooling water after the dry cooler
t_1Ko_1_set	° C	Set temperature of cooling water after the dry cooler
E_7Km_KT3	kWh	energy consumption of the dry cooler
Modbus_V_1Qh_1_dyn_ActStrategy	bit	Value that indicates either if any control strategy is applied to the operation of the cooling water pump or not
Modbus_V_1Qh_1_dyn_strategy	bit	Value that indicates which control strategy is applied to the operation of the cooling water pump
Modbus_t_1Ko_1_dyn_ActStrategy	bit	Value that indicates either if any control strategy is applied to the operation of the dry cooler or not
Modbus_t_1Ko_1_dyn_strategy	bit	Value that indicates which control strategy is applied to the operation of the dry cooler
		Chilled water circuit AKA Hummel
V_0Eh_1	m^3/h	Volume flow of chilled water provided by the AKA
V_0Eh_1_set	m^3/h	Set volume flow of chilled water provided by the AKA
V_0Vx_ges	m^3/h	Consumer's network chilled water volume flow
Q_0Vx_ges	kW	Cooling capacity delivered to customer
E_0Pm_1	kWh	Electrical energy consumption of the AKA chilled water pump

Q_0Ex_1	kW	Cooling capacity of the AKA
Q_0Ex_Bestand	kW	Cooling capacity of the KKA-York system
E_AAm_YIA	kWh	Electrical energy consumption of the AKA York
E_RRm_KKA	kWh	Electrical energy consumption of the KKA
E_AAm_1	kWh	Electrical energy consumption of the AKA
Modbus_V_0Eh_1_dyn_ActStrategy	bit	Value that indicates either if any control strategy is applied to the operation of the chilled water pump or not
Modbus_V_0Eh_1_dyn_strategy	bit	Value that indicates which control strategy is applied to the operation of the chilled water pump
		Other variables
t_7Ki_M	° C	ambient temperature

Table 3.5. List of variables considered for the analysis of HENK site

3.5. SEHC Stuttgart

This site uses one single absorption chiller Bumblebee type along with two parallel compression chillers and a free heat exchanger between cooling and chilled water circuits. The driving heat source is district heating from a CHP plant.

The absorption chiller uses its own cooling circuit (secondary) connected through a heat exchanger to the primary cooling water circuit, which uses four parallel dry coolers. This primary cooling circuit supplies the two compression chillers and the free heat exchanger to the chilled water circuit.

The elements included in the analysis are the primary and secondary cooling water circuits and the chilled water circuits until the customers' distribution network.

The elements not included are the whole hot water circuit with the burner and the boiler, the customers' chilled water distribution network and the chilled water storage tank. The Table 3.6 shows the variables taken for the analysis of this site:

Variable	Units	Description
		Cooling water circuit
V_1Qx_1	m³/h	Volume flow of cooling water in the AKA cooling circuit
V_1Qx_1_set	m³/h	Set volume flow of cooling water in the AKA cooling circuit
E_1Pm_1	kWh	Electrical energy consumption of the AKA cooling pump
E_4Pm_AKA	kWh	Electrical energy consumption of the primary cooling pump
Q_1Qx_1	kW	Reject heat capacity of the AKA
t_4Ko_RKW1	° C	Temperature of cooling water after the dry coolers 1 and 2

t_4Ko_RKW2	° C	Temperature of cooling water after the dry coolers 3 and 4
t_4Ko_RKW1_set	° C	Set temperature of cooling water after the dry coolers 1 and 2
t_4Ko_RKW2_set	° C	Set temperature of cooling water after the dry coolers 3 and 4
E_7Km_RKW1	kWh	Electrical energy consumption of dry coolers 1 and 2
E_7Km_RKW2	kWh	Electrical energy consumption of dry coolers 3 and 4
Modbus_V_1Qx_1_dyn_ActStrategy	bit	Value that indicates either if any control strategy is applied to the operation of the cooling water pump or not
Modbus_V_1Qx_1_dyn_strategy	bit	Value that indicates which control strategy is applied to the operation of the cooling water pump
Modbus_t_1Ko_1_dyn_ActStrategy	bit	Value that indicates either if any control strategy is applied to the operation of the dry cooler or not
Modbus_t_1Ko_1_dyn_strategy	bit	Value that indicates which control strategy is applied to the operation of the dry cooler
		Chilled water circuit
V_0Ex_1	m^3/h	Volume flow of chilled water provided by the AKA
V_0Ex_1_set	m^3/h	Set volume flow of chilled water provided by the AKA
V_0Vx_KV	m^3/h	Consumer's network chilled water volume flow
Q_0Vx_KV	kW	Cooling capacity delivered to customer
E_0Pm_1	kWh	Electrical energy consumption of the AKA chilled water pump
Q_0Ex_1	kW	Cooling capacity of the AKA
Q_0Ex_KKA1 / 2	kW	Cooling capacity of the KKA1 / KKA2
E_AAm_1	kWh	Electrical energy consumption of the AKA
E_RRm_KKA1 / 2	kWh	Electrical energy consumption of the KKA1 / KKA2
Modbus_V_0Ex_1_dyn_ActStrategy	bit	Value that indicates either if any control strategy is applied to the operation of the chilled water pump or not
Modbus_V_0Ex_1_dyn_strategy	bit	Value that indicates which control strategy is applied to the operation of the chilled water pump
		Other variables
t_7Ki_1	° C	Ambient temperature

Table 3.6. List of variables considered for the analysis of SEHC site

3.6. ICCJ Irbid Chamber of Commerce

This site uses one single absorption chiller Bee type along with a single compression chiller. The driving heat source is a solar heating system.

The absorption chiller uses its own cooling circuit with a single dry cooler, while the compression chiller uses its own cooling system.

The elements included in the analysis are the absorption chiller cooling circuit and its dry cooler, the compression chiller and its cooling system as a whole and the chilled water circuits from the absorption and compression chillers.

The elements excluded from the analysis are the whole hot water system. The Table 3.7 shows the variables taken for the analysis of this site:

Variable	Units	Description
Cooling water circuit		
V_1Qx_1	m^3/h	Volume flow of cooling water in the AKA cooling circuit
V_1Qx_1_set	m^3/h	Set volume flow of cooling water in the AKA cooling circuit
E_1Pm_1	kWh	Electrical energy consumption of the AKA cooling pump
Q_1Qx_1	kW	Reject heat capacity of the AKA
t_1Ko_1	° C	Temperature of cooling water after the dry cooler
t_1Ko_1_set	° C	Set temperature of cooling water after the dry cooler
E_7Km_K	kWh	Electrical energy consumption of dry cooler
Modbus_V_1Qx_1_dyn_ActStrategy	bit	Value that indicates either if any control strategy is applied to the operation of the cooling water pump or not
Modbus_V_1Qx_1_dyn_strategy	bit	Value that indicates which control strategy is applied to the operation of the cooling water pump
Modbus_t_1Ko_1_dyn_ActStrategy	bit	Value that indicates either if any control strategy is applied to the operation of the dry cooler or not
Modbus_t_1Ko_1_dyn_strategy	bit	Value that indicates which control strategy is applied to the operation of the dry cooler
Chilled water circuit		
V_0Ex_1	m^3/h	Volume flow of chilled water provided by the AKA
E_0Pm_1	kWh	Electrical energy consumption of the AKA chilled water pump
Q_0Ex_1	kW	Cooling capacity of the AKA
Q_0Ex_KKA	kW	Cooling capacity of the KKA
E_AAm_1	kWh	Electrical energy consumption of the AKA
E_RRm_KKA	kWh	Electrical energy consumption of the KKA
Other variables		
t_7Ki_1	º C	Ambient temperature

Table 3.7. List of variables considered for the analysis of ICCJ site

4. Approach to the analysis

The approach to the analysis of the different sites consists on defining and designing the energetical evaluation of the sites in order to reach conclusions about the performance of the actors involved in the absorption cooling plants operation, and compare them between different sites and different operating conditions.

In the approach to the analysis, the actors included in the analysis have been selected among all the actors involved in the operation of the absorption cooling plants. Also, in order to compare between different operating modes, some control strategies applied to the operation of the plants have been selected for this evaluation among all the control strategies that exist. These strategies are going to be explained further in this chapter.

In order to select the time periods where each control strategy is active or non-active for each site, the behaviour of the variables involved in the strategies will be analysed since the beginning of 2016 until June 2017 and plotted.

4.1. Actors to be analysed

In the absorption chiller cooling plants, the part that holds the most of the power consumption is the cooling water circuit, with values between 80% and 90% of the electrical consumption. For that reason, special focus will be put on the two main actors of the cooling circuit: the cooling water pump and the dry cooler, if installed.

The other water circuit of critical importance to the system is the chilled water circuit, which is the one responsible to deliver the desired chilled cooling capacity to the customer. Therefore, the chilled water pump will also be evaluated.

The absorption and compression chiller(s) are also included in the energetical analysis. Their performance under certain operation conditions will be evaluated.

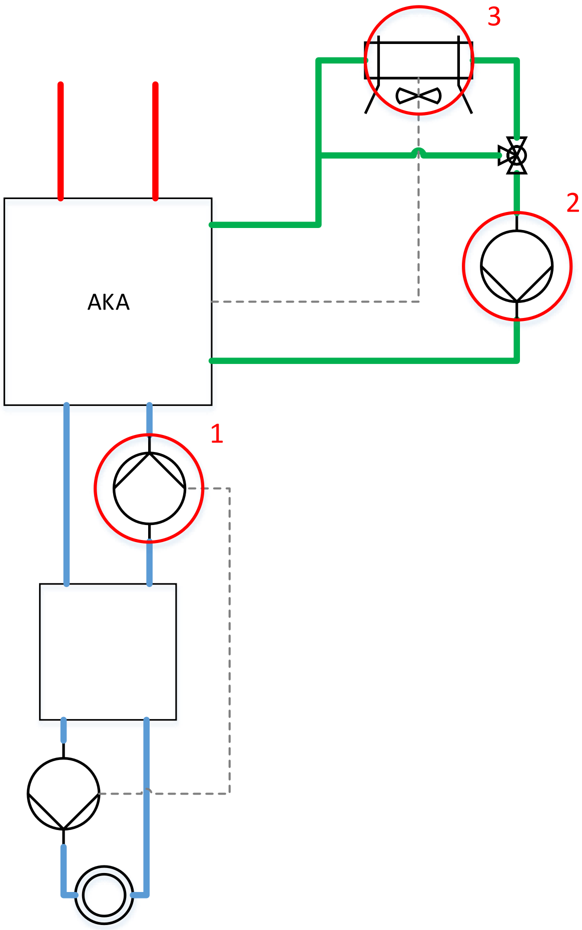


Figure 4.1. Scheme of the agents to be evaluated and location of the strategies - Visio

4.2. Extended Control strategies

There are some control strategies to regulate the behaviour of some variables of the system, therefore some actors involved in the operation. The strategies considered in this thesis are three: one involving the volume flow at chilled water pump, another involving the volume flow at cooling water pump, and the third one involving the temperature at the outlet of the dry cooler. See Figure 4.1.

Strategy A. Volume flow control of chilled water pump

The target of this strategy is to operate the chilled water circuit pump at a speed that maintains a volume flow equal to the volume flow of the water network at the consumer end. If the strategy is not activated, the pump speed remains constant, and so does the volume flow in the chilled water circuit.

Each control circuit has a digital signal bit type for activating the strategy control in general. For the chilled water pump control, the variable that contains this binary signal is *Modbus_V_0Ex_1_dyn_ActStrategy.* As there are several control strategies for this circuit, the variable *Modbus_V_0Ex_1_dyn_strategy* indicates which control strategy is set.

Digital variable	**Value**	**Meaning**
Modbus_V_0Ex_1_dyn_ActStrategy	0	No control strategy active on chilled water pump
	1	Control strategy active on chilled water pump
Modbus_V_0Ex_1_dyn_strategy	0	Strategy A set. *V_0Ex_1_set* is function of *V_0Vx*

Table 4.1. Explanation of digital variables for control strategies on chilled water pump

In some sites, the evolution of these digital variables is not stored as data; therefore the status of the control strategy cannot be determined by analysing these variables. In this case, the physical variables of the system involved in the strategy have to be analysed in order to find whether the strategies are active or not.

These variables are the actual volume flow of water in the chilled water circuit *V_0Ex_1*, the set value for the volume flow in the chilled water circuit *V_0Ex_1_set* and the actual volume flow of water in the chilled water distribution network on the consumer's side *V_0Vx*[1].

When the strategy is not active, it can be seen that the value of *V_0Ex_1_set* remains constant or changes on a stepped way, as manually changed. Then, the value of *V_0Ex_1* oscillates around the value of *V_0Ex_1_set*, with a constant trend. When the strategy is active, the value of *V_0Ex_1_set* follows the trend described by *V_0Vx*, and so does the value of *V_0Ex_1*. This can be seen in Figure 4.2.

[1] The nomenclature of the variables can change slightly depending on the site.

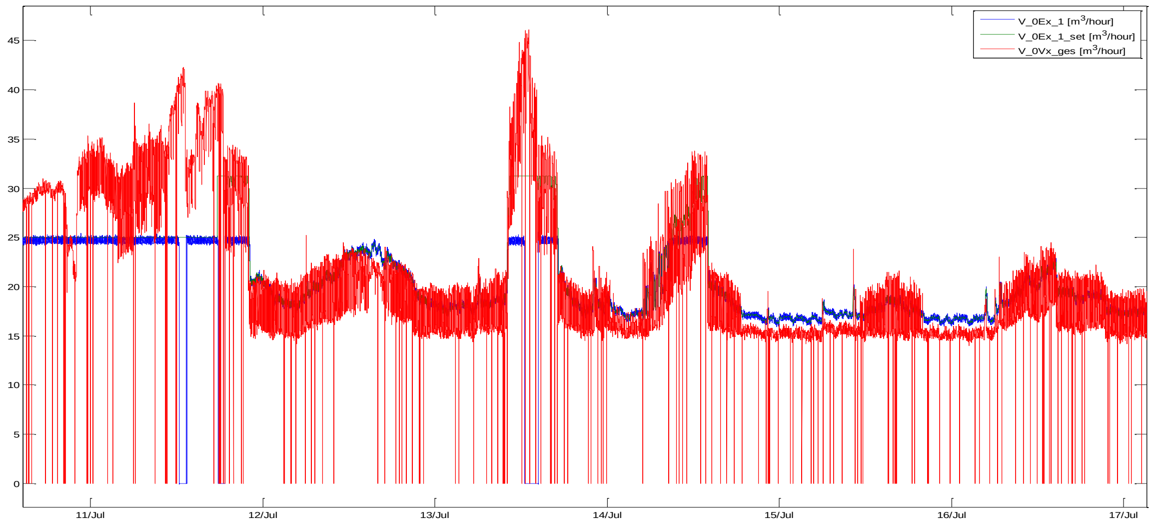


Figure 4.2. Evolution of V_0Ex_1 (blue), V_0Ex_1_set (green) and V_0Vx (red) al in m3/hour - Matlab

Strategy B. Volume flow control of cooling water pump

The target of this strategy is to operate the cooling water circuit pump at a speed that maintains a volume flow that ensures a constant temperature difference between absorber inlet and condenser outlet (dt for cooling water at inlet/outlet of the AKA). If the strategy is not activated, the pump speed remains constant, and so does the volume flow in the chilled water circuit and the dt at inlet/outlet of the AKA is not constant anymore.

For the cooling water pump control, the variable that contains the binary signal for strategy active / non-active is *Modbus_V_1Qx_1_dyn_ActStrategy.* The variable that indicates which control strategy is set on the cooling water pump is *Modbus_V_1Qx_1_dyn_strategy.*

Digital variable	Value	Meaning
Modbus_V_1Qx_1_dyn_ActStrategy	0	No control strategy active on cooling water pump
	1	Control strategy active on cooling water pump
Modbus_V_1Qx_1_dyn_strategy	2	Strategy B set. *V_1Qx_set* is function of *dt(t_1Ai_1, t_1Co_1)*

Table 4.2. Explanation of digital variables for control strategies on cooling water pump

The physical variables involved in this strategy are the actual volume flow of water in the cooling water circuit *V_1Qx_1*, the set value for the volume flow in the cooling water circuit *V_1Qx_1_set*, the temperature at the inlet of the absorber *t_1Ai_1* and the outlet temperature of the condenser *t_1Co_1*[2].

[2] Some of the sites do not have the variable *t_1Co_1*. In this case, the variable taken into account

When the strategy is not active, it can be seen that the value of *V_1Qx_1_set* remains constant or changes on a stepped way, as manually changed. Then, the value of *V_1Qx_1* oscillates around the value of *V_1Qx_1_set*, with a constant trend. The difference between the values of *t_1Ai_1* and *t_1Co_1* does not remain constant. See Figure 4.3.

When the strategy is active, the value of *V_1Qx_1_set* changes in a soft way and so does the value of *V_1Qx_1*. It can also be observed that the difference of values of *t_1Ai_1* and *t_1Co_1* remains constant. See Figure 4.4.

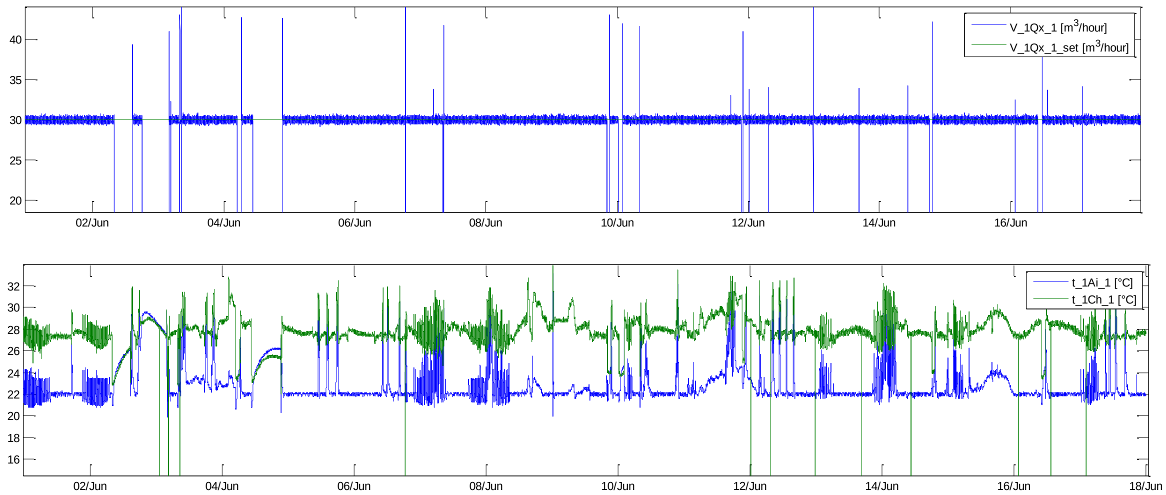


Figure 4.3. (top) Evolution of V_1Qx_1 and V_1Qx_1_set in m³/hour. (bottom) Evolution of t_1Ai_1 and t_1Ch_1 in ºC. Strategy B not active - Matlab

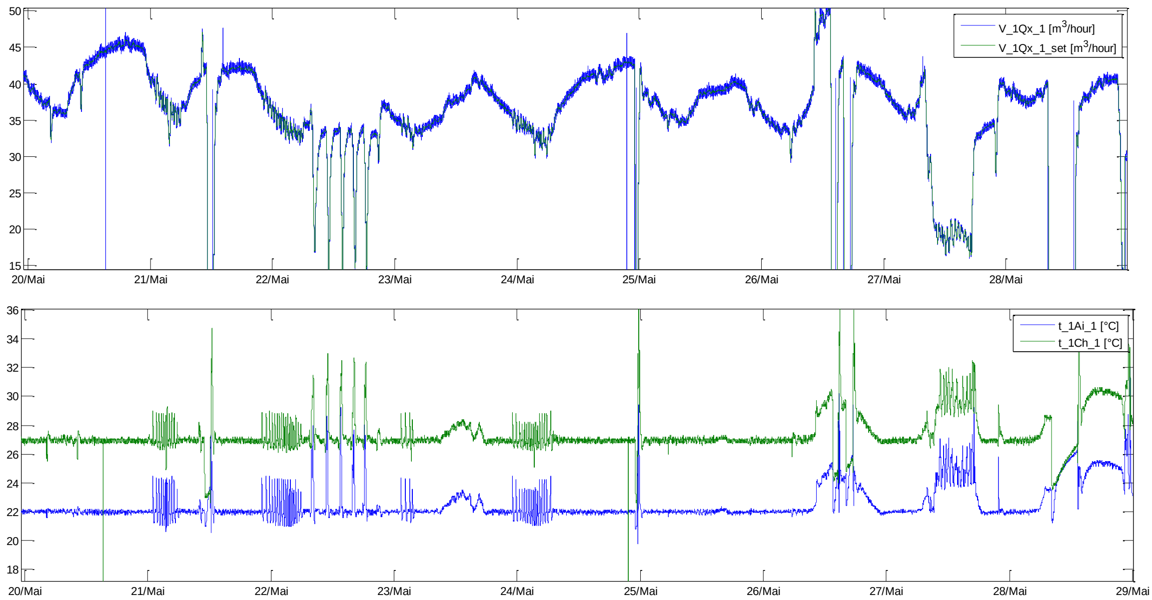


Figure 4.4. (top) Evolution of V_1Qx_1 and V_1Qx_1_set in m3/hour. (bottom) Evolution of t_1Ai_1 and t_1Ch_1 in ºC. Strategy B active - Matlab

as condenser outlet is *t_1Ch_1*.

Strategy C. Variable set point temperature at outlet of the dry cooler

This strategy determines that the set temperature at the outlet of the dry cooler *t_1Ko_1_set* has to be function of the ambient temperature *t_7Ki_1* [3] as the following equation shows:

$$t\_1Ko\_1\_set = t\_7Ki\_1 + offset$$

Where the offset can be positive or negative and it is the variation of the water temperature due to the distance between the dry cooler and the absorber.

If the strategy is not activated, the set temperature at the outlet of the dry cooler *t_1Ko_set* is a constant value or a function of the set temperature at the inlet of the absorber *t_1Ai_set* as the following equation shows:

$$t\_1Ko\_1\_set = t\_1Ai\_1\_set + offset$$

For the dry cooler control, the variable that contains the binary signal for strategy active / non-active is *Modbus_t_1Ko_1_dyn_ActStrategy.* The variable that indicates which control strategy is set on the dry cooler is *Modbus_t_1Ko_1_dyn_strategy.*

Digital variable	Value	Meaning
Modbus_t_1Ko_1_dyn_ActStrategy	0	No control strategy active on dry cooler
	1	Control strategy active on dry cooler
Modbus_t_1Ko_1_dyn_strategy	0	Strategy C set. *t_1Ko_set* is function of *t_7Ki_1*

Table 4.3. Explanation of digital variables for control strategies on the dry cooler

The physical variables involved in this strategy are the ambient temperature *t_7Ki_1,* the actual temperature at the outlet of the dry cooler *t_1Ko_1* and the set temperature at the outlet of the dry cooler *t_1Ko_1_set.*

When the strategy is not active, it can be seen that the value of *t_1Ko_1_set* remains constant or has a fluctuation dependent of the set absorber inlet temperature *t_1Ai_1_set*. When the strategy is active, the value of *t_1Ko_1_set* changes according to the variation of *t_7Ki_1* with an offset. See Figure 4.5.

[3] Not all sites use the nomenclature *t_7Ki_1.* Some of them use the nomenclature *t_7Ki_M.*

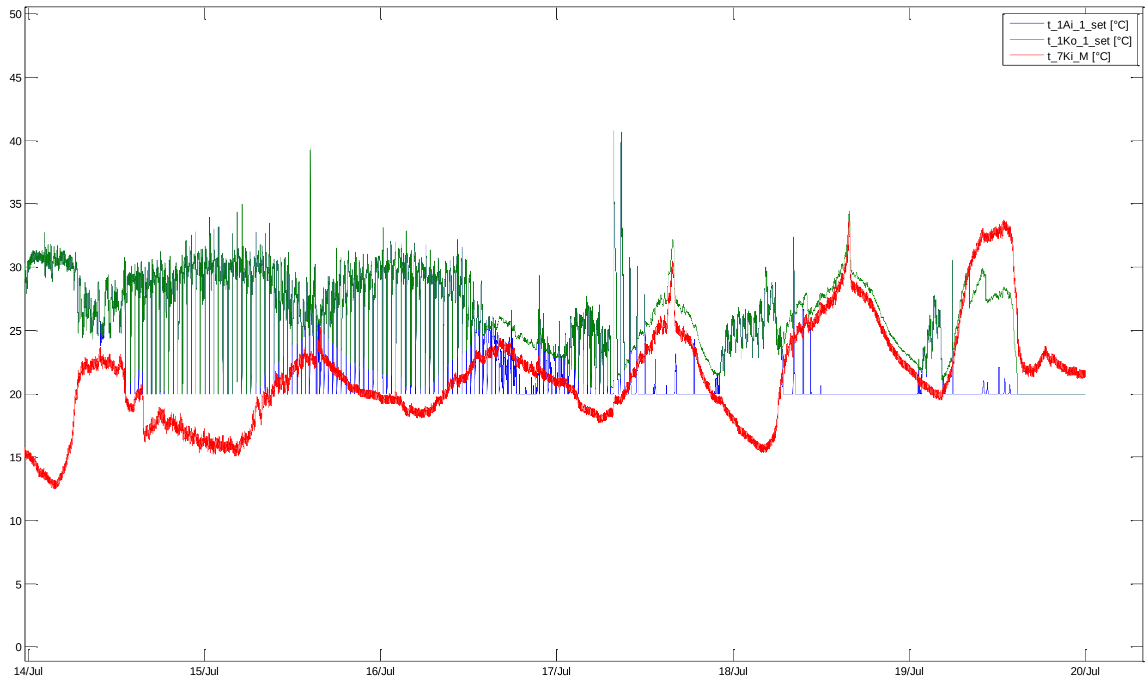


Figure 4.5. Evolution of t_1Ai_1_set (blue), t_1Ko_1_set (green) and t_7Ki_M (red) al in ºC - Matlab

4.3. Parameters to be evaluated

The energetical evaluation of the absorption chiller will be done through some parameters, which are the output of the data handling process.

In a first stage of the evaluation, as a previous overview, the cooling capacity of each cooling device of the site will be seen. In addition, the cooling demand of the consumers or cooling load of the plant will be seen, so it can be compared to the cooling capacity of each device in order to see which proportion of cooling load supports every device.

Cooling capacity

The cooling capacity is the cooling power that is able to provide the absorption chiller, compression chiller or free heat exchanger in the period when the analysis is done. The equation for this parameter is the following:

$$Q = \dot{V} \cdot \rho \cdot Cp \cdot (t_{chill,in} - t_{chill,out})$$

Where $\dot{V}$ is the volume flow of chilled water, in m^3/h, that flows through the device, $t_{chill,in}$ is the temperature of the ambient water, in ºC, that enters the cooling device, and $t_{chill,out}$ is the temperature of the chilled water, in ºC, that comes from the cooling device.

Cooling load

The cooling load or cooling demand is the cooling power that is demanded from the customers in the period then the analysis is done. The equation for this parameter is the following:

$$Q_{cons} = \dot{V}_{cons} \cdot \rho \cdot Cp \cdot (t_{chill,cold} - t_{chill,hot})$$

Where $\dot{V}_{cons}$ is the volume flow of chilled water in, m^3/h, that flows through the chilled water distribution network, $t_{chill,cold}$ is the temperature of the chilled water in, ºC, that arrives to the customer, and $t_{chill,hot}$ is the temperature of the water in, ºC, that returns from the customers to the absorption cooling plant.

The variables shown in the equations above are listed in the Table 4.4.

Parameter	**Symbol**	**Units**	**Object of evaluation**
Cooling capacity	Q_{AKA}	kW	Absorption chiller
	Q_{KKA}		Compression chiller
	Q_{FH}		Free heat exchanger
Cooling load	Q_{cons}	kW	Customer(s)

Table 4.4. List of parameters to be evaluated in the first overview of the analysis

In the evaluation itself, the parameters evaluated are shown in thermal efficiency, coefficient of performance (COP), specific electrical consumption and specific primary energy consumption of the. These parameters are listed in the Table 4.5.

Parameter	**Symbol**	**Units**	**Object of evaluation**
Thermal efficiency	η_{th}	-	Absorption chiller
Specific electrical consumption	SC_{el}	-	Chilled water pump
			Cooling water pump
			Dry cooler
Specific primary energy consumption	$SC_{P.E.}$	-	Chilled water pump
			Cooling water pump
			Dry cooler

Table 4.5. List of parameters to be evaluated in the energetical evaluation

Thermal efficiency

The thermal efficiency is the dimensionless ratio between the useful output of a device and the input, in energy terms. For thermal systems, the input, $E_{th,in}$, is heat, and the output is mechanical work, W_{out}, or heat, $E_{th,out}$.

In this case, the heat input is the driving heat provided by the hot water circuit, $E_{driving}$, and the output is the heat removed to the chilled water, $E_{cooling}$, as shown in the next equation:

$$\eta_{th} = \frac{E_{cooling}\ [kWh_{cooling}]}{E_{driving}\ [kWh_{driving\ heat}]}$$

From the first law of thermodynamics, the energy output cannot exceed the input, so the value of η_{th} is always comprised between o and 1, not being able to reach the value of 1.

Specific electrical consumption

The specific electrical consumption is defined as the electrical energy consumption of a certain component of the system per unit of cooling energy delivered to the customer, as seen in the next equation:

$$SC_{el} = \frac{E_{el}\ [kWh_{el}]}{E_{cooling}\ [kWh_{cooling}]}$$

The goal of evaluating the specific electrical consumption is to be able to determine which components require more electrical resources than others in the different cases proposed.

Specific primary energy consumption

The specific primary energy consumption is defined as the primary energy consumption of a certain component of the system per unit of cooling energy delivered to the customer. In this case, the primary energy is the heating energy provided by the hot driving water from the district heating network or the solar heating installations plus the primary energy needed to produce the electricity consumed by the setup elements. The calculation for this parameter is shown in the next equation:

$$SC_{P.E.} = \frac{PE_{driving} + \sum_{devices} PE_{el}\ \ [kWh_{P.E.}]}{E_{cooling}\ [kWh_{cooling}]}$$

The goal of evaluating the specific primary energy consumption is to be able to determine which components require more resources in terms of primary energy than others in the different cases proposed.

Part II. Energetical analysis of the absorption chiller cooling plants in test fields

In this part will take part the time period selection for the analysis, the data handling and the energetical evaluation for the sites. The results obtained and the conclusions reached in this thesis will be explained.

All the data handling and analysis has been done using *Matlab*. The statistical data analysis has been done using *Minitab statistical software*.

5. Preliminary overview of the sites operation

5.1. Operating times

A preliminary determination of the operating times of the absorption chillers has been made.

This is useful, for when the time frames for the analysis have to be searched, to know which days was every absorption chiller operative and when they were not.

The determination has been made by plotting the cooling capacity delivered by the chillers, *Q_0Ex_1,* along the years 2016 and 2017. The plots can be found i

.

Site	AKA operating times 2016 and 2017
KFWK	**2016:** All 2016 except for few days in late May and early December. **2017:** All 2017 until June except for few days in early January and the second half of April.
ESTW	**2016:** Some days in January and February, the second half of March and the first half of April, entirely from May to end of October and some days in November and December. **2017:** Only few days in February and from July the 11th until the 20th.
LVRZ	**2016:** Only during the cooling season, from April to October. **2017:** Some days in January, February and March, and entirely with some non-operating punctual days during the cooling season, from April to July.
HENK	**2016:** All 2016. **2017:** All 2017 until June.
BKSP	**2016:** Only from July to October. **2017:** Only from last week of May until June.
SEHC	**2016:** From January until July and from late October. **2017:** All 2017 until June.
ICCJ	**2017:** Punctual periods of few hours in days from May to July.
RCCJ	**2016:** Punctual periods of few hours in days from October to early November. **2017:** Punctual periods of few hours in days from half May until July.

Table 5.1. Summary of the operating times in 2016 and 2017 for the sites

5.2. Identification of the active strategies

For this, the digital variables responsible for the strategies in every site have been analysed and plotted for the years 2016 and 2017 in order to find time frames to evaluate in any strategy combination for every site.

Not all sites display the digital variables as treatable data. In these cases, the identification of the periods has been done by analysing and plotting the physical variables involved in each strategy for 2016 and 2017. Some strategy combinations in some sites have not been found active.

	Strategy A	Strategy B	Strategy A + B	Strategy C
$\mathbf{KFWK_H}$	X	X	X	Non existent
$\mathbf{ESTW_B}$	X	-	X	X
$\mathbf{LVRZ_B}$	Non existent	-	-	-
$\mathbf{HENK_H}$	X	-	X	-
$\mathbf{SEHC_H}$	-	-	-	-
$\mathbf{ICCJ_B}$	-	X	-	-

Table 5.2. Summary table of the activated strategies for every site. The subscript in every site name stands for the German name of the chiller type: H for Bumblebee type (Hummel) and B for Bee type (Biene)

5.3. Setting of the periods for the evaluations

Knowing the operating times of each site and which strategies have been activated, the periods to evaluate are going to be selected. In order to compare between strategies in a same site, a reference period when any strategy is active has to be selected.

All compared periods must have similar environmental characteristics. The next table summarizes the selection of the periods.

For KFWK, where the ambient temperature is not a so important parameter, because it doesn't use a dry cooler system, so the operation of the plant is not dependent on the ambient temperature. Instead of it, the cooling capacity provided by the absorption chiller has been taken into account. Compared scenarios must have similar cooling capacity values.

KFWK		
Reference period	**6 days (24-29 June 2016)**	
Day	**Ambient temperature (ºC)**	**Cooling power (kW)**
24 Jun	26,17	53,93
25 Jun	21,2	55
26 Jun	20,11	35,5
27 Jun	19,02	25,08
28 Jun	19,93	26,22
29 Jun	21,4	30,68
Mean	21,31	37,74
Strategy A active	**11 days (20-30 August 2016)**	
Day	**Ambient temperature (ºC)**	**Cooling power (kW)**
20 Aug	21,68	30,98
21 Aug	19,46	31,32
22 Aug	19,76	30,77
23 Aug	22,17	29,24
24 Aug	24,64	40,34
25 Aug	25,98	47,73
26 Aug	26,34	52,25
27 Aug	27,55	48,26
28 Aug	25,87	24,15
29 Aug	22,31	37,67
30 Aug	20,53	33,95
Mean	23,29	36,97
Strategies A B active	**5 days (17-19 and 28-29 May 2017)**	
Day	**Ambient temperature (ºC)**	**Cooling power (kW)**
17 May	22,77	32,97
18 May	22,63	29,95
19 May	17,91	27,41
28 May	23,88	45,47
Mean	22,18	33,95

Table 5.3. Summary of analysis periods for KFWK

For the analysis of ESTW site, two reference periods will have to be set. One period in winter time for working with strategies A and B, and another reference period in summer time for working with strategies A and C.

This is due to the fact that strategy B has only been active in winter periods, while strategy C has only been recently activated, during summer time.

ESTW	
Reference period 1	**3 days (26-28 January 2016)**
Day	**Ambient temperature (ºC)**
26 Jan	11,19
27 Jan	11,26
28 Jan	7,82
Mean	10,09
Strategy A active	**3 days (13-15 December 2016)**
Day	**Ambient temperature (ºC)**
13 Dec	7,91
14 Dec	8,88
15 Dec	8,72
Mean	8,50
Strategies A B active	**6 days (3-5 and 16-18 February 2017)**
Day	**Ambient temperature (ºC)**
3 Feb	10,19
4 Feb	7,80
5 Feb	7,21
16 Feb	10,87
17 Feb	8,08
18 Feb	8,04
Mean	8,70

Table 5.4. Summary of analysis periods for ESTW strategies A and B

The analysis of the strategy C in ESTW will have to be done in a different way. The behaviour of the control strategy has been seen that is different from the other two strategies. For the periods when the strategy is activated in the controller, it is only active in the dry cooler temperature control for periods of few hours. Instead of entire groups of days, only groups of hours will be considered for the analysis.

ESTW	
Reference period 2	**3 days (20-22 July 2016)**
Time	**Ambient temperature (ºC)**
20 Jul 7h – 18h	33,38
21 Jul 8h – 18h	29,31
22 Jul 12 h- 19h	27,53
Mean	30,07
Strategies A C active	**4 days (16-19 July 2017)**
Time	**Ambient temperature (ºC)**
16 Jul 16h - 21h	22,86
17 Jul 10h - 22h	23,49

18 Jul 7h - 24h	25,75
19 Jul 5h - 8h	24,67
Mean	24,19

Table 5.5. Summary of analysis periods for ESTW strategies A and C

The data has been treated in a way that in the whole duration of few hours, the every 5 seconds datapoints have been grouped in a single-mean value for every minute.

HENK	
Reference period	**7 days (1-7 June 2017)**
Day	**Ambient temperature (ºC)**
1 Jun	19,79
2 Jun	20,74
3 Jun	24,55
4 Jun	19,82
5 Jun	21,49
6 Jun	20,92
7 Jun	17,4
Mean	20,67
Strategy A active	**6 days (12-17 July 2016)**
Day	**Ambient temperature (ºC)**
12 Jul	23,4
13 Jul	20,64
14 Jul	17,88
15 Jul	17,79
16 Jul	20,3
17 Jul	22,85
Mean	20,47666667
Strategies A B active	**8 days (21-28 May 2017)**
Day	**Ambient temperature (ºC)**
21 May	19,23
22 May	20,54
23 May	21,51
24 May	17,59
25 May	18,31
26 May	20,79
27 May	24,48
28 May	25,04
Mean	20,94

Table 5.6. Summary of analysis periods for HENK

ICCJ	
Reference period	**7 days (9-11 and 13-16 May 2017)**
Day	**Ambient temperature (ºC)**
9 May	33,69
10 May	33,97
11 May	-
13 May	-
14 May	-
15 May	-
16 May	-
Mean	33,83
Strategy B active	**9 days (11-15 and 17-20 June 2017)**
Day	**Ambient temperature (ºC)**
11 Jun	28,39
12 Jun	28,10
13 Jun	28,11
14 Jun	29,42
15 Jun	29,56
17 Jun	29,85
18 Jun	30,55
19 Jun	31,15
20 Jun	27,07
Mean	29,13

Table 5.7. Summary of analysis periods for ICCJ

6. Evaluation of the sites

6.1. Thermal efficiency

Thermal efficiency of the absorption chillers has been calculated for KFWK, ESTW and HENK sites in each scenario and during the period selected in the previous chapter. The results obtained are shown and commented below.

KFWK

Scenario	$E_{cooling}$ (kWh)	$E_{driving}$ (kWh)	η_{th}
Reference	614,35	955,41	0,6422
Strategy A active	878,98	1387,81	0,6336
Strategy B active	532,03	888,39	0,5934
Strategies A and B active	805,09	1270,75	0,6300

Table 6.1. Summary of thermal efficiency for KFWK

ESTW

Scenario	$E_{cooling}$ (kWh)	$E_{driving}$ (kWh)	η_{th}
Reference 1	265,55	607,81	0,4367
Strategy A active	299,98	657,29	0,4563
Strategies A and B active	281,28	605,51	0,4565
	$Q_{cooling}$ (kW)	**$Q_{driving}$ (kW)**	**η_{th}**
Reference 2	14,08	28,44	0,4915
Strategies A and C active	17,12	51,95	0,3385

Table 6.2. Summary of thermal efficiency for ESTW

HENK

Scenario	$E_{cooling}$ (kWh)	$E_{driving}$ (kWh)	η_{th}
Reference	1481,31	1939,74	0,7615
Strategy A active	1636,75	2142,15	0,7631
Strategies A and B active	1983,96	2539,24	0,7805

Table 6.3. Summary of thermal efficiency for HENK

ICCJ

Scenario	$E_{cooling}$ (kWh)	$E_{driving}$ (kWh)	η_{th}
Reference	131,34	239,79	0,5430
Strategy B active	110,04	205,84	0,5301

Table 6.4. Summary of thermal efficiency for ICCJ

In the four sites evaluated, it has been seen that whether strategy is activated or not does not affect the thermal efficiency of the absorption chiller in a significant way.

Except in the case of the ESTW site, where the thermal efficiency of the absorption chiller decreases around a 15% when strategy C is active respect the reference case.

6.2. Specific electrical consumption

Sites with active strategies

Specific electrical consumptions have been calculated for KFWK, ESTW and HENK sites in each scenario and during the period selected in the previous chapter. The results obtained are shown and commented below.

The complete results obtained for every day of each scenario can be found in Appendix C. Specific consumptions.

KFWK

This site has a particularity: strategy A is only active when there is a high cooling demand from the consumers' network. This can be seen in the graphic identification of the active strategies. See chapter 5.2. Strategy A is not active until the volume flow of the consumers network surpasses a set threshold, then strategy is active until this volume flow goes below this threshold again. See Figure 6.1.

This implies that the analysis of active strategy A is only done under conditions of high customers network volume flow, which means high cooling demand. This applies also to the scenario of both strategies A and B active.

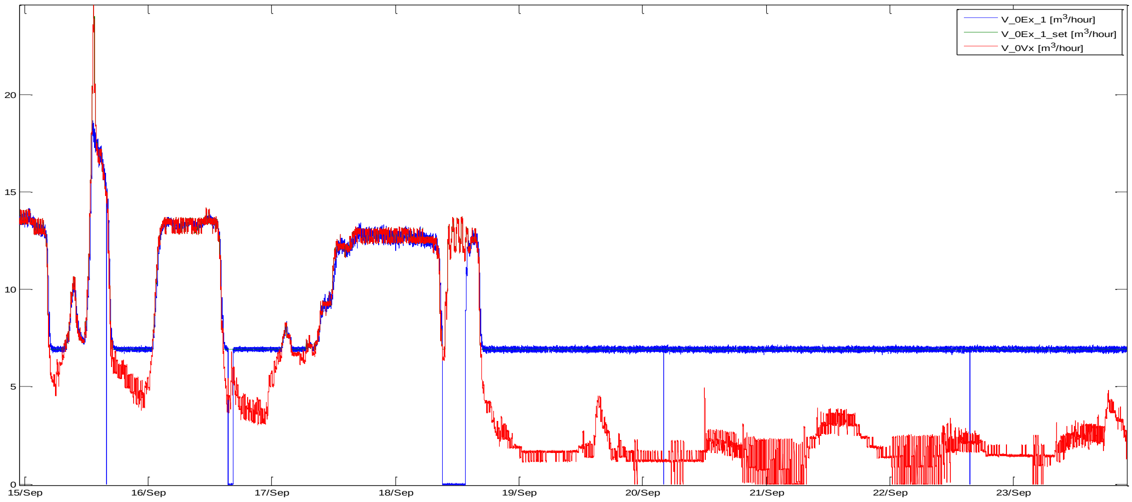


Figure 6.1. Evolution of V_0Ex_1 (blue), V_0Ex_1_set (green) and V_0Vx (red) al in m3/hour for KFWK – Matlab

Below, the values of specific electrical consumption of chilled, cooling and hot water pumps are shown in and plotted in **¡Error! No se encuentra el origen de la referencia.**, grouped in each scenario, in order to compare and discuss these values.

Scenario	SC_{el} chilled pump	SC_{el} cooling pump	SC_{el} hot pump
Reference	0,0040	0,0068	0,0152
Strategy A active	0,0073	0,0078	0,0457
Strategies A and B active	0,0182	0,0061	0,0399

Table 6.5. Summary of specific electrical consumptions for KFWK

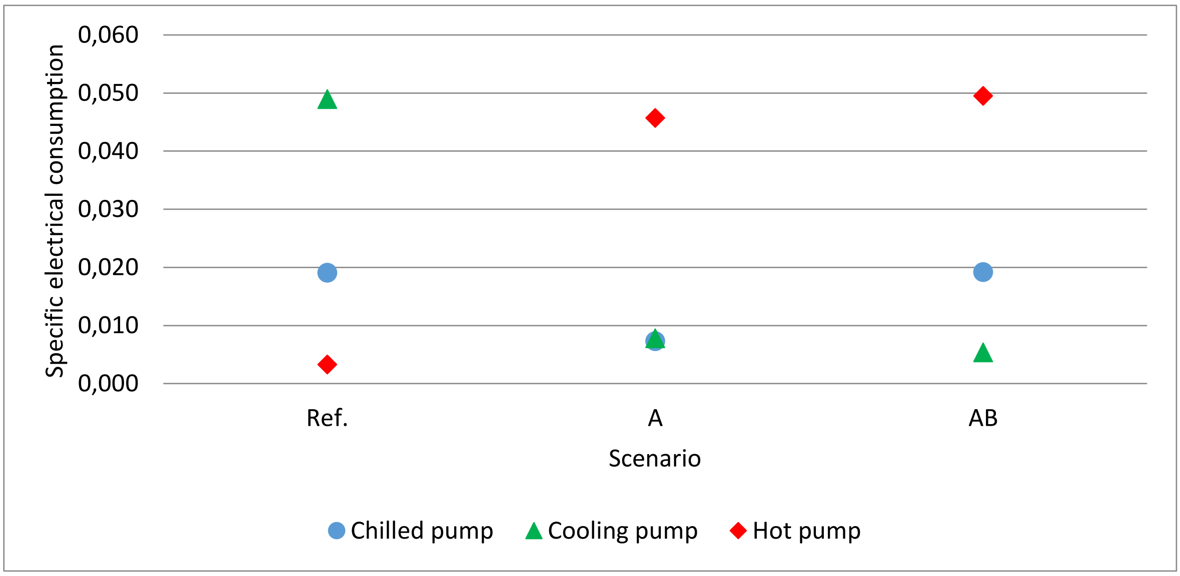


Figure 6.2. Specific electrical consumption of the actors according to the scenario for KFWK - Excel

Analysing the results and the plots it can be seen that the specific electrical consumption of the chilled water pump decreases significantly when strategy A is active alone respect the reference scenario. The value of specific electrical consumption remains constant when strategies A and B are active together respect the reference scenario.

The specific electrical consumption of the cooling water pump decreases notably from reference case to cases where strategy A alone and strategies A and B are active. This is due to the fact that in the reference scenario, the set volume flow for the cooling pump was 40 m^3/h and in the scenario A the set value changes from 15 to 18 and 20 m^3/h, values far from the 40 m^3/h that the reference scenario has.

The hot water pump shows an increase respect the reference scenario when strategy A is active and when both strategies A and B are active. This notable increase of specific consumption of hot water pump is due to the fact that the hot driving water circuit in this site has a second pump that drives water from the return district heating pipe to the inlet of the chiller driving hot water circuit. These higher values can be explained because this second pump is active.

ESTW

Scenario	SC_{el} chilled pump	SC_{el} cooling pump	SC_{el} dry cooler
Reference 1	0,0581	0,1308	0,0197
Strategy A active	0,0173	0,0985	0,0197
Strategies A and B	0,0153	0,0193	0,0167
Reference 2	0,0256	0,1208	0,4026
Strategies A and C	0,0273	0,1074	0,2099

Table 6.6. Summary of specific electrical consumptions for ESTW

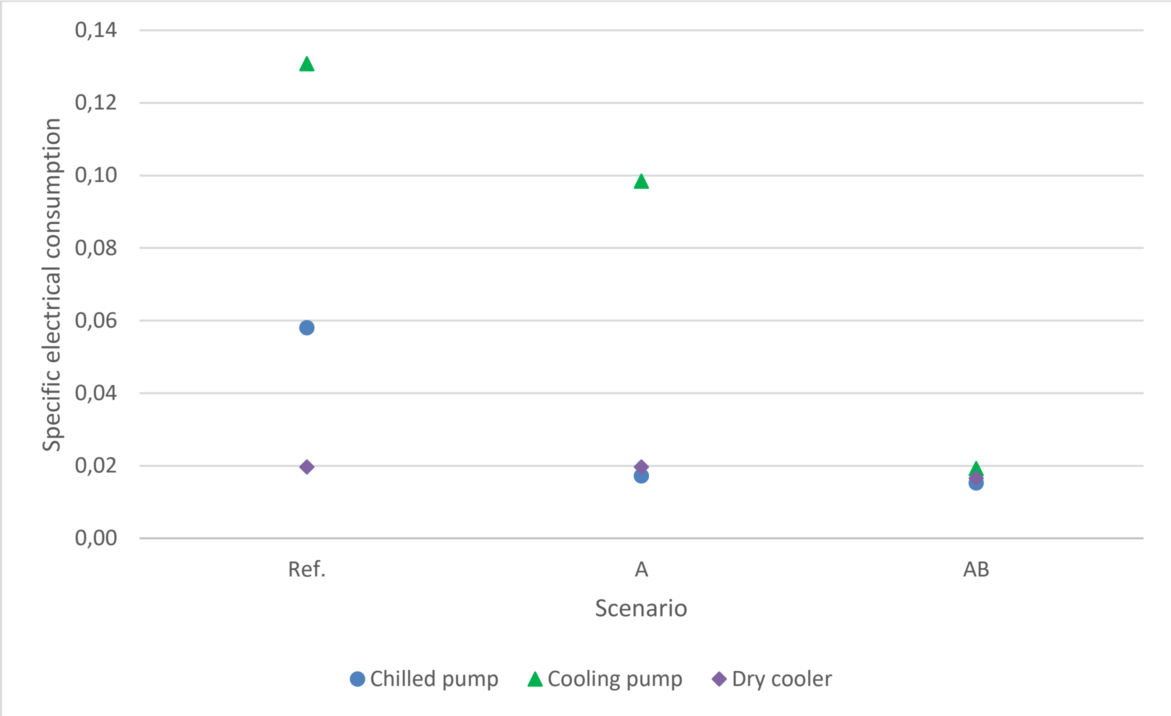


Figure 6.3. Specific electrical consumption of the evaluated actors according to the scenario for ESTW in wintertime - Excel

Analysing the previous plot and table, it can be seen that the specific electrical consumption of the chilled water pump is reduced to one third when strategy A is active, alone or combined with strategy B.

The cooling water pump has its specific electrical consumption by around six times when strategy B is active respect from the reference period.

The values for the dry cooler remain constant, since any scenario involves strategy C which is the one controlling the operation of the dry cooler.

The following figure shows the comparison between the summertime reference scenario and the case where strategies A and C are active. In the reference scenario, days as hot as in the strategy C active scenario have been searched and that the set output temperature of the dry cooler was set below the value of the ambient temperature so the dry cooler had to work at capacity.

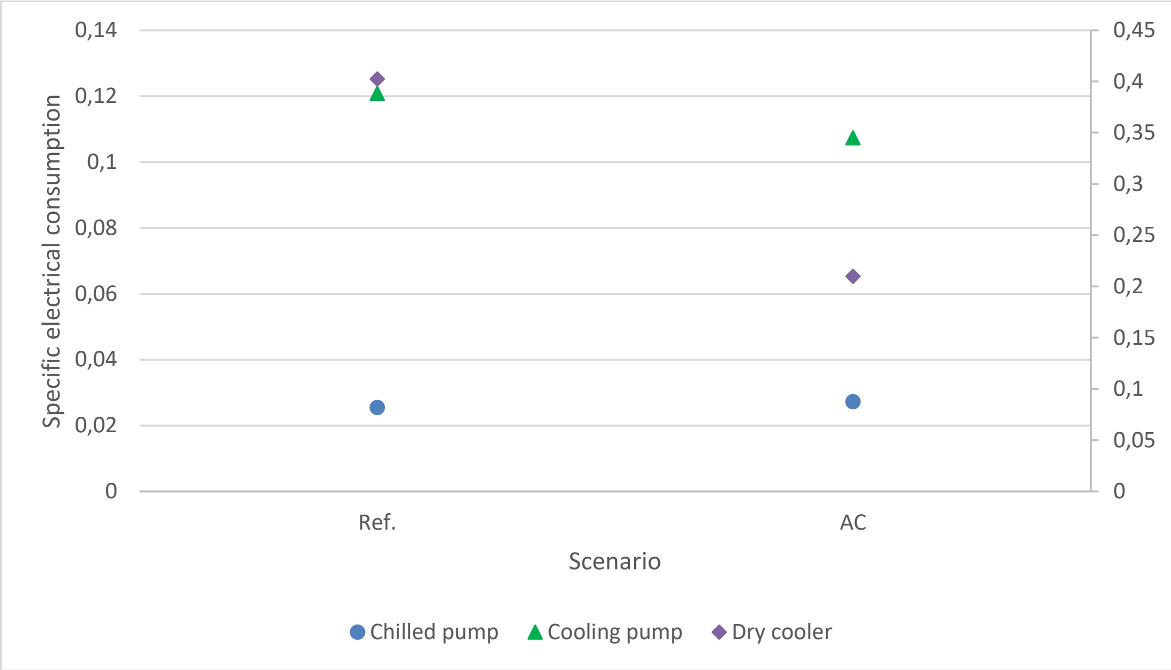


Figure 6.4. Specific electrical consumption of the evaluated actors according to the scenario for ESTW in summertime. The left vertical axis indicates the values of SCel for chilled and cooling pumps (blue and green respectively); while the right vertical axis indicates the values of SC_{el} for the dry cooler (purple). This is due to the difference between values - Excel

Specific electrical consumption of the chilled water circuit pump does not differ significantly from reference scenario to the scenario where strategies A and C are active. This is caused because in this analysis, the object to evaluate is the influence of strategy C on the system, and the reference scenario includes strategy A active.

The specific consumption of the cooling pump does not differ either significantly.

The dry cooler reduces in half its specific consumption when strategy C is active. This is caused by the fact that, when strategy C is not active on a hot day, and set temperature at the outlet of the dry cooler, *t_1Ko_1_set*, has a value below the curve of the ambient temperature, forces the dry cooler to work at 100% capacity to try to achieve the set temperature at the outlet. On the other hand, when strategy C is active, set outlet temperature forces the dry cooler to provide an outlet temperature that follows the curve pf ambient temperature, plus an offset, causing the dry cooler not to work at capacity all the time.

While doing the analysis of the specific electrical consumption of the dry cooler, it has been detected that its value depends completely on the ambient temperature. In order to quantify this dependence, SC_{el} dry cooler has been plotted in function of ambient temperature.

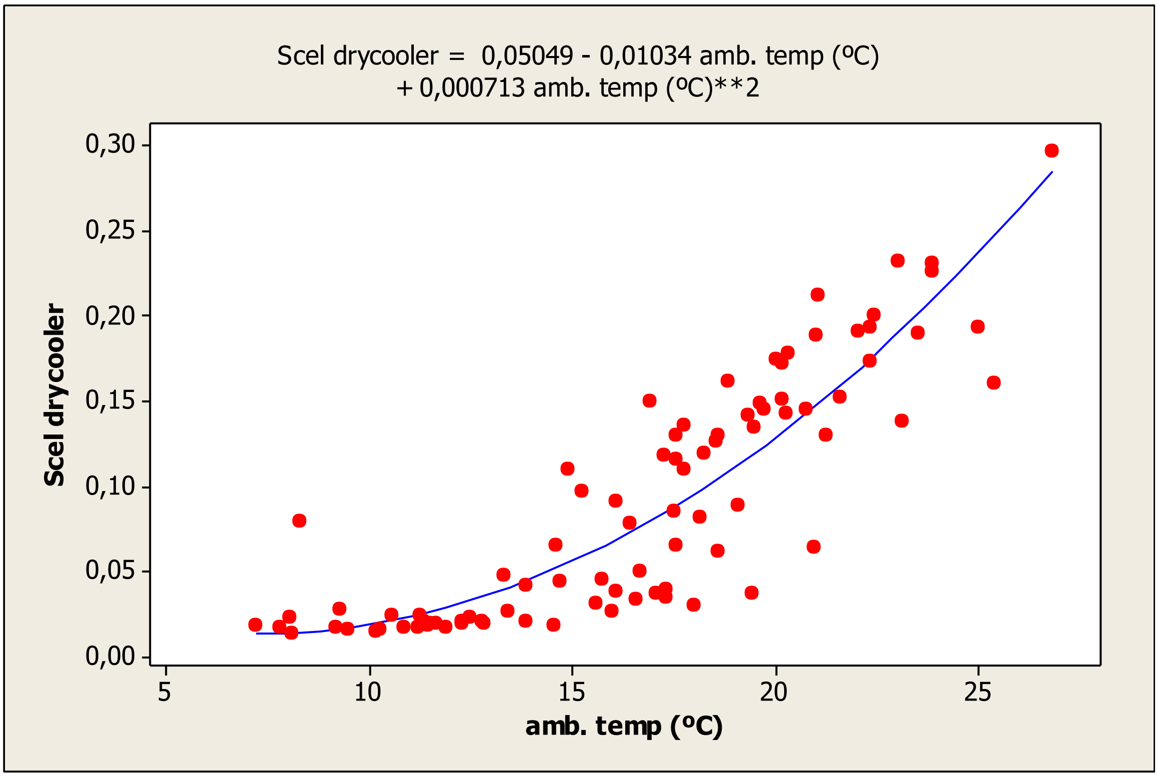


Figure 6.5. Quadratic regression for ambient temperature and dry cooler specific electrical consumption - Minitab

The Pearson correlation coefficient for these two parameters is 0,854 and the regression parameters are R^2 = 0,787 and the equation is the following:

$$SC_{el} = 0{,}0505 - 0{,}0103\,t + 0{,}0007\,t^2$$

HENK

Scenario	SC_{el} chilled pump	SC_{el} cooling pump	SC_{el} dry cooler
Reference	0,0133	0,0158	0,0891
Strategy A active	0,0080	0,0171	0,1115
Strategies A and B	0,0095	0,0231	0,0926

Table 6.7. Summary of specific electrical consumptions for HENK

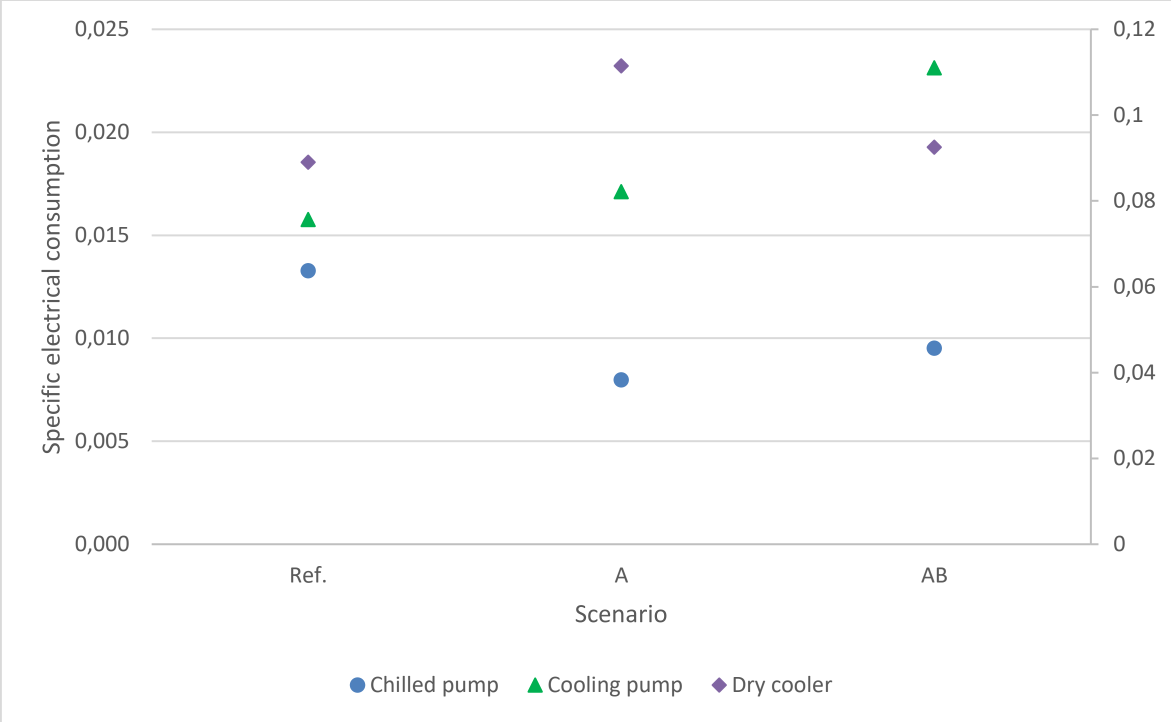


Figure 6.6. Specific electrical consumption of the evaluated actors according to the scenario for HENK. The left vertical axis indicates the values of SCel for chilled and cooling pumps (blue and green respectively); while the right vertical axis indicates the values of SC_{el} for the dry cooler (purple). This is due to the difference between values - Excel

The specific electrical consumption of the chilled water pump decreases when strategy A is active, while specific electrical consumption of cooling water pump increases when strategy B is active. This is due to the fact that when strategy B is inactive, the fixed set value for the volume flow of the cooling pump *V_1Qx_1_set* is 30 m^3/h, and when the strategy is active, the values for this volume flow oscillate between 35 and 45 m^3/h. This causes that, despite the strategy is active, the specific electrical consumption is higher.

ICCJ

Scenario	SC_{el} chilled pump	SC_{el} cooling pump	SC_{el} dry cooler
Reference	0,0127	0,0314	0,2556
Strategy B active	0,0199	0,0199	0,0801

Table 6.8. Summary of specific electrical consumptions for HENK

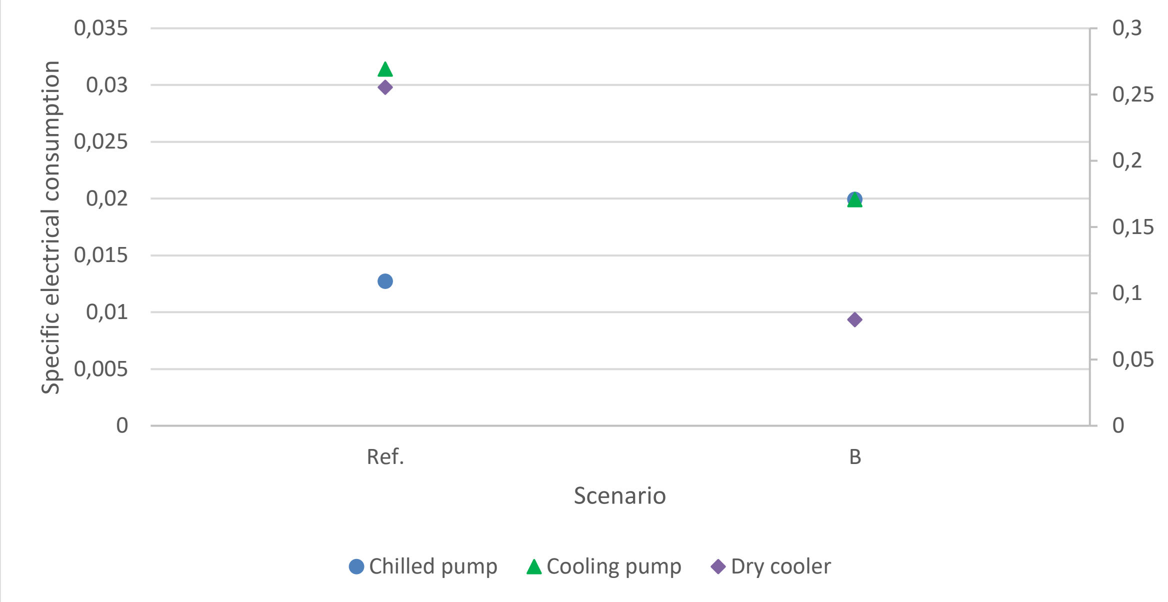


Figure 6.7. Specific electrical consumption of the evaluated actors according to the scenario for ICCJ. The left vertical axis indicates the values of SCel for chilled and cooling pumps (blue and green respectively); while the right vertical axis indicates the values of SC_{el} for the dry cooler (purple). This is due to the difference between values - Excel

Specific electrical consumption of the chilled water pump has increased slightly due to the fact that in the reference scenario, the set volume flow for this pump was 6,3 m^3/h, while in the scenario B, this set value for the pump volume flow was 8 m^3/h.

Specific electrical consumption of the cooling water pump has a decrease of one third when comparing the reference scenario and the scenario when the strategy B is active.

The noticeable decrease of the dry cooler specific consumption could be caused by the fact that during the reference period the set outlet temperature for the dry cooler is 31ºC and 32ºC, and for the B period, this value is always set to 33ºC, so a higher outlet temperature needed, a lower consumption of the dry cooler. When the ambient temperatures are low or moderate the activation of this strategy would be not necessary.

Sites without active strategies

For two sites where any strategy has been found to be active, LVRZ and SEHC, specific electrical consumptions have been plotted along the year in order to see which agents are influenced by the environmental conditions.

LVRZ

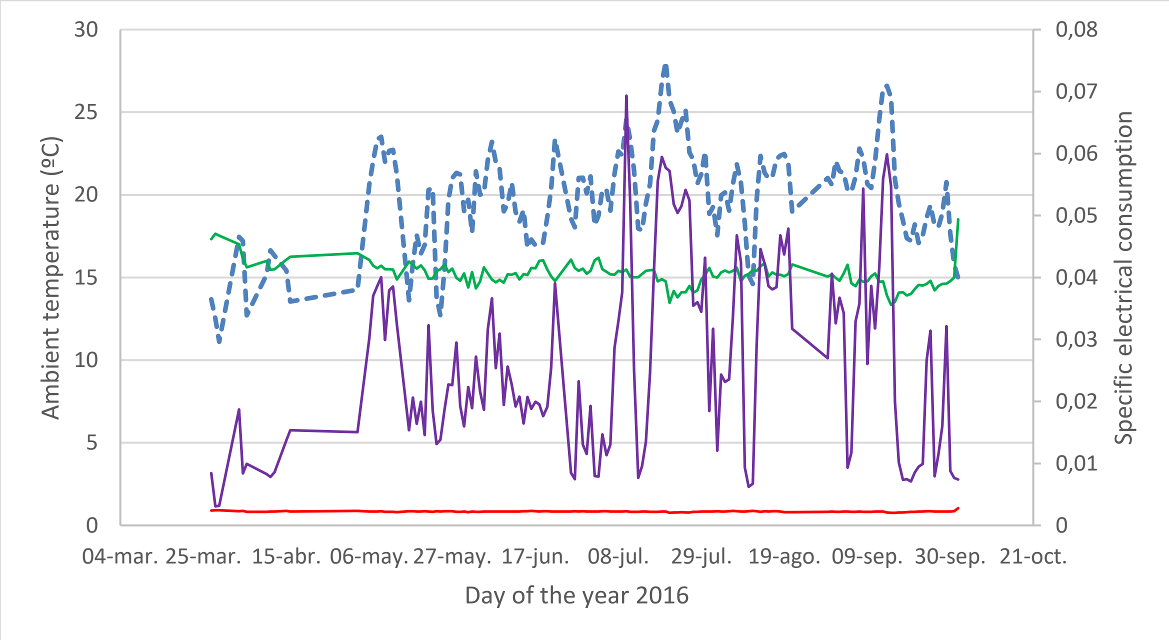


Figure 6.8. Evolution of ambient temperature (blue, discontinuous), SC_{el} of cooling circuit pump (green), SC_{el} of dry cooler (purple) and SC_{el} of hot circuit pump (red) during the operating hours of LVRZ in year 2016 - Excel

It can be seen that the specific electrical consumption of both cooling and hot circuit pumps do not depend on the ambient temperature. In addition, the specific electrical consumption of the hot circuit pump is significantly lower than the values of the other devices, so it can be considered negligible. At the same time, the specific electrical consumption of the dry cooler is completely dependent on the ambient temperature.

This correlation between the parameters can be numerically determined through the Pearson coefficient of correlation. (Minitab Inc. 2017) (Anon 2017)

Variable X	Variable Y	Pearson coefficient of correlation (ρ)
Ambient temperature	SC_{el} cooling pump	-0,524
Ambient temperature	SC_{el} dry cooler	0,832
Ambient temperature	SC_{el} hot pump	-0,486

Table 6.9. Pearson correlation analysis for LVRZ

The Pearson correlation analysis confirms that barely exists any correlation between the ambient temperature and the specific electrical consumption of both cooling and hot circuit pumps, and however it exists a direct correlation of 0,832 between the ambient temperature and the dry cooler specific consumption.

SEHC

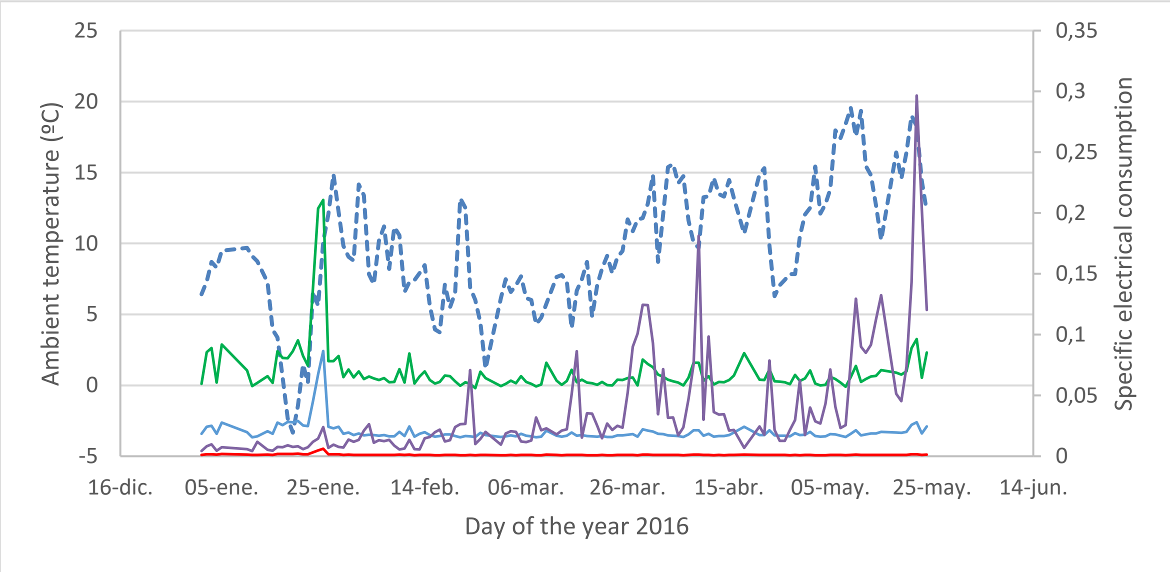


Figure 6.9. Evolution of ambient temperature (blue, discontinuous), SC_{el} of chilled circuit pump (blue), SC_{el} of cooling circuit pump (green), SC_{el} of dry cooler (purple) and SC_{el} of hot circuit pump (red) during the operating hours of SEHC in year 2016 - Excel

It can be seen that the specific electrical consumptions of the three pumps (chilled, cooling and hot water circuits) do not depend on the value of the ambient temperature. Nevertheless, a certain correlation between dry cooler specific electrical consumption and ambient temperature can be noticed.

Variable X	Variable Y	Pearson coefficient of correlation (ρ)
Ambient temperature	SC_{el} chilled pump	-0,123
Ambient temperature	SC_{el} cooling pump	-0,103
Ambient temperature	SC_{el} dry cooler	-0,168
Ambient temperature	SC_{el} hot pump	0,454

Table 6.10. Pearson correlation analysis for SEHC

Like in the case of LVRZ, the Pearson correlation analysis confirms that it does not exist any correlation between the ambient temperature and the specific electrical consumption of the pumps. However, and unlike LVRZ, there is no significant correlation between the ambient temperature and the specific electrical consumption of the dry cooler either. This phenomena could be explained by the fact that the dry coolers could be over dimensioned. Another reason could be that the compression chillers in the system were working and providing cooling power, so the specific electrical consumption of the dry coolers, which is the ratio between the electrical consumption and the cooling power provided by the AKA were not dependant because part of this electrical consumption would have to be attributed to the compression chillers.

7. Conclusions

7.1. Summary

The operation of different absorption chiller plants under different control strategies and operating conditions has been seen. It could be identified when the different described strategies were active in the sites through a graphic analysis of the evolution of the variables involved in these strategies.

Reasonable results for the evaluation of all considered scenarios were obtained, according to the expectations. These evaluations enable the finding of the conditions that are more suitable for operating with active strategies.

It has been seen that thermal efficiency is not affected by the activation of strategies A and B, but it is reduced when strategy C is active.

When there are no abnormal operation conditions when strategies are active, like it the KFWK case, the specific electrical consumption of the components involved in the strategies is significantly reduced, helping the absorption cooling plant to be more energy efficient.

7.2. Potential for improvement

One improvement would be to consider more than one strategy for each component analysed, being able to do a comparison for the same device between no strategy and different strategies active. This would be possible if the strategies were active and the data available, maybe not currently for some sites, but in a near future.

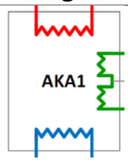
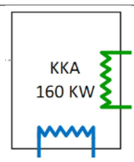
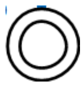
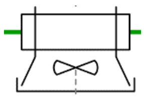
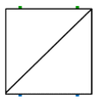
Another improvement would be to do the analysis of the specific consumptions taking periods of few hours during the day instead of periods of whole days, as it has been done in the ESTW site for strategy C. This would eliminate taking data from night time when cooling demand is lower or inexistent.

In the case of SEHC site, where elements like the dry coolers are not exclusive for the absorption chiller, but are shared between the absorption and the compression chillers, when doing an exhaustive analysis of the specific electrical consumptions, these consumptions should be distributed according to some considered logics.

8. Appendices

8.1. Appendix A. Hydraulic schemes of the sites

For the system overview and hydraulic configurations of the sites, the components of each site will be shown in the schemes that describe those systems. The following table shows and describes each component depicted on the schemes.

Actor	Pictogram
Absorption chiller (AKA)	
Chilled water pipe	
Compression chiller (KKA)	
Condenser (KKA)	
Condenser – Absorber (AKA)	
Consumer / Producer	
Cooling water pipe	
Desorber (AKA)	
Dry cooler	
Energy consumption datapoint	
Evaporator (AKA and KKA)	
Heat exchanger	
Heat load calculation point	

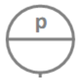
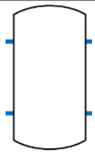
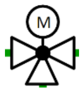
Hot water pipe	
Pressure datapoint	
Pump	
Storage / mixing tank	
Temperature datapoint	
Three-way valve	
Valve	
Volume flow datapoint	

Table 8.1. Depiction of the components in the hydraulic schemes of the sites

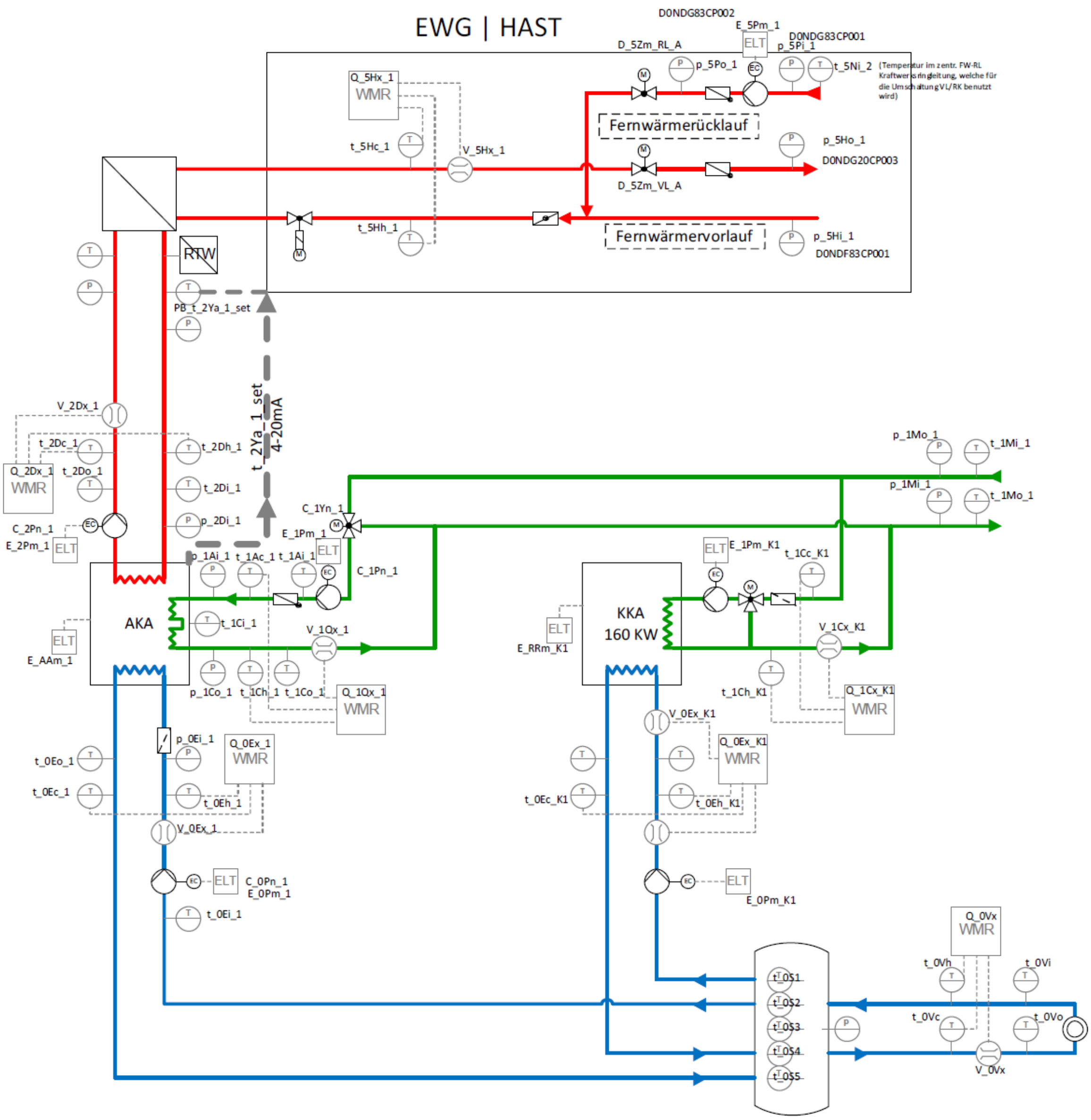


Figure 8.1. Hydraulics scheme of KFWK site (TUB 2016)

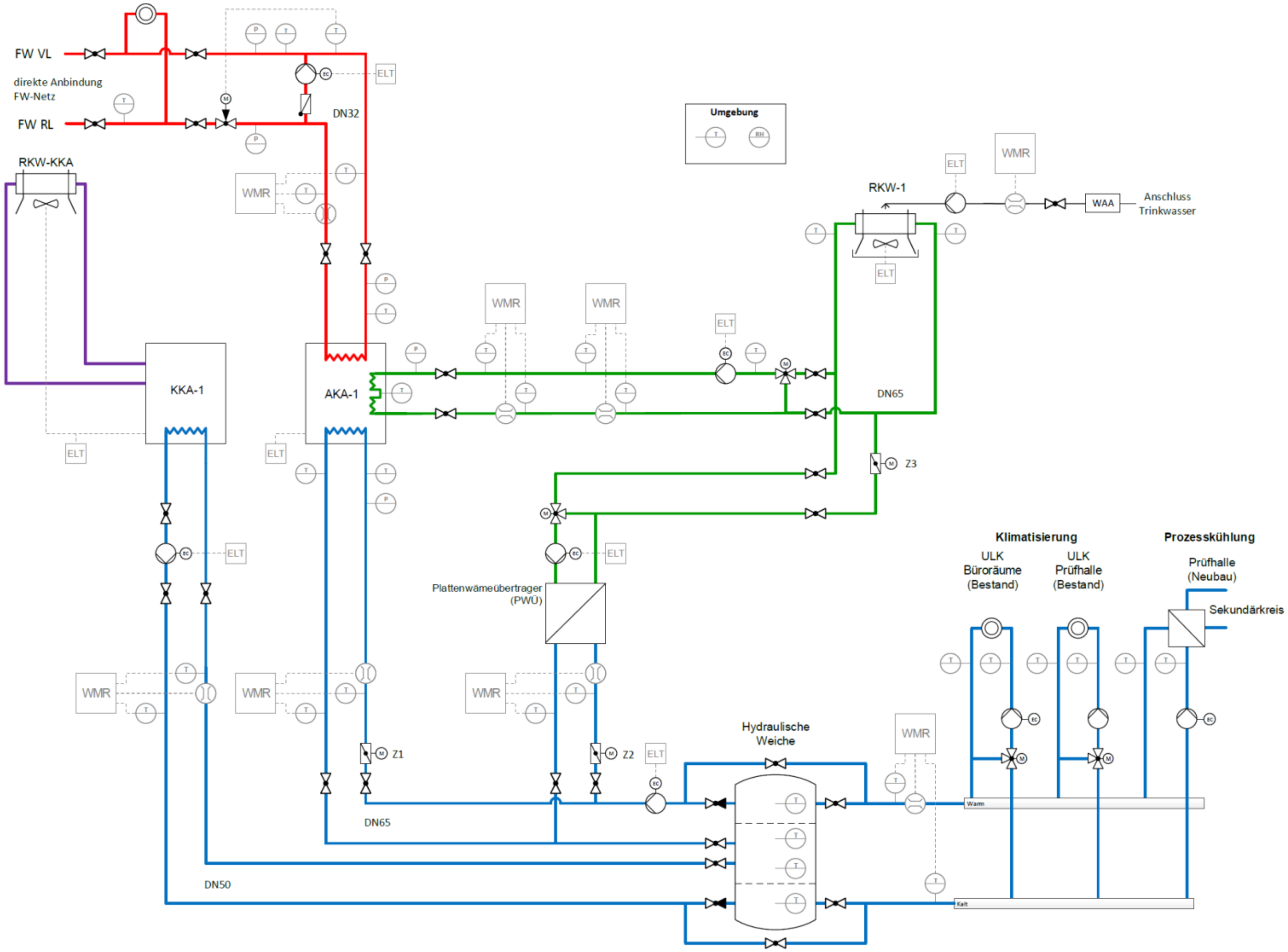


Figure 8.2. Hydraulics scheme of KFWK site (TUB 2016)

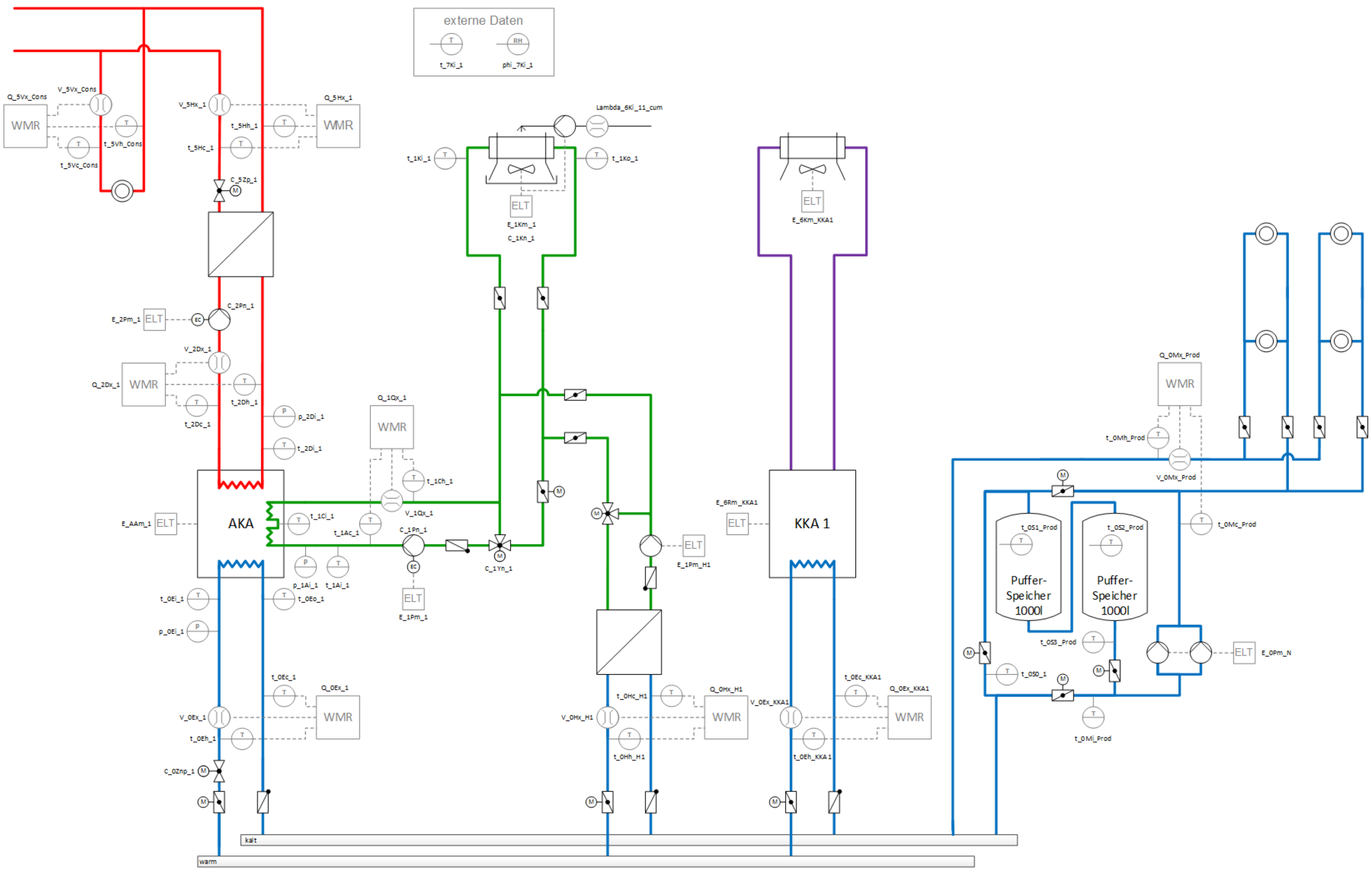


Figure 8.3. Hydraulics scheme of LVRZ site (TUB 2016)

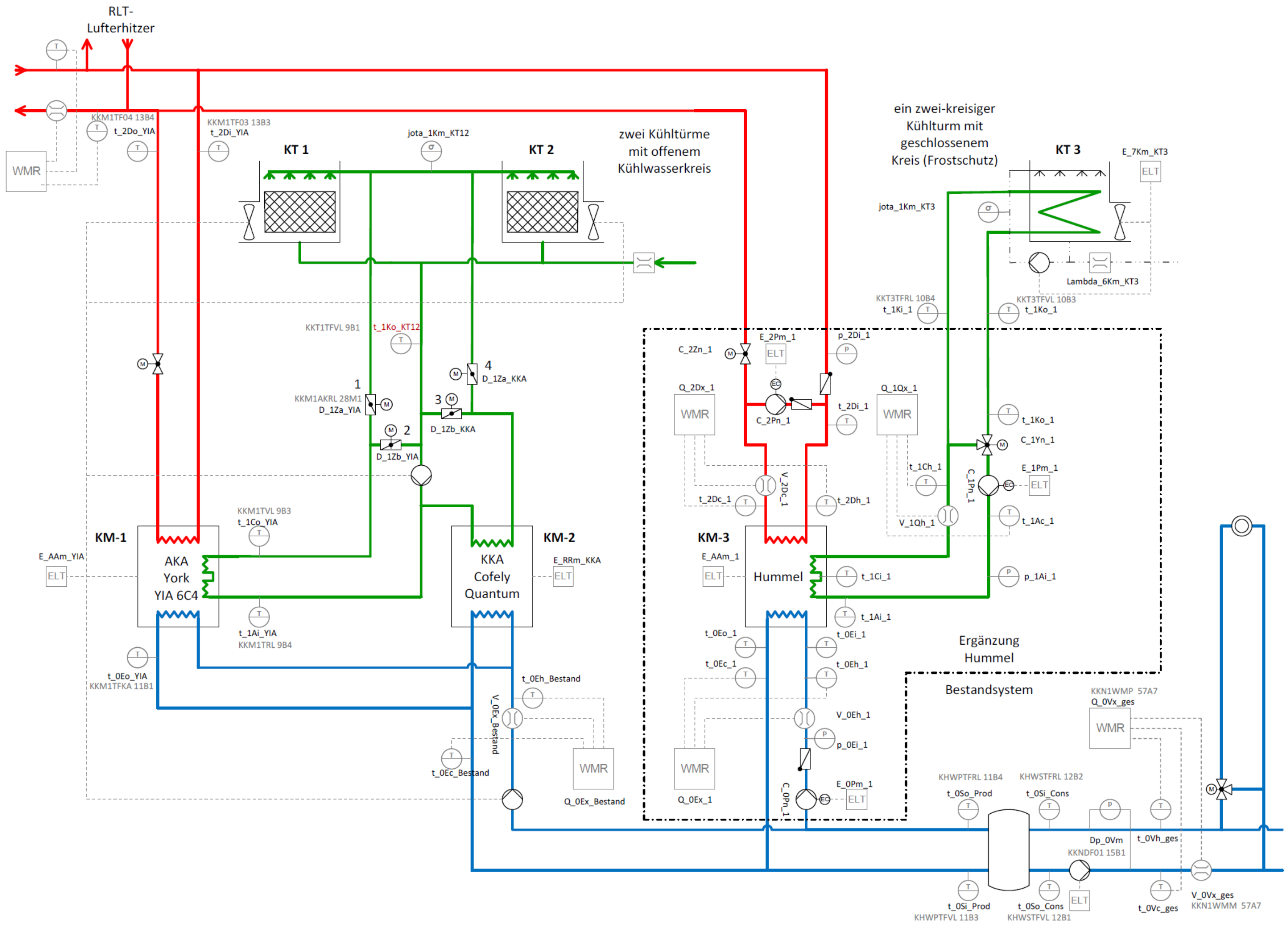


Figure 8.4. Hydraulics scheme of HENK site (TUB 2016)

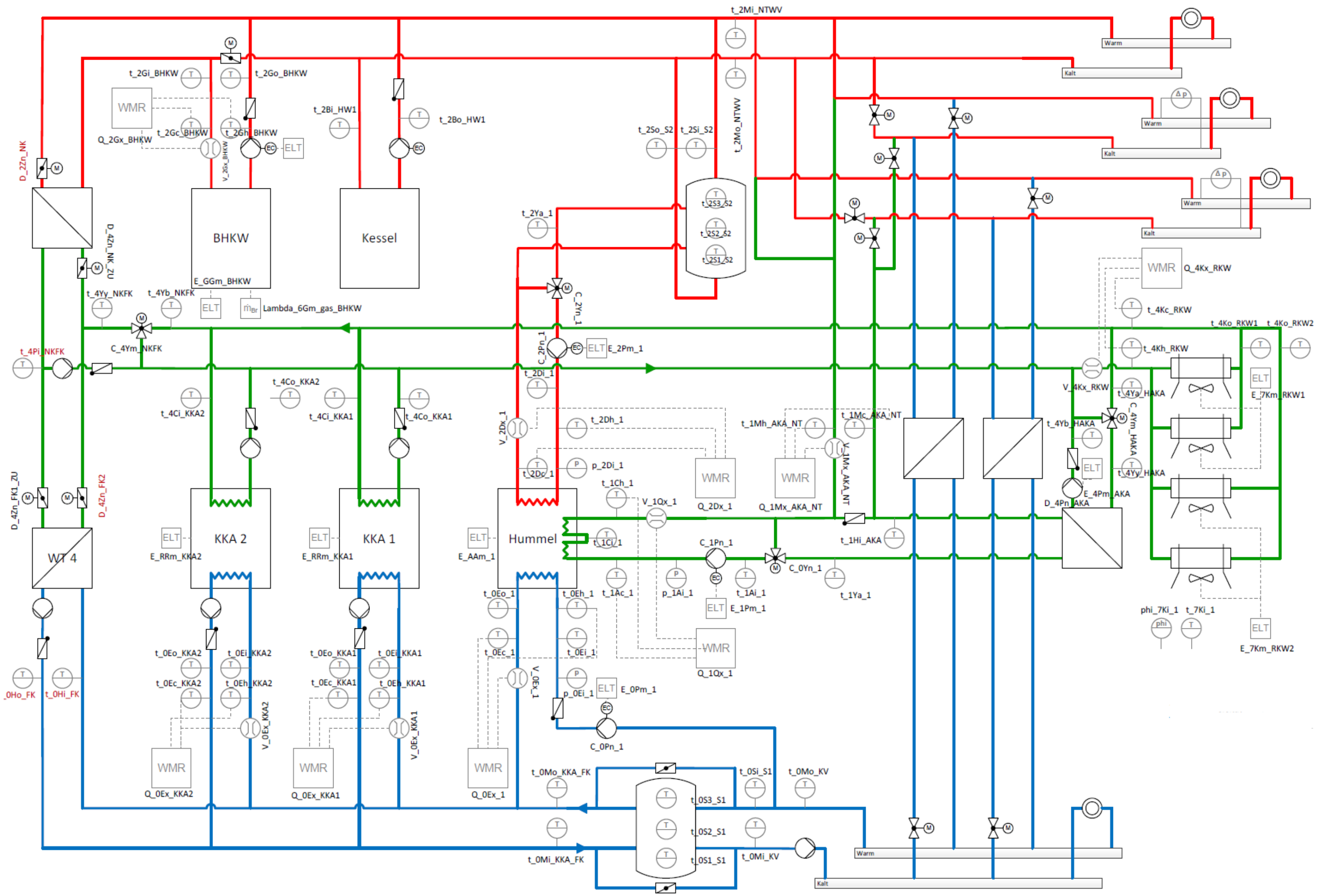


Figure 8.5. Hydraulics scheme of SEHC site (TUB 2016)

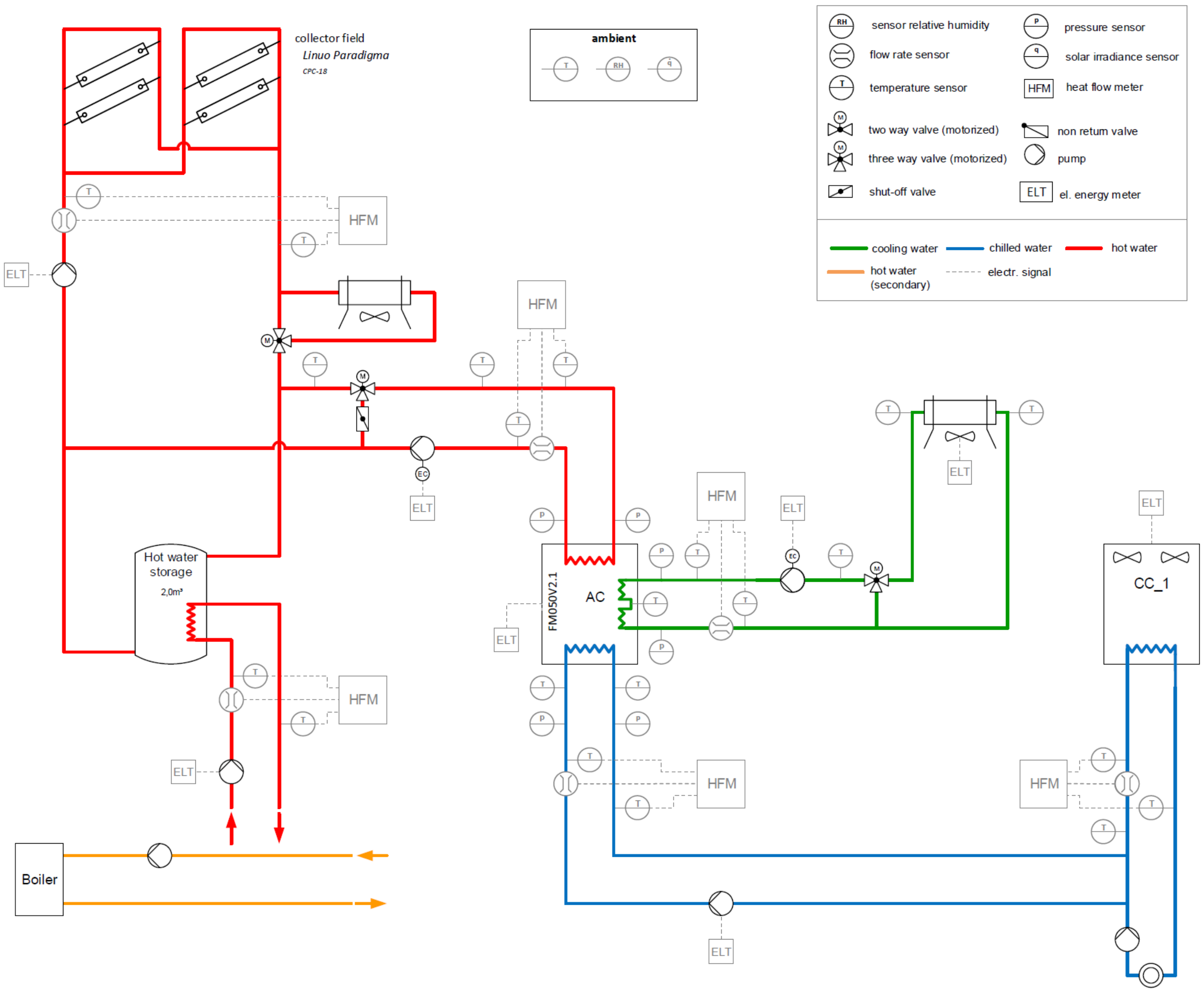


Figure 8.6. Hydraulics scheme of ICCJ site (TUB 2016)

8.2. Appendix B. Operating hours of the sites

An overview of the operating hours of the sites during 2016 and 2017 has been done. The cooling capacity provided by the AKA has been plotted through the years 2016 and 2017. The plots are shown in this appendix.

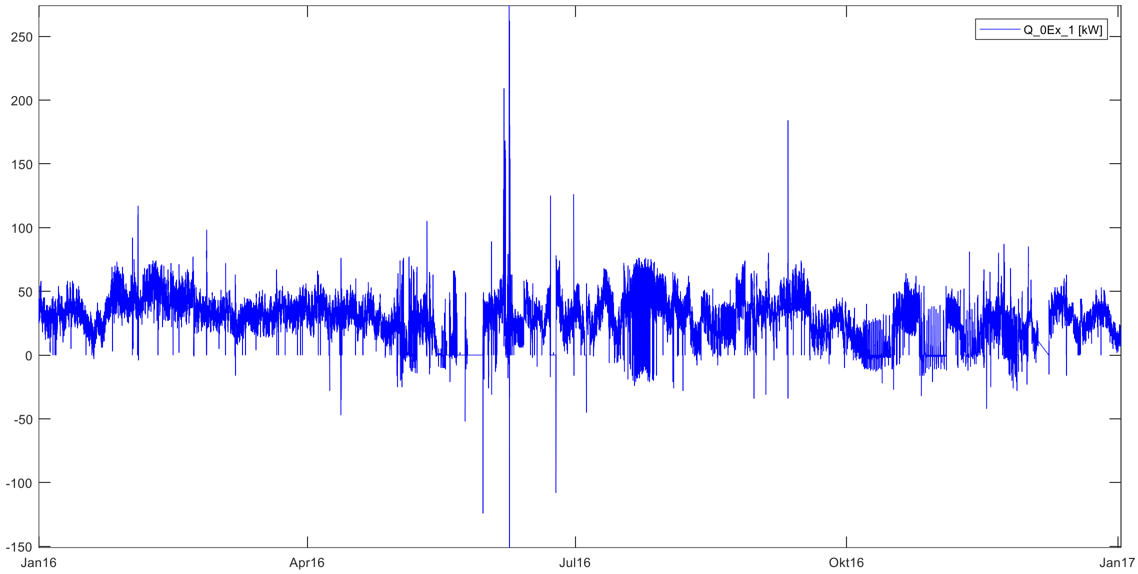


Figure 8.7. AKA cooling capacity for KFWK in 2016 - Matlab

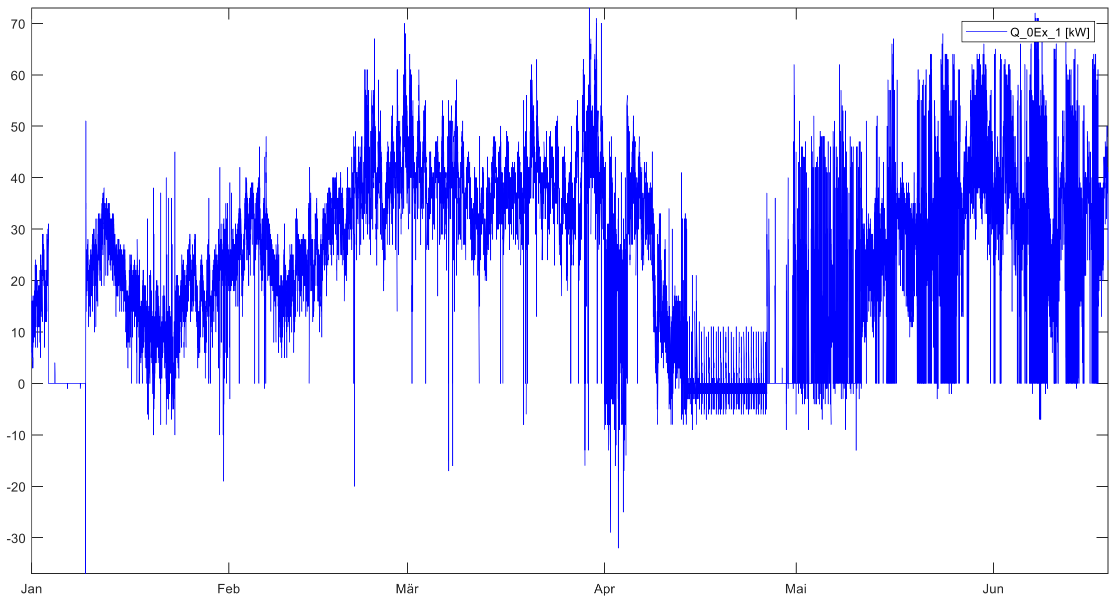


Figure 8.8. AKA cooling capacity for KFWK in 2017 - Matlab

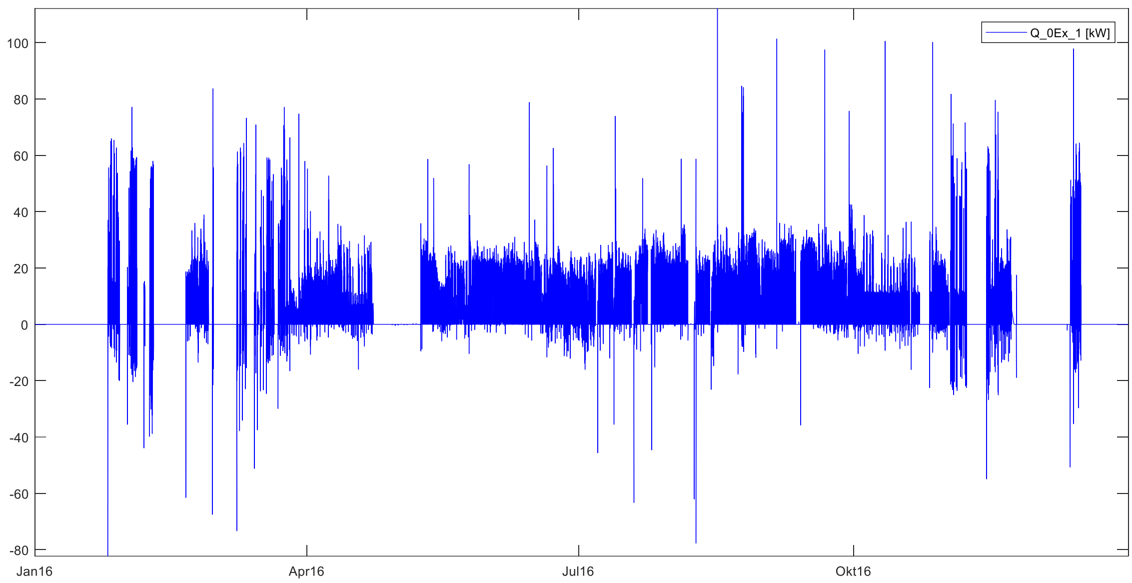


Figure 8.9. AKA cooling capacity for ESTW in 2016 - Matlab

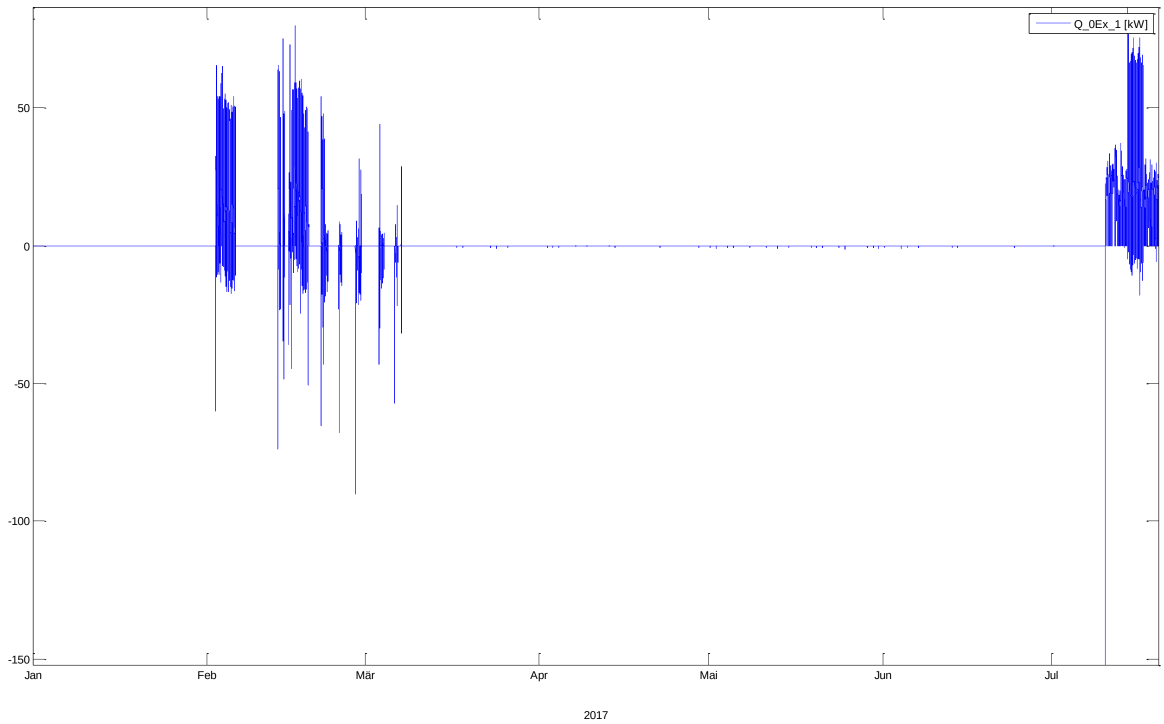


Figure 8.10. AKA cooling capacity for ESTW in 2017 - Matlab

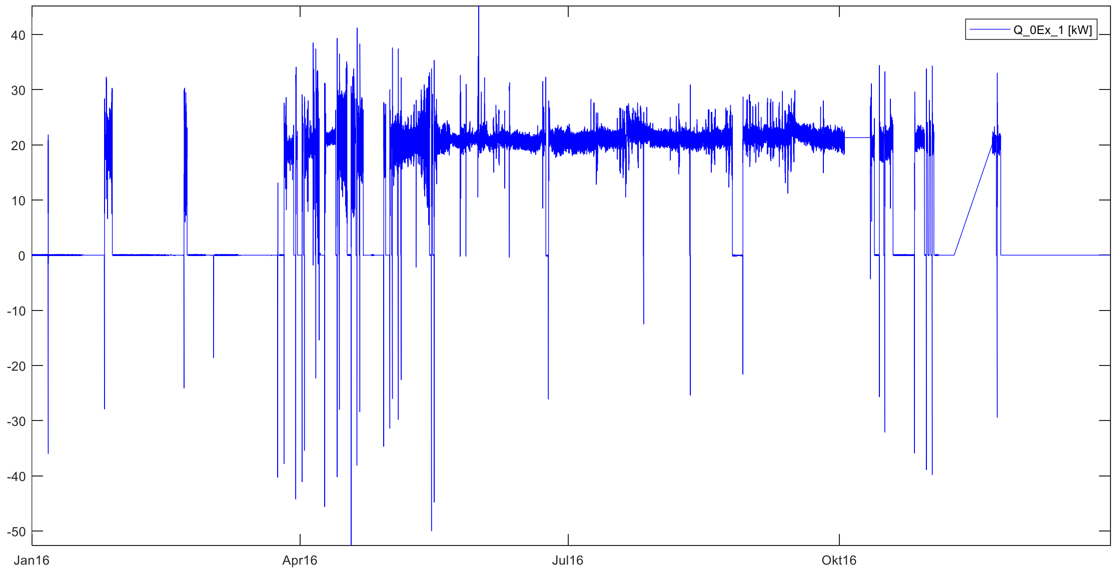


Figure 8.11. AKA cooling capacity for LVRZ in 2016 - Matlab

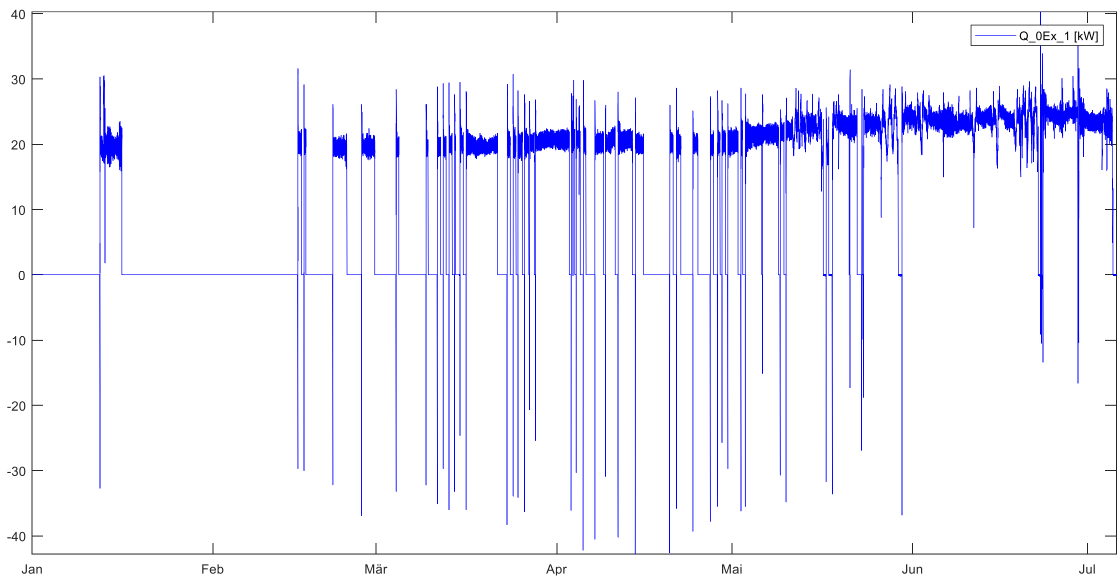


Figure 8.12. AKA cooling capacity for LVRZ in 2017 - Matlab

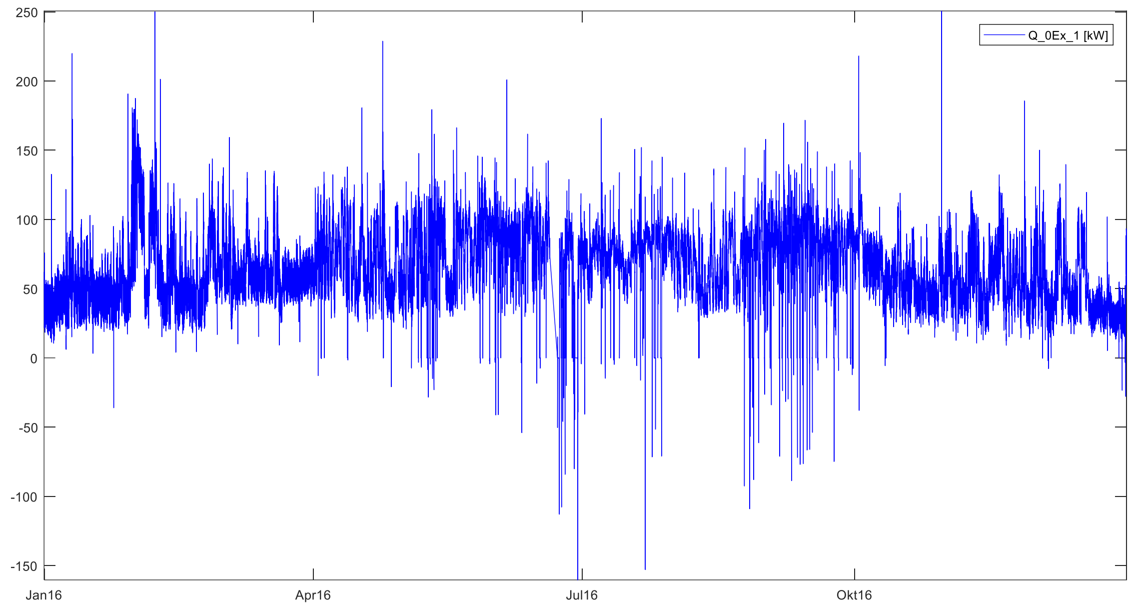


Figure 8.13. AKA cooling capacity for HENK in 2016 - Matlab

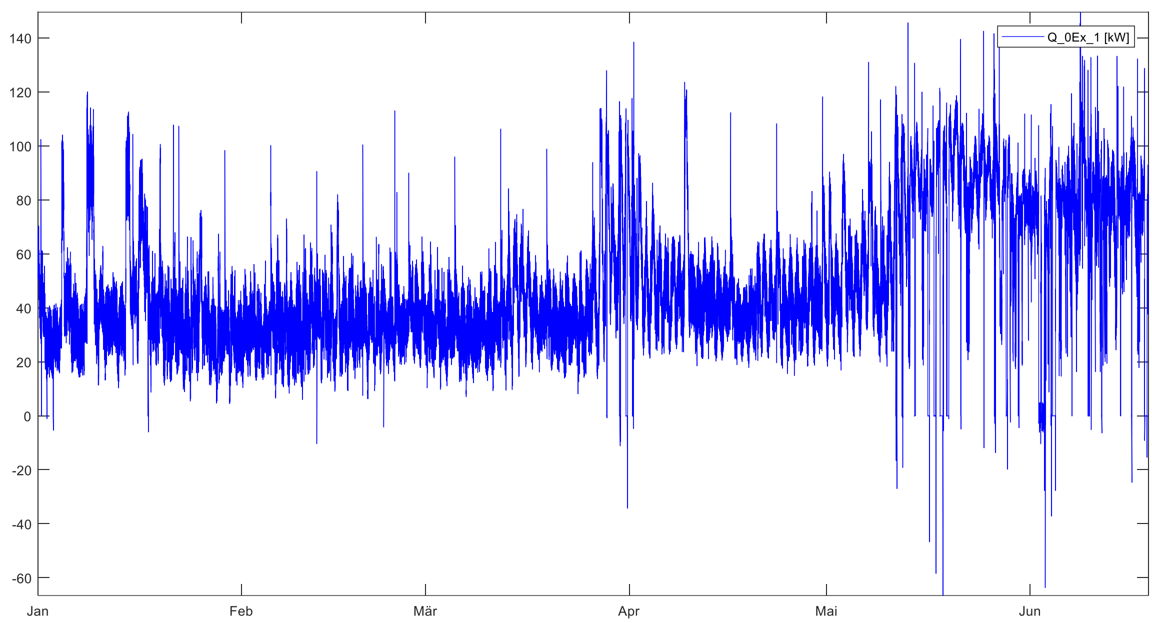


Figure 8.14. AKA cooling capacity for HENK in 2017 - Matlab

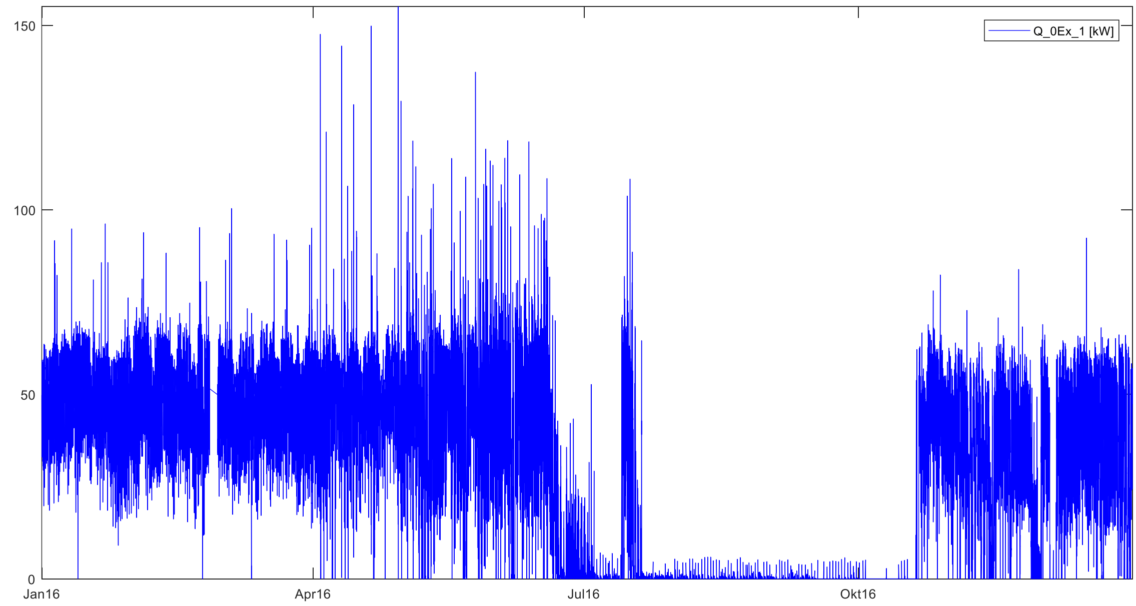


Figure 8.15. AKA cooling capacity for SEHC in 2016 - Matlab

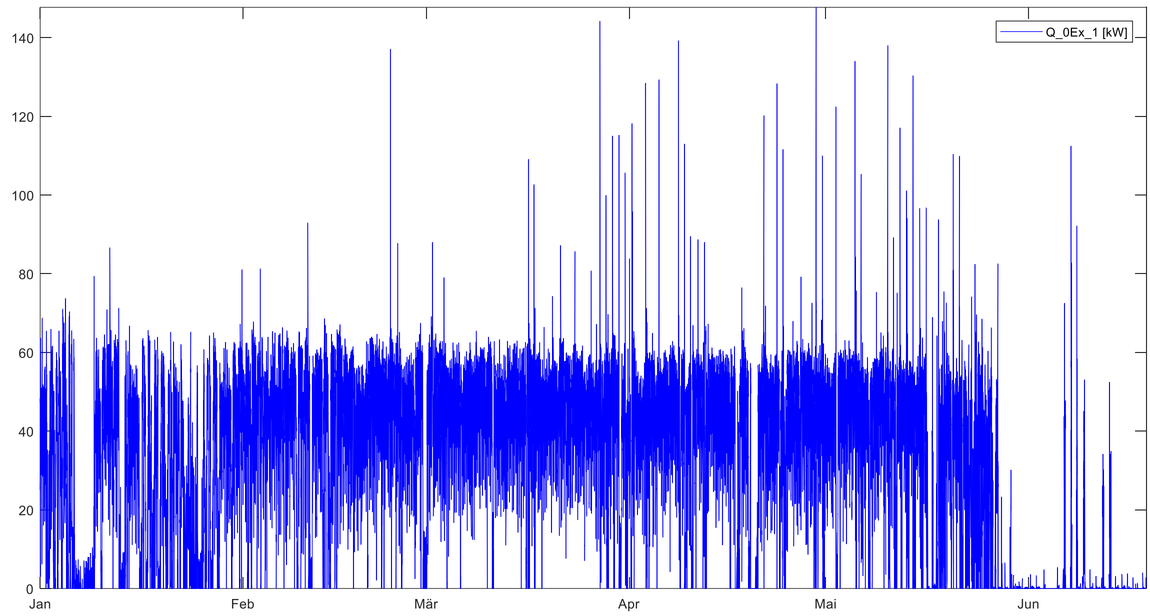


Figure 8.16. AKA cooling capacity for SEHC in 2017 – Matlab

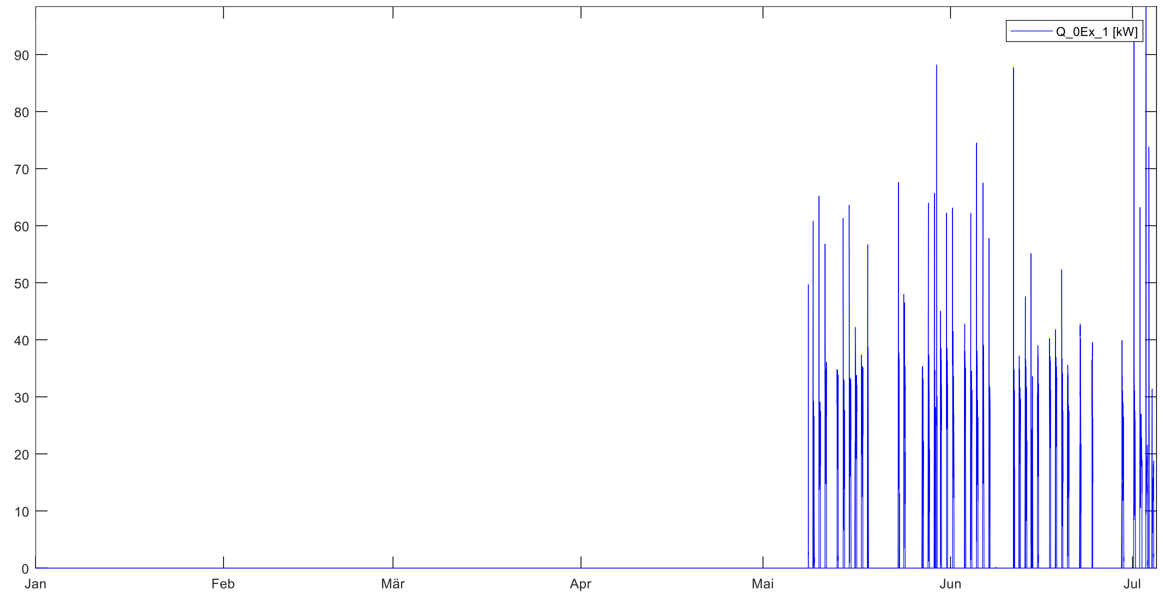


Figure 8.17. AKA cooling capacity for ICCJ in 2017 – Matlab

8.3. Appendix C. Specific consumptions

KFWK			
Day	**SC_{el} chilled pump**	**SC_{el} cooling pump**	**SC_{el} hot pump**
Scenario: reference period			
24 Jun 2016	0,0100	0,0399	0,0032
25 Jun 2016	0,0110	0,0325	0,0018
26 Jun 2016	0,0250	0,0538	0,0029
27 Jun 2016	0,0350	0,0700	0,0041
28 Jun 2016	0,0285	0,0680	0,0040
29 Jun 2016	0,0048	0,0293	0,0036
Mean	**0,0191**	**0,0489**	**0,0033**
Scenario: strategy A active			
20 Aug 2016	0,0060	0,0045	0,0766
21 Aug 2016	0,0052	0,0041	0,0747
22 Aug 2016	0,0057	0,0050	0,0768
23 Aug 2016	0,0066	0,0045	0,0799
24 Aug 2016	0,0066	0,0044	0,0330
25 Aug 2016	0,0051	0,0060	0,0015
26 Aug 2016	0,0063	0,0063	0,0014
27 Aug 2016	0,0083	0,0088	0,0194
28 Aug 2016	0,0160	0,0191	0,0998
29 Aug 2016	0,0099	0,0099	0,0362
30 Aug 2016	0,0042	0,0125	0,0037
Mean	**0,0073**	**0,0078**	**0,0457**
Scenario: strategies A and B active			
17 May 2017	0,0110	0,0042	0,0596
18 May 2017	0,0261	0,0043	0,0654
19 May 2017	0,0290	0,0044	0,0714
28 May 2017	0,0106	0,0085	0,0016
29 May 2017	0,0143	0,0092	0,0015
Mean	**0,0182**	**0,0061**	**0,0399**

Table 8.2. Specific electrical consumptions for KFWK

ESTW				
Day	**SC_{el} chilled pump**	**SC_{el} cooling pump**	**SC_{el} hot pump**	**SC_{el} dry cooler**
Scenario: reference period 1				
26 Jan 2016	0,0602	0,1281	0,0032	0,0162
27 Jan 2016	0,0598	0,1297	0,0033	0,0203
28 Jan 2016	0,0542	0,1348	0,0037	0,0226
Mean	**0,0581**	**0,1308**	**0,0034**	**0,0197**
Scenario: strategy A active				
13 Dec 2016	0,0191	0,1169	0,0031	0,0193

14 Dec 2016	0,0169	0,1200	0,0033	0,0208
15 Dec 2016	0,0158	0,0586	0,0030	0,0189
Mean	**0,0173**	**0,0985**	**0,0031**	**0,0197**
Scenario: strategies A and B active				
3 Feb 2017	0,0124	0,0190	0,0027	0,0139
4 Feb 2017	0,0150	0,0184	0,0037	0,0164
5 Feb 2017	0,0174	0,0174	0,0045	0,0183
16 Feb 2017	0,0128	0,0246	0,0022	0,0163
17 Feb 2017	0,0140	0,0186	0,0025	0,0127
18 Feb 2017	0,0204	0,0175	0,0050	0,0223
Mean	**0,0153**	**0,0193**	**0,0034**	**0,0167**
Scenario: reference period 2				
20 Jul 2016 7h – 18h	0,0413	0,1818	-	0,5525
21 Jul 2016 8h – 18h	0,0174	0,0784	-	0,3236
22 Jul 2016 12h – 19h	0,0180	0,1023	-	0,3319
Mean	**0,0256**	**0,1208**	**-**	**0,4026**
Scenario: strategies A and C active				
16 Jul 2017 16h - 21h	0,0199	0,0928	-	0,1639
17 Jul 2017 10h - 22h	0,0248	0,1011	-	0,1992
18 Jul 2017 7h - 24h	0,0309	0,1315	-	0,2351
19 Jul 2017 5h - 8h	0,0334	0,1040	-	0,2412
Mean	**0,0273**	**0,1074**	**-**	**0,2099**

Table 8.3. Specific electrical consumptions for ESTW

HENK				
Day	**SC_{el} chilled pump**	**SC_{el} cooling pump**	**SC_{el} hot pump**	**SC_{el} dry cooler**
Scenario: reference period				
1 Jun 2017	0,0127	0,0156	0,0007	0,0664
2 Jun 2017	0,0142	0,0169	0,0009	0,0754
3 Jun 2017	0,0160	0,0187	0,0010	0,1390
4 Jun 2017	0,0113	0,0132	0,0008	0,1217
5 Jun 2017	0,0128	0,0152	0,0008	0,0743
6 Jun 2017	0,0127	0,0151	0,0008	0,0835
7 Jun 2017	0,0132	0,0156	0,0008	0,0631
Mean	**0,0133**	**0,0158**	**0,0008**	**0,0891**
Scenario: strategy A active				
12 Jul 2016	0,0087	0,0161	0,0008	0,1304
13 Jul 2016	0,0082	0,0162	0,0007	0,0997
14 Jul 2016	0,0083	0,0164	0,0007	0,0760
15 Jul 2016	0,0064	0,0192	0,0008	0,0760
16 Jul 2016	0,0077	0,0193	0,0009	0,1307
17 Jul 2016	0,0086	0,0156	0,0007	0,1564
Mean	**0,0080**	**0,0171**	**0,0008**	**0,1115**
Scenario: strategies A and B active				
21 May 2017	0,0086	0,0261	0,0006	0,0653
22 May 2017	0,0107	0,0190	0,0008	0,0719
23 May 2017	0,0085	0,0226	0,0007	0,0984
24 May 2017	0,0089	0,0241	0,0007	0,0657
25 May 2017	0,0081	0,0238	0,0006	0,0927
26 May 2017	0,0086	0,0255	0,0007	0,1012
27 May 2017	0,0121	0,0197	0,0009	0,1271
28 May 2017	0,0106	0,0243	0,0007	0,1182
Mean	**0,0095**	**0,0231**	**0,0007**	**0,0926**

Table 8.4 Specific electrical consumptions for HENK

ICCJ				
Day	**SC_{el} chilled pump**	**SC_{el} cooling pump**	**SC_{el} hot pump**	**SC_{el} dry cooler**
Scenario: reference period				
9 May 2017	0,0162	0,0517	0,0141	0,4224
10 May 2017	0,0151	0,0422	0,0125	0,3777
11 May 2017	0,0104	0,0278	0,0089	0,0915
13 May 2017	0,0123	0,0263	0,0097	0,1804
14 May 2017	0,0135	0,0275	0,0104	0,3380
15 May 2017	0,0112	0,0224	0,0086	0,2653
16 May 2017	0,0106	0,0219	0,0093	0,1139
Mean	**0,0127**	**0,0314**	**0,0105**	**0,2556**
Scenario: strategy B active				

11 June 2017	0,0265	0,0177	0,0172	0,1554
12 June 2017	0,0168	0,0195	0,0261	0,0489
13 June 2017	0,0155	0,0188	0,0185	0,0519
14 June 2017	0,0371	0,0220	0,0492	0,0735
15 June 2017	0,0160	0,0212	0,0191	0,0509
17 June 2017	0,0159	0,0214	0,0244	0,0764
18 June 2017	0,0157	0,0200	0,0207	0,0829
19 June 2017	0,0171	0,0200	0,0279	0,1148
20 June 2017	0,0187	0,0186	0,0324	0,0663
Mean	**0,0199**	**0,0199**	**0,0262**	**0,0801**

Table 8.5. Specific electrical consumptions for ICCJ

Nomenclature

General

A	Absorber	-
AKA	Absorption chiller	-
C	Condenser	-
CHP	Combined heat and power plant	-
Cons	Consumer	-
D	Desorber	-
E	Evaporator	-
FAkS	Feldtest Absorptionskälteanlagen für KWKK Systeme	-
H	Free heat exchanger	-
HFM	Heat flow meter	-
KKA	Compression chiller	-
LiBr	Lithium bromide	-
Prod	Producer	-
RKW	Dry cooler	-
set	Set value	-

Indices

amb	Ambient	-
c	Cold	-
el	Electrical	-
h	Hot	-
i	Inlet	-
o	Outlet	-
PE	Primary energy	-
th	Thermal, usually used for thermal efficiency	-

Parameters

Cp	Water heat capacity	kJ/(kg·K)
E	Energy	kWh
L	Electrical power consumption	kWel
Q	Power, usually heating or cooling power	kW

SC	Specific consumption	-
t	Temperature	ºC
V	Volume flow	m3/h
W	Work	kJ
η	Efficiency	-
ρ	Water density	kg/m3
Statistics		
R2	Quadratic accuracy of a regression	-
ρ	Pearson coefficient of correlation	-

List of Figures

List of Tables

Bibliography

Albers, J. & Paitazoglou, C., 2014. *Solar Cooling for Industry and Commerce. Functional Description CE-Controller (Standard)*, Berlin.

Anon, 2017. SPSS Tutorials: Pearson Correlation. *University Libraries*. Available at: http://libguides.library.kent.edu/SPSS/PearsonCorr.

Minitab Inc., 2017. Basics of correlation and covariance. *Minitab Support*. Available at: http://support.minitab.com/en-us/minitab/17/topic-library/modeling-statistics/regression-and-correlation/correlation-and-covariance/basics-of-correlation-and-covariance/.

Paitazoglou, C., 2015. *Solar cooling with highly efficient absorption chillers*, Berlin.

Petersen, S. et al., 2013. *New Absorption Chillers for Chcp or Solar Cooling System Technology*, Berlin.

Srikhirin, P. & Aphornratana, S., 2001. *A review of absorption refrigeration technologies*,

TUB, 2016. Hydraulic schemes of the Field Tests.