Commissioning and Experimental Analysis of Heat Pumps' Performance

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ABSTRACT

Nowadays, heat pumps represent one of the most innovative and high performance available technologies. Applied on HVAC plants, which require the 6% of European total electric energy demand, these can strongly reduce the consumption. However the higher difficulty of control and a lack of standards can bring to efficiency lower than the real possibility. Commissioning processes are developed to optimize the efficiency of an HVAC plant in each operating condition.

This work analyzes what is already usually done in Italy during the first phase of the project (design, construction and start up) and during the operating life. A detailed analysis concerns the start up of typical medium plants, in which is concentrated a large part of the initial commissioning. The procedures used both by installers and commissioning agents are described in detail. In general, all rules are respected and the correct functioning of each plant demonstrates the good work of the technician we followed.

Then, different data surveys and analyses are proposed to improve the commissioning level. Each of these requires a different value of time, testing frequency, number of parameters, and complexity of instruments. Some data captures are done during the start up, while mostly they are conducted during the ongoing commissioning. The data analysis has demonstrated as each survey can give a different range of information, so all are useful. In conclusion, this kind of testing is strictly recomended on sample plants to technicians and engineers in order to better understand the equipment they usually install, while it can result expensive for the owner if made on working plants.

CHAPTER SUMMARY

1. Commissioning

The first chapter develops the basic concepts of commissioning in term of standards, according with the procedures adopted during this work. After an introduction about the rules followed in Italy, in Europe and in the U.S., the purpose is to understand why commissioning is necessary and should be mandatory, in which phases it should be done, and which are the possible levels of detail.

2. Heat pumps

HVAC plants are introduced, with a particular attention to the heating and cooling heat pump systems, which are the mostly studied machineries in this work. A brief classification is followed by a detailed analysis of the refrigeration cycle, taking into account also technical concepts useful during the Cx (commissioning). The performances are defined both by European and American standards.
In the second part of the chapter, the approach is concentrated on the examined plants, introducing the used refrigerant (R407c) and the analyzed HPs (Ochsner Warmepumpen).

3. Start up procedures

A single phase of the plant life is analyzed: the start up. In July 2011, different HVAC plants are run following common procedures. In this chapter, we try to conceive a list of these procedures, from the last phases of construction to the definitive operating condition. Thermodynamic and physical considerations are made in order to give an engineering approach in addition to the experience on the field.

CHAPTER SUMMARY (continued)

4. Examined cases

Each examined plant is briefly described, without going into project details. The idea is to focus on the main characteristics, describing the location, the building, the heat pump and the thermal plant in general with its main accessories. The start up procedures are standardized in the previous chapter to facilitate the reading, so only the variations are examined separately, including a list of the main problems we had.

5. Experimental analysis

This chapter deals with the experimental surveys and the successive analysis, adding information with respect to the traditional procedure described in Chapter 3, in which manual instrumentation only was used. Now, thanks to dataloggers and computers, the following data are available:

- A series of cumulative daily data permits to know the monthly trend, the critical days and the correlation between the parameters, in particular obtaining signatures or characteristic curves of the plant.
- On the same plant, the main temperatures are known with a frequency of 5 minutes. This permits to analyze what happens during the critical days, although electrical data are not known. Also, the guarantee of a minimum internal temperature, as first purpose of the commissioning, is verified.
- Electrical data with a high level of detail are taken during a start up, giving a short-term analysis. The power factor is one of the most useful data in this survey.

6. Air-air heat pumps

The main work is concentrated on air-water and water-water heat pumps; however, since the initial idea was to examine heat pumps in general, an air-air plant was visited and briefly examined in this last chapter.

LIST OF ABBREVIATIONS

ASHRAE	American Society for Heating, Refrigerating and Air conditioning Engineers
ASTM	American Society for Testing and Materials
AWS	American Welding Society
BTU	British Thermal Unit
CFCs	Chlorofluorocarbons
COP	Coefficient Of Performance
Cx	Commissioning
DHW	Domestic Hot Water
EER	Energy Efficiency Ratio
GWP	Global Warming Potential
I-Cx	Initial Commissioning
IEA	International Energy Agency
IEE	Intelligent Energy Europe
IIS	*Istituto Italiano della Saldatura* (Welding Italian Institute)
HCFCs	Hydrochlorofluorocarbons
HFCs	Hydrofuorocarbons
HP[1]	Heat Pump
HP	High Pressure
HRV	Heat Reclaim Ventilation
HVAC	Heating Ventilation Air-Conditioning
HX	Heat exchanger
LP	Low Pressure
ODP	Ozone Depleting Potential
OTE	O-Tronic Easy (Ochsner trademark)
P	Real power
PF	Power factor
POEs	Polyolesters
Q_H	Delivery heat
Q_L	External source heat
S	Apparent power
SEER	Season Energy Efficiency Ratio
T_H	Delivery temperature
T_L	External source temperature
VRV	Volume Refrigerant Variable
W	Electric power

[1] Not used in the sections “Sub-cooling and super-heating” and “Pressure gauges” in which HP refers to High Pressure. In this case, “heat pump” is written in extenso.

INTRODUCTION

In a residential situation, more than the half of energy consumption comes from space and water heating and cooling; if an HVAC system provides all these three components, it is involved in the 60% of the energy costs, as in Figure 1. Consequently, an increasing of the HVAC performance could reduce significantly the annual energy budget of a building.

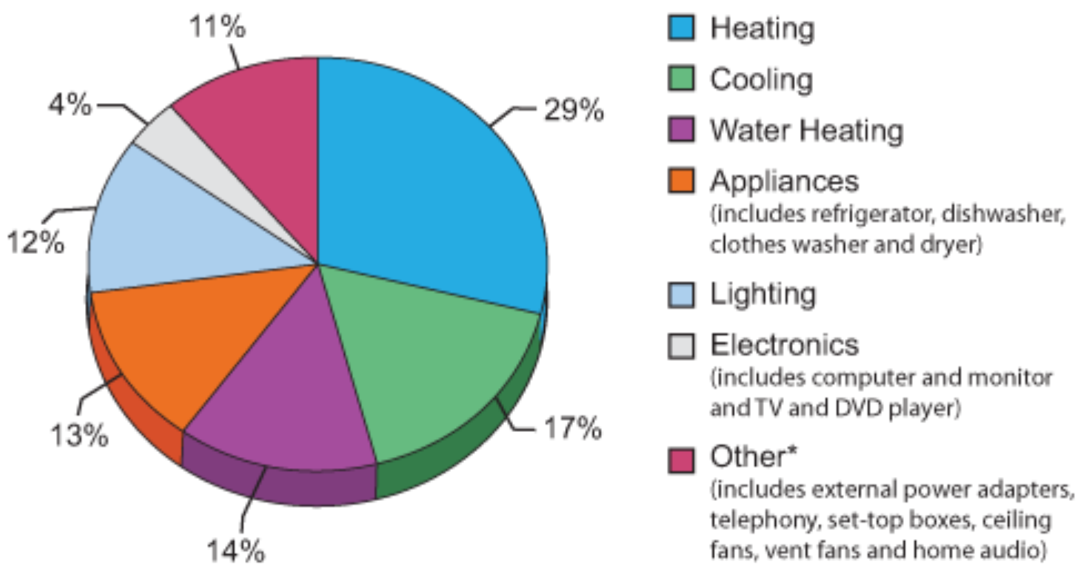

Figure 1. Distribution of energy consumption in a domestic building

The first step for a high-performance HVAC is the choice of the heating system. In terms of costs, a heating plant must both consume less and use a cheap fuel. Nowadays, heat pump plants, which will be studied in this work, have the higher efficiency a heating system can reach, as we can see in Figure 2.

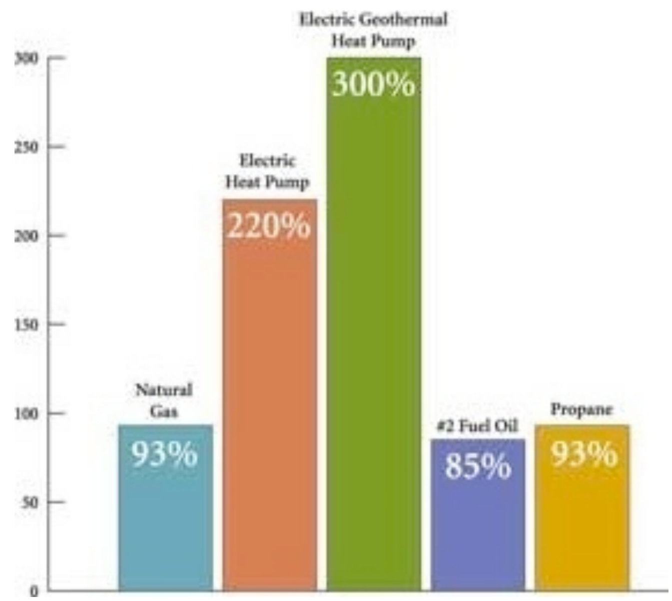

Figure 2. Estimated efficiency of heating systems

According with many data, the efficiencies above are referred to the average installed plants efficiency and not to the highest efficiency a modern plant can reach. In fact the 300% of efficiency refers to a COP = 3 and a SEER = 11, and 220% refers to COP = 2.2 and SEER = 8, which is the minimum according to Italian codes for a new heat pump plant.

As primary source, HP plants normally use electrical energy; this could be a disadvantage if the electricity is bought from the grid, where the costs due to production, transportation and sale are higher than, for example, the natural gas price.

To win in terms of cost, taking into account also the higher initial cost of a heat pump, it is necessary to optimize of the plant performance. Furthermore, usually HPs are more difficult to control than a traditional plant; for this reason, the tests and the controls must be done by expert technicians. In a more general idea, all the procedures to increase the performance are called "Commissioning" (Cx).

The first advantage due to commissioning is the reduction of energy consumption and, consequently, of pollutant emission. The quicker way to estimate the saving is to measure the SEER or the Seasonal COP, which will be better explained in a specific section of this work, and to compare it with respect to a standard machine, the manufacturer's data sheet or a survey previously done.

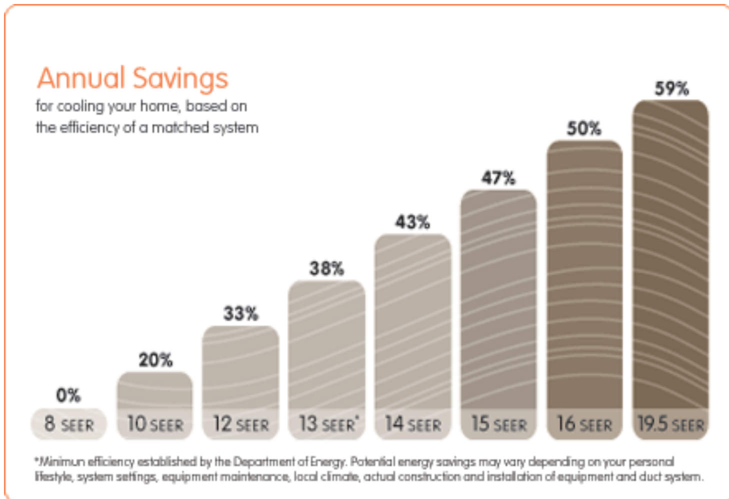

Figure 3. Percentage saving for high performance HP plants

The SEER and the Seasonal COP are two practical ways for a comparison, since the saving is nothing else that the ratio between the reference value and the measured value, subtracted to 1. A HP with SEER equal to 16 consumes the half with respect to a SEER 8 system, as you can see in Figure 3.

Other improvements, summared in Figure 4, due to commissioning are not linked to a direct energy gain as reported in the following chart, where the percentage numbers represent, on a set of plants (100%), how many time the improvement is the most important. These advantages will be discussed in Chapter 1.

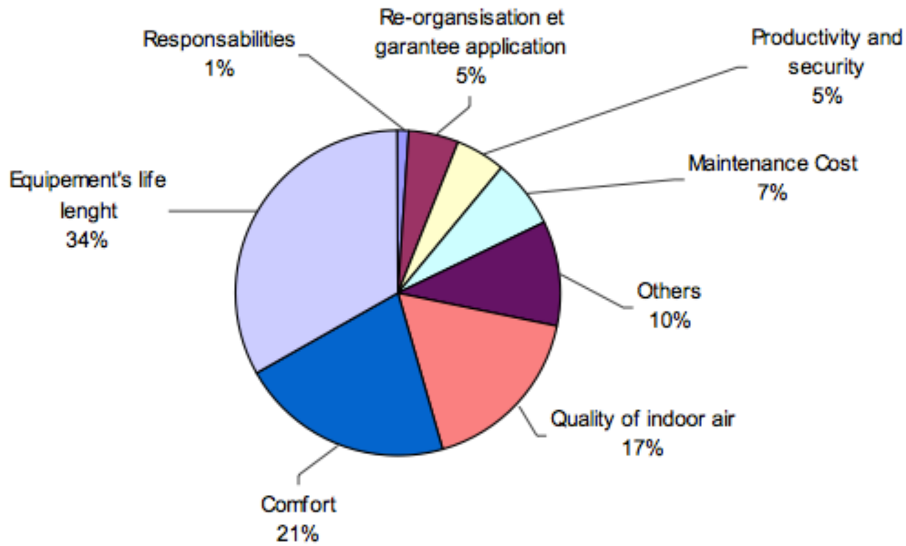

Figure 4. Main improvements due to Commissioning (from Annex 47)

1. COMMISSIONING

1.1. Standards

The International Energy Agency (IEE) supports over 50 international projects, called Annex, collected into the “Energy Conservation in Buildings and Community Systems” program.

Dealing with a wide energy field, representing a third of the global energy consumption, each annex works on a more specific sector with the aim of defining standard and common procedures adopted in different countries, including U.S. and Italy.

In particular, two projects have addressed Commissioning:

-Annex 40: “Commissioning of Building HVAC Systems for Improved Energy Performance”

Developed from 2001 to 2004 and followed, from 2005 to 2009, by the:

-Annex 47: “Cost Effective Commissioning of Existing and Low Energy Buildings”

A parallel project was developed in the U.S. by the “American Society of Heating, Refrigerating and Air Conditioning engineers” (ASHRAE) trying to report a unique approach. The two complementary reports to deal with commissioning are:

-Guideline 0:2005 “The Commissioning Process”

-Guideline 1:200x “Technical Requirements for the Commissioning Process”

In addition, this work has followed some suggestions from the project “Building EQ” developed by the EU-funded IEE (Intelligent Energy Europe) program, in particular for what it concerns the analysis of data and graphs during continuos commissioning

1.1.1. A common procedure

The Annexes collect a large variety of commissioning methods developed because of the lack of specific codes and suggest some possible standardized methods. In particular, Annex 40 focuses on the Functional Performance Testing.

However, this work is developed analyzing what is usually done in Italy by a proficient company in the field (*Chapter 3 and 4*), and what could be added to the common procedures to improve performances (*Chapter 5*).

Especially for the first initial part and in general, the Annexes and the commissioning adopted during these cases are similar, so the Annex 40 list of common procedures and classifications is useful to introduce the context.

In particular, in all these guidelines, it appears clear that the first phase of the commissioning consists in planning it in detail, analyzing the building, the context, the plant and the owner requirements.

1.2. Type of Commissioning

The Annex 40 catalogues four kinds of commissioning, as in Figure 5, depending on when they are made:

Initial Commissioning

The I-Cx represents the first type: it starts with the design phase and finishes only when the whole plant correctly runs. It ensures that both the plant and the building are running at the higher performance, according to the project.

Ongoing Commissioning

After an I-Cx, Cx should not be stopped, continuing with an Ongoing Cx. In this case, it is possible to talk about Continuos Cx, which includes also the initial Cx. The Continuos-Cx guarantees that the high initial performances are maintained during the whole life of the plant.

The Continuos Cx can be applied also when the I-Cx was interrupted or never done: in this case, the Ongoing Cx follows a Re or a Retro Cx.

Recommissioning

If the Cx is stopped after the start up, the equipment can loss performance during its life, due to several variables that could change. It is possible to do a Re-Cx in a second time, comparing its results with the initial values, if the owner wants to verify and to document the actual situation.

Retro-commissioning

In some working plants, Cx was never done: in this case, we talk about Retro-Cx. This should do a complete analysis as the initial commissioning, including final documents.

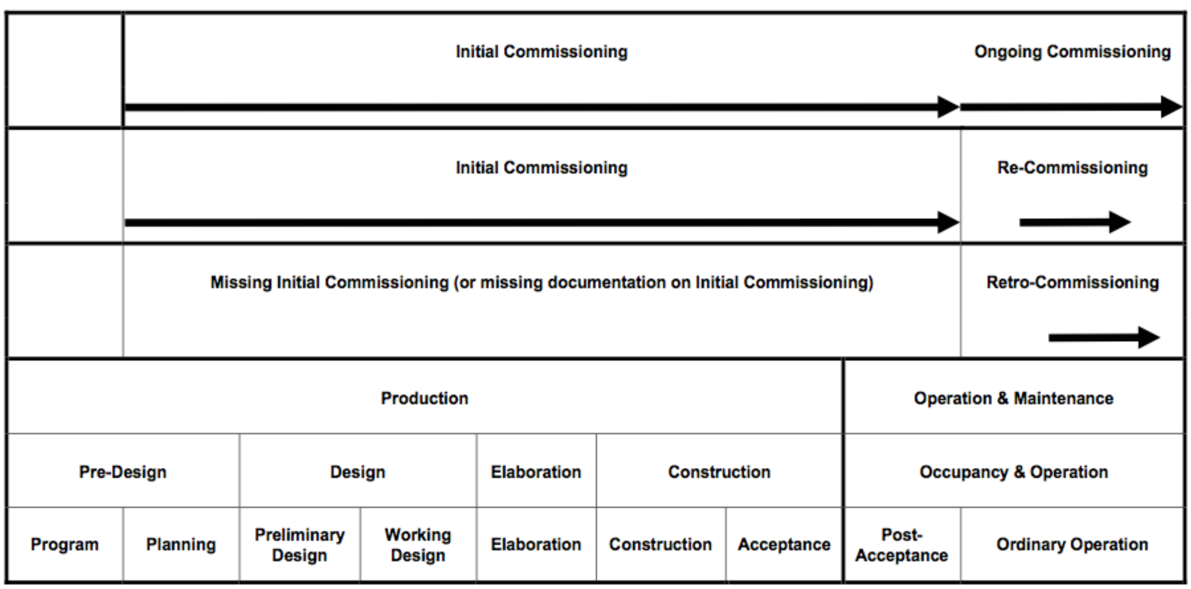

Figure 5. Type of commissioning with respect to the plant life cycle (from Annex 40)

1.2.1. Plant life cycle

Usually, the history of an HVAC plant starts with a preliminary contract between owner and builder, who makes some proposal in terms of technologies, dimensions and price, evaluating the context of the building. The initial commissioning should start from this phase, called Pre-Design.

The builder intervenes principally in two large phases: the design and the construction.

As the Economy teaches, each choice or modification taken during the project, or at least during the construction, has a much lower cost than during the system operation.

At the end of the construction, or during it in case of complex projects, the acceptance must be made and could consist in two parts. This first one, mandatory by law, makes a technical-administrative analysis, which consists of verifying if the construction was done according to the project requirements. The second one is optional but strictly recommended, and it consists in a testing acceptance.

An important moment of the plant life, between the construction and the occupancy, is represented by the start up phase. It confirms the positive end of the construction by doing acceptance procedures and documents, then running the plant. This event concludes also the Initial Commissioning phase.

The occupancy is the longest period of the life plant: usually the plant is designed in order to work well between 20 or 25 years; during this period, the maintenance is regularly planned and done.

1.3. Level of Commissioning

An other interesting classification in Annex 40 distinguishes five type of Cx complexity, according to three parameters:

Size of the building

We can classify a building by dimension (small, medium, large) or by use (residential, commercial, industrial). In larger buildings, the risk of malfunctions increases due to the higher number of components and links; furthermore a large plant is more difficult to start up.

Complexity of the HVAC plant

Independently on the size of the building, the owner and the designer can adopt different choices. First of all, HVAC plants can fulfill to different number of tasks; it is possible to adopt a large single unit or multiple units; auxiliary functions, such as hot water production, can be made by the same equipment or by separate devices. Poor design and installation are more frequent in integrated systems: in this case a more intensive Cx must be done.

Level of risk

Principally, the level of risk is evaluated by two conditions:

-In general, the risk is calculated in function of how many problems can give a malfunction of the plant. In some cases, this can simply bring on a lower internal air temperature for some days; in other ones, in particular laboratories or computer centers, this can produce worse effects, such as equipment failure: in this case the level of risk increases. In residential buildings, the age of tenants should also be considered: children and aged people can suffer more during a breakdown.

-In addition, the owner can decide the level of risk he is able to accept and modify it, increasing or reducing the level of Cx. In this choice, other factors are also important, such as the environmental awareness, the inclination to spend (or, better, to invest) and the level of desired comfort.

An indicative example for the five levels of Cx can be the following one:

Type 1:	small size building	w/ simple HVAC system
Type 2:	medium size building	w/ simple HVAC system
Type 3:	medium size building	w/ complex HVAC system
Type 4:	large commercial building	w/ complex HVAC system
Type 5:	critical building	w/ complex HVAC system

1.4. Audiences

Annex 40 defines as audience every person or company that participate directly or indirectly at the Commissioning:

The owner

Commissioning rules are not yet mandatory, especially for small plants. If a designer plans a commissioning, the owner will have higher initial costs; also if the designer always plans the commissioning, the owner could ask someone cheaper. It is important that he could understand the advantages for him and for his plant. Furthermore, he must be present at the start up day to learn few rules to follow.

The system designer

As I said before, the I-Cx starts from the design and the designer has the role of planning fully the procedures of the Cx, writing into the design documents. He has also to recommend and justify this to the owner.

The manufacturers

During the Cx, the performances must be compared with known values and in case of I-Cx, the values are provided by the manufacturers. Their role is also to produce well-tuning machines or adjustable components; furthermore, the product should incorporate pressure, temperature and electrical sensors and pre-fittings for external sensors.

Installers

The installers have to respect each indication given by the designer to carry out the commissioning. In small plants, it can manage also the start up and the testing procedure during this.

Commissioning manager

(ASHRAE defines it as commissioning authority)

The commissioning manager is designated to run the plant and, in order to conduct important phases of the Cx, he could be the designer himself. The Annex 40 defines also the Commissioning authority, in case this is different from the designer or the manager, but it is evident that many involved audiences can be difficult to coordinate and this further subdivision should be avoided.

1.5. Advantages of Commissioning

While talking about drawbacks of a Cx could be an absurd, except for a higher initial cost, there are different kinds of advantages, which are not limited to the economic and environmental results.

Occupant satisfaction

The occupant satisfaction should be the first advantage of a proper design and commissioning, in direct and indirect way. Directly, the occupant feels to live better thanks to a high level comfort. Indirectly, if the occupant is the owner, it will be satisfied to have payed a useful service; if the owner is an investor and he rents his apartment, he will not have problems due to complaints by the tenants.

System performance verification and documentation

During the operation phase, the Ongoing Cx verifies the efficiency of the equipment under a whole range of external condition and internal demand. Throughout this process, possible breaking or malfunctions can be easily seen, especially in situations in which the occupant couldn't notice these, for example during the night or a in very short period of time. Finally, all this data are recorded in a documentation that can be useful for following operations, renovations, upgrades, repairs or maintenance.

Reduced maintenance

Maintenance could mean a cost for the owner, an unpleasant situation for the occupants (plant stopping, technicians in own house, noises) and a loss of time for the maintainers. If during the Cx the maintainer is involved, he could learn how the plant works, how it is tuned and how it should be regulated, reducing the time of his service. Proving the final Cx documents, the maintenance results easier also when the maintainer doesn't know the plant. Furthermore, the Cx reduces the number of unscheduled maintenance.

Air quality and comfort

The involved parameters in air quality and comfort are several and variable, so the only way to know them is by measuring and analyzing during the Ongoing Cx. A modern commissioned HVAC could provide a level of comfort never reached before, especially if we consider a large range of features: constant internal temperature, low temperature heating source, ventilation with low thermal gradient, low noise, automatic functioning and self-regulating of the plant, zero emissions, etc.

1.6. Level of detail

Different levels of detail are defined by the rules. Principally, it is possible to operate a commissioning on the whole building, on a single system, on a sub-system, or on a single component. This level of detail is strictly related to the level of risk. A more accurate subdivision, with examples, is shown in Figure 6.

1.6.1. Direction of the Commissioning

There are two opposite directions to follow the chart in Figure 6, and both are described in the Annexes 40 and 47 documents. The first one consists in starting from the main system or from the building and going in details, when large range Cx is finished; it is called "Top Down" representing exactly the direction followed in the chart. The opposite one is called "Bottom Up", starting the analysis from each component then going to the whole system.

The "Top Down" approach starts commissioning the whole plant. In some cases this could be a very fast operation, without time losses on the details. However this implies the drawback that some components could not work as well as they could. Usually the Top Down approach analyzes the sub system or the components only if some malfunctions are revealed.

At the opposite, the "Bottom Up" approach is a very accurate and safer model, but it generally requires more time while some problems could be easily solved at a lower level of details.

The experience of the manager, as I saw on the field, is very important to reach faster the right level of the problem. Apart from the technical experience, some problems can be solved knowing the theoretical and physical functioning and comparing it with the actual one: in the *Chapter 4*, the problems that occurred during the start up are explained and solved in this way.

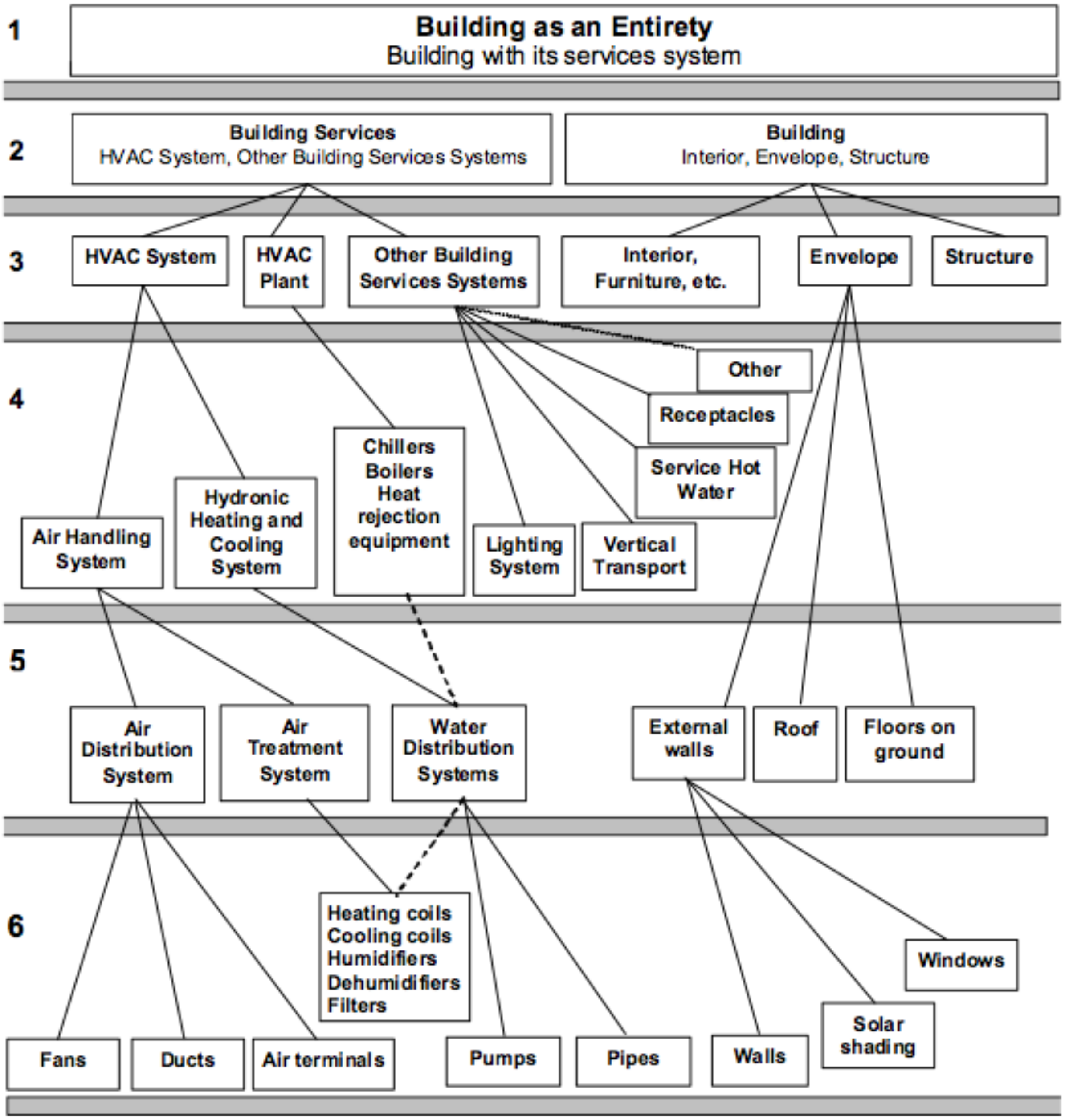

Figure 6. Commissioning components on different level of detail (from Annex 47)

2. HEAT PUMPS

2.1. HVAC systems

The acronym refers to Heating, Ventilation and Air Conditioning. An HVAC system is designed to provide environmental comfort to occupants and adequate indoor air quality in buildings. The main parameters for a heating system that provides comfort are temperature, relative humidity and velocity of indoor air. Furthermore, there are non-numeric parameters to analyze for a good level air quality: principally, these are the olfactory perception and the presence of hazardous contaminants, such as smoke, dust, airborne bacteria, carbon dioxide, etc. The HVAC intervenes on the air quality by an emission control at the source, a ventilation system and a filtration of air.

All the plants analyzed in this work provide both heating and air conditioning using a single device: a heat pump. The ventilation is done with a separate mechanical system; however, an accurate project and a complete commissioning must deal with the plant as a single system.

2.2. Heat pumps

The heating can be provided by a furnace, a boiler or a heat pump through water, air or steam source. When the building has an integrated photovoltaic plant, the long-term best choice is surely the heat pump. The basic physical principle of a HP is to provide heat from a cold source to a hot source providing work, according to the second law of Thermodynamics; Figure 7 summarizes this phenomenon.

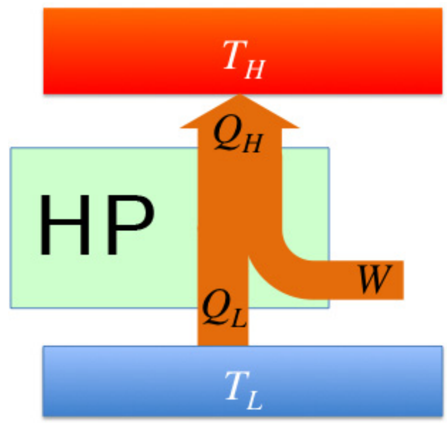

Figure 7. Energy flow in a HP in heating condition

Using a natural and infinite "cold" source, such as air or water, the HPs are classified as partially renewable energy systems, also without using renewable electric energy. In addition, this permits to reduce the electric consumption, since a part of heat comes from the cold source. Naturally, it is easy to understand the best performances could be obtained using a cold source as hot as possible.

The air source is free, "infinite" and everywhere present, so this made the air the most used source in HP plants. However its low temperature, especially in the heating season, gives a performance not as high as for a water source. In fact, water can be found in the subsoil at higher and constant temperatures (in Torino region, about 54°F or 12°C). Nonetheless, it can be difficult to find a clean well in stable conditions over many years. The subsoil itself can be used as a geothermal cold source, using a fluid carrier, as air or water, reducing the gap between low and high temperature and giving one of the higher performances that a HP can reach.

2.3. Thermodynamic cycle

Looking at Figure 8, when the liquid refrigerant enters in the evaporator, its temperature is lower than the cold source, since it lost many degrees of temperature during the expansion. The evaporator is a heat exchanger between refrigerant and air or water. At constant pressure, the refrigerant goes out in vapor phase, due to the heat exchanged. The next stage, the compression, increases its pressure and consequently its temperature, using electrical energy converted in compression work.

The condenser operates in opposite way of the evaporator: on the high-pressure side, the gaseous refrigerant loses heat in favor of the hot source, which will provide heat to the building. At the last step, an expansion valve provides the pressure drop from the high to the low-pressure circuit.

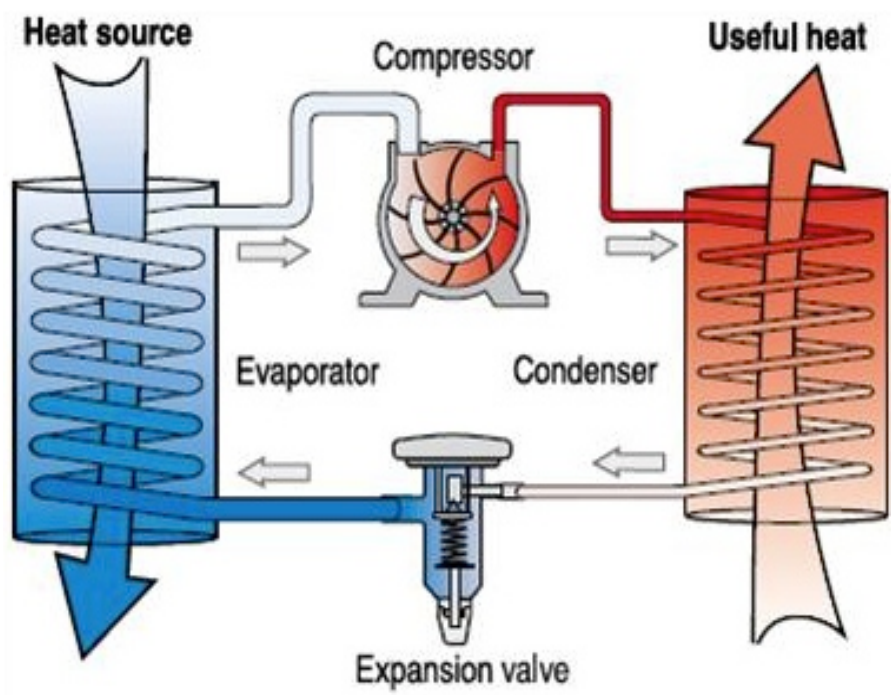

Figure 8. Main components in a non-reversible HP

Thermodynamically, these four components can be associated with four thermodynamic processes:

4 > 1	Isobaric evaporation
1 > 2	Isentropic compression
2 > 3	Isobaric condensation
3 > 4	Isenthalpic expansion

HPs commonly use the direct refrigeration cycle, with the sequence previously described. In cooling operation a changeover is performed, thereby reversing the function of evaporator and condenser. The cycle is shown in Figure 9.

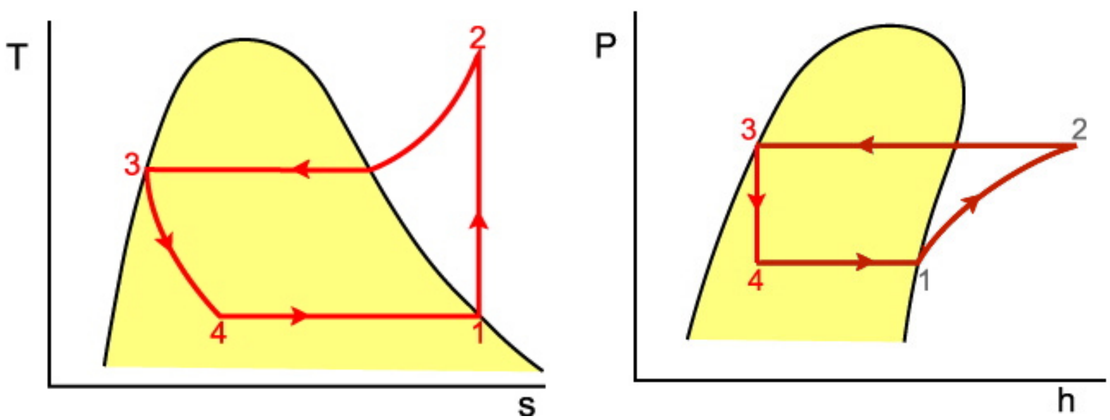

Figure 9. Ideal refrigeration cycle in heating condition. a) T-s diagram, b) p-h diagram

2.3.1. Sub-cooling and super-heating

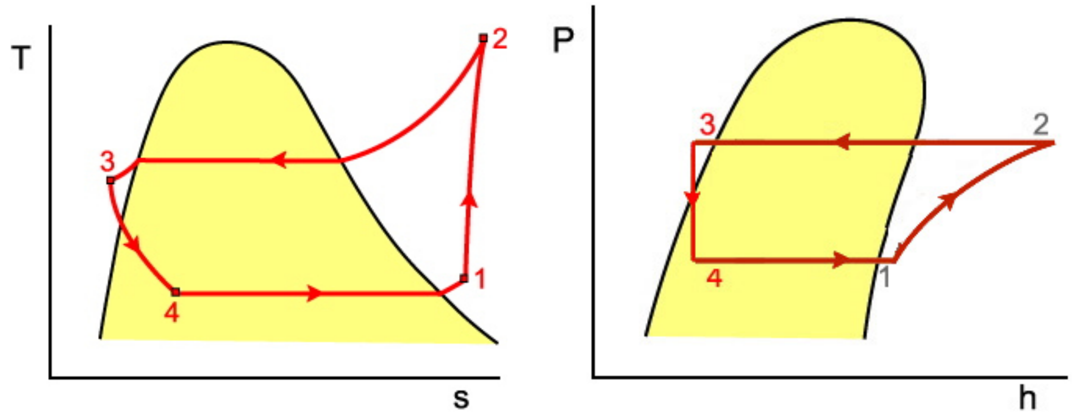

Figure 10. Actual refrigeration cycle in heating condition. a) T-s diagram, b) p-h diagram

On the p-h diagram, a large part of the refrigeration cycle crosses the two-phase region but the little parts in the liquid region and in the vapor region are as much important. It is called sub-cooling the part of the isobaric transformation below the liquid saturation curve and super-heating the part of the isobaric transformation above the vapor saturation curve, as in Figure 10.

These two phenomena must always be present and they need a detailed study during the commissioning. Apart from reducing the performances, a lack of one of these can seriously damage the equipment.

In fact we need sub-cooling in order to allow the expansion valve to work properly. In terms of performance, the sub-cooling increases the heat capacity of the refrigerant. The super-heating is principally done to avoid a partially liquid refrigerant entering in the compressor, which may cause serious damage.

During commissioning, these two parameters must be measured in terms of temperature difference. Both of this phenomena occur at constant pressure, which can be measured at the outlet of the condenser and evaporator; the saturation temperature at a given pressure is well known using the R407c charts. The expansion valve inlet temperature must be lower than the liquid saturation temperature and this difference represents the sub-cooling amount. At the opposite, the compressor inlet temperature must be higher than the vapor saturation temperature and the gap is the over-heating amount.

To sum up, we need four parameters to calculate the sub-cooling and the over-heating: two pressure values (high pressure side and low pressure side) and two temperature values. An advanced heat pump have integrated sensors to measure these values; however during the commissioning is advisable to use a manual pressure gauge, since a precision of a tenth of K on the final result is required.

$$\Delta T_{subcooling} = T_{sat}(p = HP) - T_{HP,OUT} \qquad (2\text{-}1)$$

$$\Delta T_{\sup heating} = T_{LP,OUT} - T_{sat}(p = LP) \qquad (2\text{-}2)$$

2.4. Definitions of performance indexes

Some parameters are defined by the technical standards and codes for permitting a comparison between different heat pumps or between different operating conditions of the same heat pump.
Physically, the efficiency is defined as the ratio of the useful energy to the energy input (or energy spent). If we consider all the energy input, work or heat from the cold source, the efficiency will be always equal or lower than 1, according to the conservation of energy law. However, as we said before, the HPs use a part of solar heat there is into the external source and this part must not be considered into the efficiency definition. Consequently, the value describing the heat pump performance could be often higher than 1. This choice was done in order to compare the performance also between HPs and different heating system, such as boilers or furnaces.

$$COP_{heating} = \frac{Q_H}{W} = \frac{Q_H}{Q_H - Q_L} \qquad (2\text{-}3)$$

This formula, written in power terms , obviously refers to unit time; from this, it is possible to calculate the COP for a day, a week, a month or the whole season. There are several methods, from simple ones to complex ones: the quicker method is to write the formula in terms of total energy:

$$\mathrm{COP}_{seasonal} = \frac{Heating\ Production}{\text{Electrical Energy Consumption}} \tag{2-4}$$

This COP represents the efficiency with the losses. The maximum efficiency for a heat pump operating between two temperatures has been defined by Carnot in the following formula:

$$COP\max_{heating} = \frac{T_H}{T_H - T_L} \tag{2-5}$$

The same calculation can be done during the summer, taking care that, in this case, the useful energy is represented by the cold side heat.

$$COP_{cooling} = \frac{Q_L}{W} = \frac{Q_L}{Q_H - Q_L} \tag{2-6}$$

$$COP\max_{cooling} = \frac{T_L}{T_H - T_L} \tag{2-7}$$

The energy values can be written in Joule (J), which is the S.I. correct unit, or in British Thermal Unit (BTU); in the same way for the power, we can use Watts (W = J / s) or in BTU/h. However the BTUs cannot be used for electrical energy; this problem has yielded a new definition, the EER, in which the heat is written in BTU/h and the electrical power in W, giving a result 3.42 times than the COP.

$$EER = 3.42 \cdot COP \tag{2-8}$$

The SEER is the American equivalent for the Seasonal COP.

$$SEER = 3.42 \cdot COP_{seasonal} \qquad (2\text{-}9)$$

It is useful to know the seasonal COP and the instant COP on a time history, especially during the ongoing commissioning. This gives the possibility to compare different seasons during the years, similar plants or different days.

However, COP doesn't include the final results, in terms of internal temperature and comfort. So, the purpose of commissioning must not be limited to the analysis of the COP, since this datum could hide some problems.

2.5. Refrigerants

Since the 1996 Montreal Protocol, CFCs are phased out; in a second time, also HCFCs are gradually reduced in use (the production stopped in 2009).
New generation refrigerants, such as R134a, R407c and R410a, know as HFCs, have become the most used in air conditioning plants and heat pumps, although they are not free of drawbacks. The research is going to develop alternative fluids, which may be less dangerous for the global warming.

2.5.1. R407c

This work doesn't describe each refrigerant, but it looks at the R407c, which is the refrigerant used in the analyzed plants. R407C is a blended refrigerant, specifically it is a mixture of R32, R125 and R134A. R407C has zero ODP (ozone depleting potential) but it has the disadvantage of a GWP (global warming potential) equal to 1600. Technically speaking, the success of R407c is probably due to its similarity with the R22, a HCFC largely used before the phasing out.
It is a zeotropic fluid, because at a given pressure each part of the blend boils at a different temperature. This means that, in each saturation condition, the liquid composition is different to the vapor one. This is the reason why the cylinders must contain liquid R407c and they cannot be used wholly to avoid using the vapor part at the bottom.

2.5.2. R407c lubricants

The lubricant, compatible with R407c, is a synthetic polyolester (POE). The pump, its accessories and its piping, and the used equipment must be compatible with R407C and polyolester lubricants. Furthermore, they must not be used with other refrigerants, which (in particular the R22) are soluble in POEs.
The POEs are hygroscopic and they absorb air: this is one of the reasons because we use Nitrogen flow during the welding and the components are sold sealed. In general, a little quantity of air is kept by the oil, although the evacuation is made. To reduce this amount it is possible to install a dry filter.

2.6. Ochsner characteristics

Four analyzed plants are powered by Ochsner[2] HPs, in detail three reversible air-water HPs and a traditional water-water HP.

The air-water systems have a separate and external evaporator, principally constituted by a chassis in stainless or varnished steel, a heat exchanger, one or more fans and the expansion valve for the heating condition.

The HP body contains the other components, mounted on a soundproof suspended double chassis and leant on a damping mattress. The HP is connected by input and output of the refrigerant circuit from/to the evaporator, by delivery and suction of the hot water circuit, by the electric circuit (220V and 380V) and by the signals from the external accessories (control unit, evaporator sensors, boiler, etc.).

Internally, an electric panel receives external and internal signals and electricity and sends feedings to the internal components and signals to the external electro-motorized actuators on the hydraulic circuit is valves. Also, two important safeties are mounted on this one: a phase control (the compressor doesn’t start if the phases are inverted) and a soft starter for reducing the compressor current during its starting.

The internal condenser receives high pressure vapor from the compressor and sends liquid to the external expansion valve crossing a vessel, a filter and a spy-hole, on which it is possible to see if there is flow (green signal) and if there are no vapor bubbles (there should be only liquid).

The pump must work also in reverse cycle; so, it is necessary to add a 4-way valve, two bypass valves, and an other expansion valve with respect to a traditional heat pump. The following scheme is useful to understand these modifications, representing a heating situation.

[2] Ochsner Warmepumpen is one of Europe's foremost heat pump manufacturers, founded in 1978. It is distributed in Italy by Heliant: an interview with the Heliant president at the end of this dissertation explains better the role of these two companies.

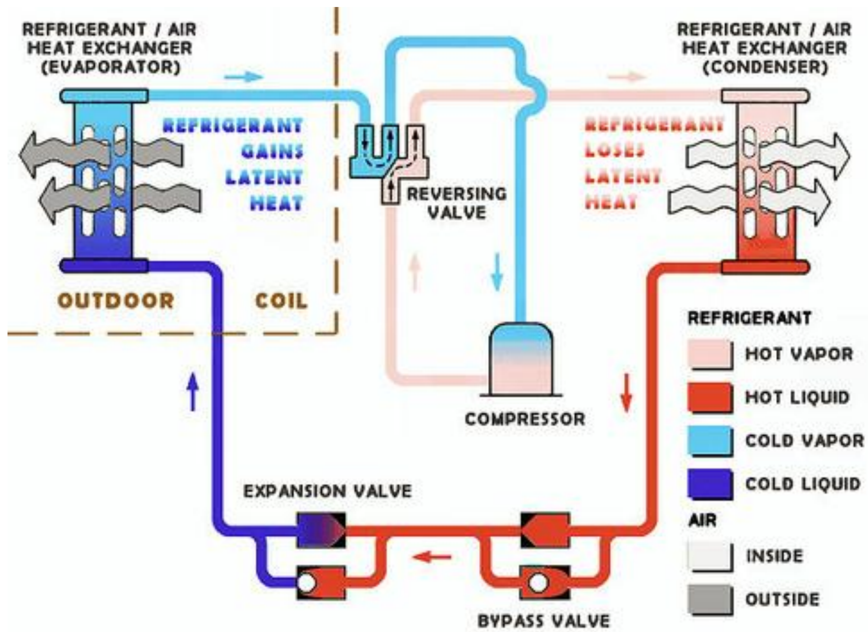

Figure 11. Main components in reversible HP

It is necessary to have two expansion valves in a reversible heat pump: in fact they permit to have two different tunings, apart from avoiding additional circuit modifications. This additional valve is thermostatic and it has a limited working range because the temperature band on summer is not too large; on the other hand, the expansion valve for heating conditions is a controllable electro-valve because it must permit to work on a high range of temperatures.

On the hydraulic circuit, which crosses the condenser, a pump inside the HP is mounted; on more recent machines, its speed is variable in function of the temperature to optimize the efficiency and its pressure head must reach the storage tank. On that last one, it is mounted the electric resistor that must supply heat in case of very cold weather. An expansion vessel is also necessary on the hydraulic circuit.

On a water-water Ochsner plant, the HP receives a water input, taken directly from the source or from a closed circuit heated by a heat exchanger; in order to transfer heat to the refrigerant, the HP uses an internal evaporator, similar to the condenser. The other components are similar, but in this case the HP can be not reversible.

2.7. Vapor injection technology

The most advanced Ochsner products use the vapor injection technology, which consists in introducing vapor at an intermediate point of the scroll compressor, as in Figure 12. The Ochsner designers indicate the condenser output as the best point where taking the vapor.

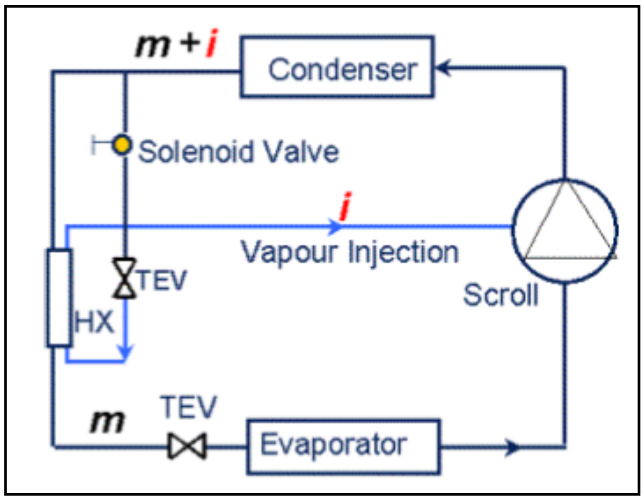

Figure 12. Main components in HP with Vapor Injection

This operation modifies the thermodynamic cycle (Figure 13): after the condenser sub-cooling, the cycle is split in two parts, the mass flow *i* is partially expanded into the new expansion valve. The HX permits to sub-cool further the flow *m* and to overheat the flow *i*. The additional sub-cooling permits to reduce the temperature from T_{LI} to T_{LO}, so the enthalpy is reduced too.

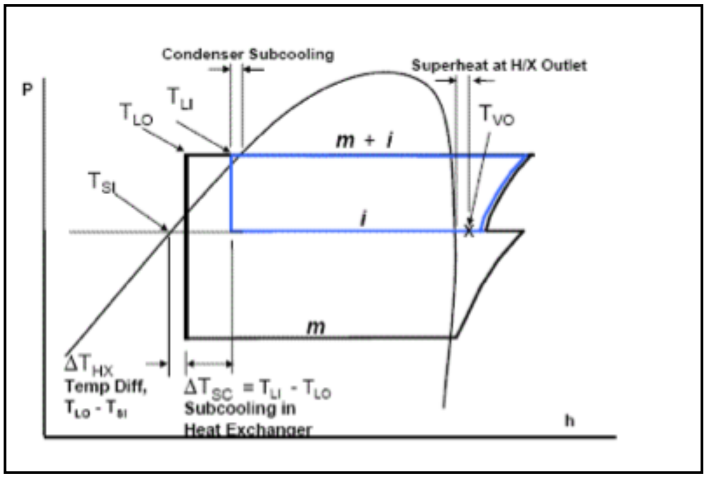

Figure 13. Refrigeration cycle in HP with Vapor Injection

As said before, the vapor is added in an intermediate point of the compressor, through two symmetrical ports; Figure 14 explains schematically this. In this way, the injected vapor is compressed only in the high-pressure stage, reducing the amount of necessary energy with respect to a whole compressing stage.

Figure 14. Schematic section of scroll compressor

Figure 15. Detail of the vapor injection compressor in one of the examined plants

2.7.1. Advantages and drawbacks

The advantages of this technology consist in an increased efficiency and in an outlet temperature than can reach 65°C.

Additional components are necessary: a solenoid valve, an additional expansion valve, a heat exchanger and further copper pipe. Therefore, the drawbacks of this technology are the higher complexity of the heat pump and a more expensive initial investment.

In practical terms, this technology should be adopted when a high hot source is required, such as for old radiators that must reach more than 50°C or, more in general, if the customer accepts to spend more, about one thousand euro more on a medium size plant, with the concrete hope to additionally reduce consumption and pollution.

3. START UP PROCEDURES

The first day of running is often also called commissioning for many typologies of plants while, to avoid confusion, this work use the term start up. For this thesis, this day gave a large amount of useful information and data, having assisted to three startups in July 2011.

During those intense days, the commissioning phases consist in:

-Verifying if the construction has respected all the criteria given by the project. The points to control are listed in a “Check in list”.
-Controlling the final phases of the construction, which consist in refrigerant circuit welding, testing and charging.
-Testing all the components
-Running the plant in all the possible configurations
-Taking all the data given by the internal sensors on the heat pump and filling a commissioning report with these.
-Making additional numerical survey with external instruments and analyzing them.

In this chapter, each phase, except the last one (see *Chapter 5*), is analyzed deeply.

3.1. Check in list

The check in list consists in a series of initial controls that must verify if the installation has been done following the project and the HP manual. The whole thermal station, including HP, piping, each accessory and, if present, the evaporator are examined. At this moment, external instruments are not necessary because the analysis is done fully with visual controls.
This is the first step and, in case of a situation different from the optimal one, it signals a problem that must be solved before the plant starting.

Heat Pump
We have to verify there are all parts and these are correctly assembled and not modified. The position of the pump should be done in order to easily walk around.
We have to verify if there is the genuine sound insulation and if it was added on the bottom of the HP. When the HP is located outdoors, such as in a wood shed, this also must be insulated.

External sensors
One of the first things to look at is the external sensor: this is often located in a easy place, while it should be located in a neutral zone, possibly on the north surface (in order to avoid direct irradiation) and far from cold or hot sources (e.g. doors, manholes, etc. or the evaporator itself). Both standards and heat pump manuals indicate in detail its right position. Naturally, this must be rightly connected to the control unit.
In four air source plants we examined, the sensor was in a wrong position twice.

Electrical system
It is necessary to control the power panels: they should include independent lines of compressor and control unit, with separate and labelled switches and the right voltage, frequency and phases for each. In addition, the panel must contain also the electrical protections.
About the cables, each component must be connected to the electrical system using named cables with appropriate diameter, of the right length (not too short and too long) and following a logic path. The external connections must be done into waterproof boxes.

Refrigerant circuit

We have to verify the refrigerant circuit from the heat pump to the evaporator. The welding is made during the commissioning day, so it is not difficult to look at the circuit. The project imposes a maximum length not to be exceeded, while diameters are indicated in the HP manual. In the case of Ochsner products, there is the possibility to use a single pipe with prefabricated curves (adopted for the Montiglio plant, see *Chapter 4*) or more than one small diameter bending pipe (adopted for the Rivalta plant).

The tubes must be well fixed, coated and protected from water infiltrations.

Hydraulic circuit

Each component that completes the hydraulic circuit must be examined. First of all, the tank has to be on the right size, respecting the project that usually considers 30 liters / kW. It has to include the electric resistor. The expansion vessel has to be preloaded at a given value.

On the whole, the circuit needs to be filled and the air must be totally expelled. Before doing this, it is mandatory to wash the circuit, putting in circulation running water, in order to clean this from the dust accumulated during the works; otherwise the risk is to clog very soon the filter.

Evaporator

We must verify the evaporator is intact, undamaged and well set up: it must be flat, located on a drain floor and have a sufficient walk around space. Also the distance and the height difference with the HP must be below a certain limit.

Accessories

Sensors and actuators must be connected. The remote controls in the apartments must be located in the right places indicated by the project, connected and assigned to the control unit.

3.2. Air source procedures

The main procedures to start the plant can be split in two parts: the first consists in preparing the refrigerant circuit and it must make by both installers and the managers, that designated to run the HVAC plant; the second one, which consists in testing on the equipment, are made by the managers.

3.2.1. First part

The refrigerant circuit is one of the most fragile parts of the HP, so it is important that a supervisor is there and these procedures are also part of the initial commissioning.

<u>Opening the circuit</u>

Both heat pump and external evaporator circuits are provided by the constructor completely sealed, with Nitrogen in pressure. This is a warranty that there is not any dangerous dust or water.

Before opening the circuits, it is necessary to remove all the pressure. It is possible to do this by linking a pressure gauge to a pressure sensor and opening its output.

After a couple of minutes, the internal pressure will be close to the atmospheric pressure: at this moment, it is not necessary that the circuit is totally empty of Nitrogen, because the evacuation will be done in a second time.

This can be a first warning: if a little quantity of gas goes out from the equipment, these can have lost pressure during the transportation or the installation. Of course, they must be repaired and the start up has to stop.

Now, the installer can cut the U-pipe that close the circuit, as shown in Figure 16, linking input and output in the HP; on the evaporator, he must de-weld a pair of caps.

Figure 16. U-pipe cutting in one of the examined plants

Welding and coating

The technician makes the welding between external evaporator and the heat pump. Welding techniques are explained in a dedicated chapter.

Right after that, the coating must be added: the data, obtained during the simulations, must be similar to normal using condition and, especially in open spaces, the temperature with or without coating, can vary by a couple of degrees. Figure 17 represents an example of a correct coating

Figure 17. A well done coating between evaporator and HP

At this moment, a careful installer could make a pre-vacuum. This operation, which doesn't require more than ten minutes, is not indicated on the codes, but permits to reduce the time in which oxygen is in contact with the refrigerant oil.

Pressure testing

The first testing we have to do is the pressure testing, which is done to verify if all the weldings are well done and, consequently, if there are no losses in the circuit.

We use Nitrogen at a pressure value, depending on the refrigerant that will be used, for at least 15 minutes. A pressure gauge permits to load the circuit and then to verify the pressure doesn't drop.

A dedicated section about this instrument explains better the procedure.

Evacuation

The opposite testing is also done: with a vacuum pump (in Figure 18), we reset to zero the absolute pressure. The pump must work for at least an hour. After this hour, the same gauge used before verifies the pressure doesn't rise in the next ten minutes.

Figure 18. Typical vacuum pump

Charging

This step consists in making the refrigerant charge. The nominal charge is fixed by the constructor and by the designer; however, this represents only the minimum charge to fill the main circuit. The final charge will be higher than the nominal, taking into account pipe and accessories.

Also in this case, the pressure gauge (Figure 19a) is the link between the refrigerant cylinder and the heat pump. An electronic scale (Figure 19b) displays how much refrigerant is already in the circuit.

The first liters enter thanks to the cylinder pressure; when the cylinder and the circuit pressures are balanced, we need some tricks. An interesting one, made during the Montiglio commissioning (see *Chapter 4*) by the Austrian technicians, is to stop the evaporator fan. In this way, the low pressure goes down and the equilibrium point is lower.

If the minimum amount of refrigerant required to start the cycle is present, the compressor can be turned on (see point 6).

Figure 19. Charging accessories. a) Cylinder and pressure gauge, b) Electronic scale

3.2.2. Second part

Starting

Now, the plant is ready to start, however the refrigerant cylinder must remain connected. The temperature at which the testing should start is about 25° C. If it is higher, as it often happens when there are working solar collectors, it is necessary to reduce it with some tricks (e.g. starting the HP in reverse cycle or diffusing the heat in the radiators).

The first testing is done in heating condition: the temperature must reach at least 40°C (it could take more than an hour). At this time, we measure all the data for the commissioning report.

However, the HP start must be done gradually. By the control unit, the manager can activate each component, in particular pumps and valves, and verify temperatures and pressures. These operations must be done in parallel with Point 5 and the compressor, one of the most fragile and expensive parts of the HP, can start only when these procedures have been successful. In general, the most important condition we have to verify before starting the compressor is that there is a minimum overheating gap, in order to avoid liquid enters in the compressor, ruining it.

Defrost simulation

The second testing consists in simulating a defrost situation. In air-water plants, defrost is always necessary. So, the plant must be reversible, also if it will be used for heating only. When the temperature in the evaporator goes dramatically down, some ice can appear on the exchanger; in order to melt the ice, the HP starts in reverse cycle (or, more simply, it switches the 4-way valve), providing heat to the evaporator fins. We can artificially produce this phenomenon by stopping the evaporator fans or spilling some water on the fins or both.

An important parameter for the commissioning is the defrost end temperature. Usually, the manufacturer recommends a value, in this cases equal to 20° C. This must be the right trade off solution between having a complete defrosting and not dissipating a lot of useful energy. In summer, when we have made our commissioning cases, it was not a problem to reach and to go beyond the defrost end temperature (we reached 40° C, which is an equilibrium between outdoor and hot vapor temperature) but in winter things may change.

The number and the gap between defrosts could be monitored and analyzed in a on-going commissioning study, as we did on the Heliant plant (*Chapter 5*).

Reverse cycle testing

If requested and permitted by the project, an HVAC works also as a cooling system, and it must be tested in this condition too. This testing also verifies that the 4-way valve and some non-return valves work correctly.

DHW

In the plants where the HVAC also produce Domestic Hot Water (DHW), there is an additional step that can be done. In particular, this is not a check on the heat pump functioning but on the plant in general, because the difference between DHW production, heating production or both depends on the circuit downstream the heat pump. Two electro-motorized actuators mounted on 3-way valves are controlled by the control unit and they are rotated of 90° to switch the circuit or in a intermediate position.

3.3. Water source procedures

In a water-water heat pump, the refrigerant circuit is totally inside the HP; in fact also the evaporator, in this case represented by a water-refrigerant heat exchanger, is into the chassis.
The construction of a water-water plant is more complex; it can require more permissions and it needs digging a well and pumping the water to feed the evaporator. However, this simplifies a lot the procedures during the start up, because, in that day, weldings and refrigerant charging are not necessary.
Apart from the check in list, which must be always done, before starting the plant, the manager has to check the water circuit, checking the filter, running the pump and verifying the flow value. Then, the procedures start from the heating condition testing. Defrost is obviously not required, so it is tested in DHW functioning and in cooling mode. In some cases, the cooling mode could consist in a free cooling, where the heat pump is by-passed and only the heat exchangers and the pumps work.
It is interesting to notice that also the tuning of the HP is easier, since the machine arrives already tuned by the constructor, since the refrigerant cycle is pre-filled and sealed.

3.4. Welding techniques

The first part of the procedures is made by the installers, however the manager must be present during this operation to verify these are made correctly. This is the reason because these must be done during the start up instead of during the construction and they make a part of the commissioning itself. For this reason, now, we analyze more carefully the welding techniques applied on the Point 2 of the procedures, while in the next subchapter we will analyze the main instrument used from Point 3 to the definitive operating condition: the pressure gauge.

The American Welding Society (AWS), in collaboration with the Copper Development Association, defines the main welding procedures for copper pipes. These rules are created for American application, but are worldwide known. In Italy, the equivalent of AWS is the "*Istituto Italiano della Saldatura*" (IIS), which provides similar data-sheets according with the UNI EN rules about copper welding.

The mostly used welding techniques are brazing and soldering. The procedures and the theory are the same for both technologies, but the working temperature changes.
The AWS has defined as copper soldering all welding processes below 840°F (450°C) while as copper brazing the processes above this temperature. Commonly, soldering is made between 350°F (180°C) and 600°F (320°C) and brazing from 1100°F (600°C) to 1500°F (800°C). The operating conditions, in particular the service temperature, determine which is the best technique; furthermore, when there is a great joint strength, brazing should be used.
The procedure, except for fluxes, filler metals and heat used, is similar for both techniques:

Measuring

The installer has copper pipes in several diameters, curves and joints. Before starting the work, it is necessary to study the path to follow and where the joints will be located, trying to reduce the number of curves and the length. A well-done project can help this work, but usually too many variables during the installation change these details. A good compromise is the installer could make his personal path based on his experience, following some mandatory guidelines from the designer and the constructor. After that, the pipes are measured and marked.

Cutting and reaming

There are different cutting methods: the most used one is the disc-type tube cutter (Figure 20a), which guarantees rapidity and orthogonality. Cutting produces a small burr that can be dangerous creating turbulence; so, the next step consists in reaming the pipe ends: it is possible to use a precise and quick de-burring tool (Figure 20b), otherwise a file or a knife could make the same work.

Figure 20. Cutting tools. a) Disc-type tube cutting, b) De-burring tool

At this moment, the pipe end diameter can be increased to create the right junction between tubes, if necessary.

Cleaning

It is mandatory that pipes are completely clean internally, both for making a right welding and for keeping the refrigerant circuit clean. The best way to have a clean tube is to never soil it. To clean the internal surface, properly sized fitting brushes are available.

The external surface, in particular the pipe end, which is surely the dirtiest, can be cleaned with sand clothes or abrasive pads.

<u>Fluxing, assembly and support</u>

The ASTM B 813 requires to apply a re-oxidant on the pipe surface before using a soldering flux able to dissolve surface oxides.

Then, technicians proceed to assembly two pipes together and support these before soldering.

<u>Heating and applying the filler metal</u>

The soldering is made by melting a filler metal on the junction, in order to obtain a complete and stable seal of the connection. The filler metal is usually melted with an air-fuel torch. This work doesn't deal with the detailed procedures to make the right soldering, which are well explained in the AWS rules.

All brazing during our commissioning were made using inert gas flow, such as Nitrogen. Introducing Nitrogen in an open junction of the circuit during the welding process permits to eliminate Oxygen on the internal surfaces, reducing the oxide formation. This operation is also known as "purging".

a)

b)

Figure 21. a) and b) Copper soldering during one of the examined plants

In the picture above, it is easy to see all operations made during the soldering: the filler metal in the left hand, the air-fuel torch in the right hand and the Nitrogen flow entering the pipe on the right of the picture. In this photo, the support is simply represented by a concrete block.

Cooling and cleaning

This kind of operation, usually made by Italian technicians, is different from the AWS codes. AWS prescribes a natural cooling, in order to avoid cracks due to shock cooling. This is absolutely true but, unfortunately, the weldings in refrigerant circuit are often made near components. These accessories can be damaged by the high temperature that the welded pipes reach. For example, the evaporator side welding is made near the electronic expansion valve. So, some wet rags are rolled up around these components during the welding; then, further ones are put on the welded pipe for dropping the temperature and preventing the heat diffusion. The same rags have the function of cleaning the pipes.

3.5. Pressure gauges

The analogical pressure gauge is surely the most important instrument during the first phases of the start up. The utilized heat pumps contain internal pressure sensors, but the accuracy of this external gauge is usually better. Its functioning is fairly simple but all its potential is know only to experts.

Before explaining its role during the start up, we briefly summarize the functioning. Usually, it is composed by two pressure gauges, three hoses, two valves and a metallic body, as in the Figure 22.

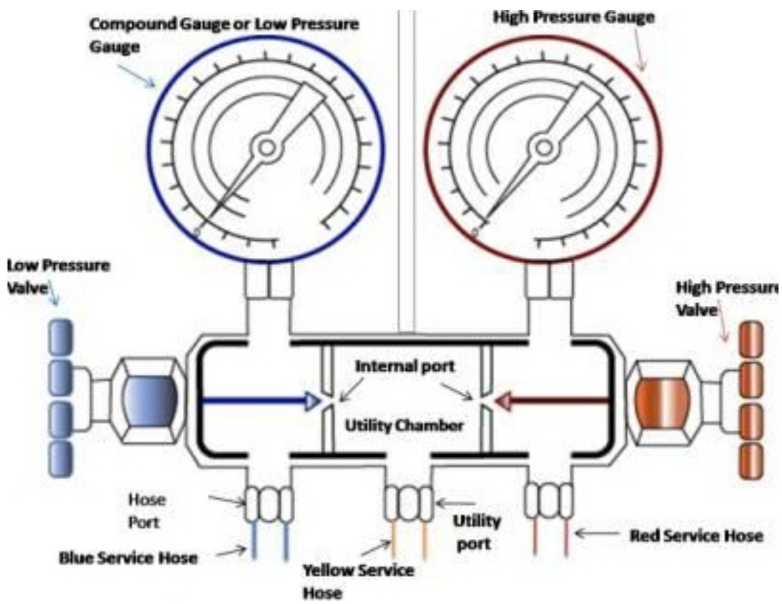

Figure 22. Pressure gauge scheme

The red pressure gauge has a high-pressure range and is dedicated to measure the high pressure side on a plant. Apart from the pressure scale, it has internal temperature scales, with which it is possible to know the saturation temperature for the most common refrigerants. The blue gauge is similar, except for a lower but more accurate pressure range, useful to measure the low-pressure side; Figure 23a and 23b show the difference.

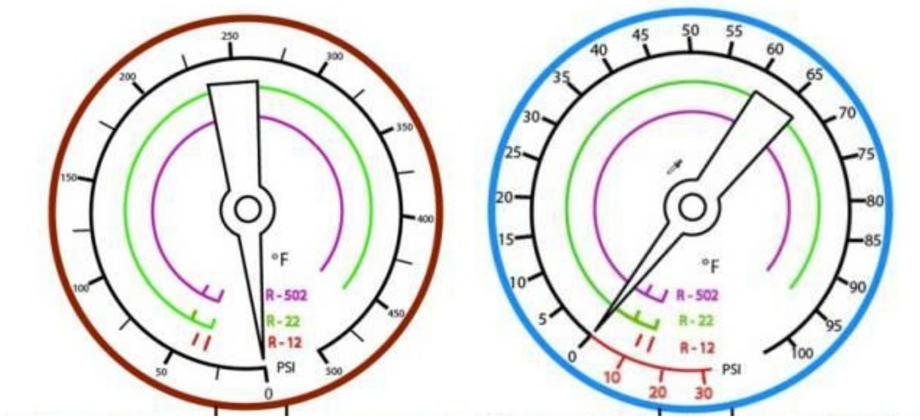

Figure 23. Pressure gauges. a) High pressure side, b) Low pressure side

The three hoses have the role to link the gauges to the equipment. In our case, the blue hose (or, better, the hoses before the LP gauge, because the colors are useful but the hoses could be easily exchanged) is connected on the pressure outlet between the evaporator output and the compressor input. The HP hose must be connected between the condenser output and the expansion valve input. The central hose (usually yellow) connects the gauge to external devices and permits to this instrument to become a connection between the HP and the devices, for example the R407c cylinder or the Nitrogen one.

The hoses contain oil; obviously, the oil must be compatible with the refrigerant. This is one of the reasons why a pressure gauge can be used only with a single type of refrigerant.

Several possible configurations can be created using the two valves on the sides, taking care that a wrong use could seriously damage the heat pump, the gauge itself or, worse, the workers. As in the figure above, the valve can open the gate between the LP or the HP side and the utility hose. These are closed during a simple pressure reading and opened during the charging and the evacuation.

3.5.1. Digital pressure gauges

A logical evolution is represented by the digital pressure gauge, represented in Figure 24. For what it concerns the pressure, the instrument doesn't change, except for the reading display type; however, it usually adds a function: two temperature sensors can be connected to the instrument, in order to calculate automatically the sub-cooling and over-heating values.

Figure 24. A working digital pressure gauge

3.6. Commissioning report

When the plant is running correctly, the Ochsner technician concludes the start up day by filling a commissioning report. This is a final survey of the working conditions, which concludes the Initial Cx. It doesn't require additional instrumentations (except a classical electrical tester) reading directly the information from the OTE control unit, obtained by the sensors mounted onboard the HP: so it could be done also by a qualified installer.

The main difference with respect to a commissioning testing with computerized instrumentation, is that this report represents an instantaneous situation, while a computerized method can record a time history, as described in *Chapter 5*.

Principally, the commissioning report includes electrical parameters, temperature and pressure data and the settings; also, for the sake of completeness, it reports the information about the model of each component and the technician personal details.

<u>Electrical parameters</u>

Using an electrical tester, the technician reads voltage, current and power information on the HP electrical panel. First of all, he records the input values from the power line, separating the three phases (all phases are measured) and the mono phase. Secondly, he verifies the current value on the protection systems and, last, he measures the absorption of the working components (compressor, evaporator fans, pumps, etc). In details, the three values of current, the voltage, the power, the rotation way and the power factor are required.

<u>Temperatures and pressures</u>

The temperature and pressure measurement is followed with a right logic, from the heat source to the final use. So, input and output temperatures of the source are reported, in addition to piping information (diameters, lengths, materials, number of sensors, etc). On the refrigerant circuit, temperature and pressure are measured to obtain super heating and sub cooling temperature differences; the models "Plus" with Vapor Injection Technology have additional temperatures and pressures to measure in order to calculate a second value of super heating and sub cooling.

Final, the heating circuit is measured, both in heating condition and in domestic hot water production, obtaining the input and the output temperatures and their difference.

Expansion valve setting

This includes a complete description of expansion valve model and tuning, including a sketch or a photo of its location. Of course, on reversible HPs, separate data are reported for both expansion valves.

Plant tuning

The tuning operations, mainly made parallel to the first starting simulations, are one of the most difficult procedures and require the knowledge of the heat pump, of the plant, of the user needs and a good level of technical experience. The manufacturer recommends default values, useful for the first attempt, which will be changed during the testing to improve the performance or, principally, to solve problems. This part can require a couple of hours, usually distributed by the technician along the whole start up day.

A large part of the tuning is made directly using the Ochsner OTE control unit and each setting is reported on the commissioning report. The main parameters are the indoor temperature and the heating/cooling curve, with respect to the external temperature, and the threshold between heating and cooling mode. If the HP produces also DHW, the settings can be and usually are different for direct heating mode, DHW mode or mixed mode; consequently, each parameter is reported in three different tables. These are followed by general settings for the HP, such as the threshold of compressor intervention and defrost cycle start and stop.

4. EXAMINED CASES

4.1. First commissioning

Location:	Rivalta, TO, Italy
Heat source:	Air
Heat pump:	Ochsner GMLW 14 Plus
Thermal power:	14 kW
Cycle:	Reversible, Vapor Injection
Duties:	Heating, DHW, Cooling
Cx Type:	Initial Cx

Figure 25. The HP without cover

In Rivalta, near Torino, a commissioning study was done on an interesting plant, using an HVAC with an Ochsner Heat Pump with "Vapor Injection Technology", a GMLW 14 Plus, photographed in Figure 25, matched with solar collectors and a photovoltaic system. It feeds radiant floor through the heating system and produces also hot water until 65° C (150° F).

Figure 26 shows the evaporator during the welding phase. According to the check in list, it is flat (verified in each direction by the spirit level on the picture), it is located on a drain floor (after the welding, the remaining space will be filled by stones) and it has a walk around space.

Figure 26. The external evaporator

The 14kW heat pump supplies four apartments, with separate remote controls and valves. Each valve is controlled by the HP through an electro-motorized actuator. In addition, on each channel, there are analog (on delivery and return) and electric (on delivery) thermometers. See Figure 27.

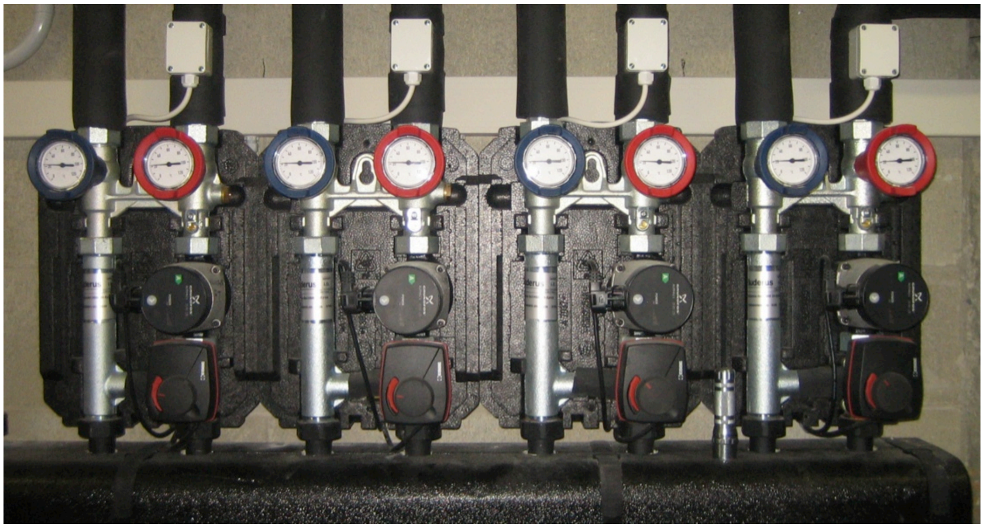

Figure 27. The four-channel circuits

4.1.1. Start up

During the start up day, started at 8am and finished at 7pm, the procedures described in Chapter 3 are respected: the weldings and the pressure testings, parallel with the check in list, required the morning; during the lunch break a one-hour evacuation was made; then, in the afternoon, each simulation was successfully completed. The nominal charge was nine liters but the compressor was started right after that the first four liters were inside; the final charge exceeded the nominal one of more than a half-liter.
An electrical data logger was mounted during the simulation; the data are analyzed in the Chapter 5.

4.1.2. Problems

Any important problem happened during the Rivalta start up, however the procedures required more than the initial planned time, especially during the weldings and the assignation of the remote controls.

4.2. Second commissioning

Location:	Loranzè, TO, Italy
Heat source:	Water
Heat pump:	Ochsner GMWW 15
Thermal power:	15 kW
Cycle:	Non reversible
Duties:	Heating, DHW, Free cooling
Cx Type:	Initial Cx

Figure 28. The HP without cover

The Loranzè commissioning regarded a water-water HP (Figure 28), the only water source plant analyzed in this work. A well supplies water at an average temperature of 12°C and a 40 l/min flow is required by the project. The temperature of the water has a double advantage: in winter, this is higher than the air temperature, increasing the performance with respect to an air-water HP; while in summer, it is lower than the indoor comfort temperature, so it permits free cooling. In this way, the pump has not to work in reverse cycle, consequently there is low energy consumption and it is possible to use a traditional HP, which is cheaper, more reliable and easier to regulate.

Drawbacks of the water source are the necessity to make long-term analysis of the stability of the well and a lot of bureaucracy in Italy. In this particular case, the analysis found a high amount of limestone so it was necessary mounting a water-water heat exchanger between source and evaporator, shown in Figure 29. A filter, mounted before the heat exchanger, blocks the usual quantity of mud.

During the start up, the temperature gap between the two sides was between 1.5 K and 2 K, so the HX was well dimensioned by the project.

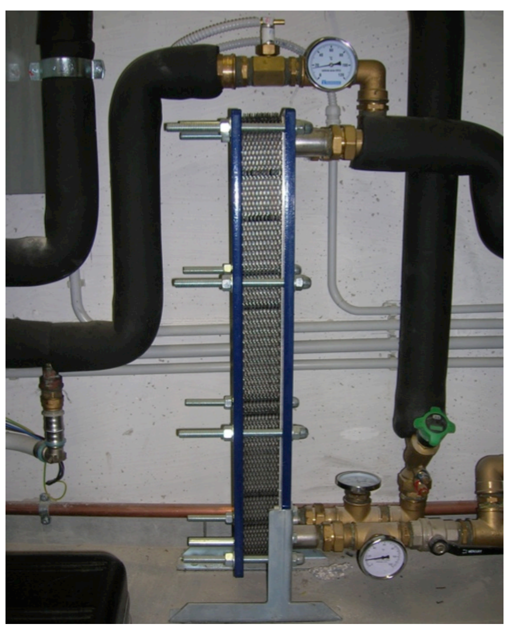

Figure 29. The heat exchanger between source and evaporator

The building is a new residence, with a single apartment on two floors above the ground level. This permits to calibrate the expansion vessels on 0.9 bar, when the circuit is empty. The heating circuit is split in two deliveries as in Figure 30: the main one feeds the apartment and is adjustable while the non-adjustable secondary one feeds the basement when required.

Figure 30. The two-channel circuit

On this plant, there is an example of a very well located external sensor, on a completely free wall, faced north, far from any heating source and from irradiation. Look at Figure 31.

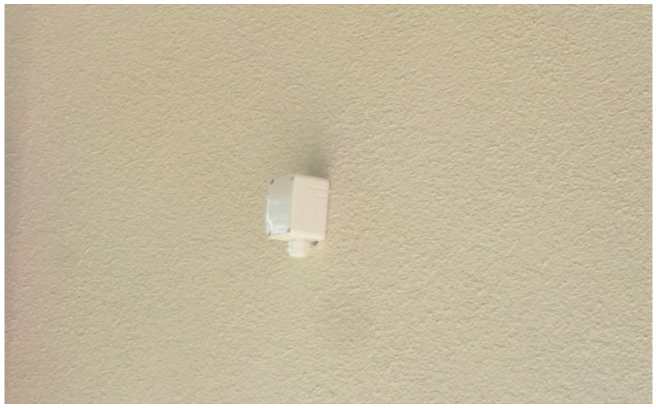

Figure 31. The position of external sensor

4.2.1. Start up

A non-reversible heat pump is easier to start up, considering that on the water source, the manufacturer already did the weldings. All procedures, as described in Chapter 3, were made in a half-day. The cooling doesn't use the refrigeration cycle and involves only the control units and the piping of the HP, so it is easy to tune.

4.2.2. Problems

The commuting between heating and DHW is the most complex phase in this plant, and during this, a couple of problems incurred. The first problem was due to inverted electric phases, then correctly exchanged. Then, the ice formation was too frequent on the low-pressure side during the commuting: the compressor start was delayed of two minutes with respect to the valves commuting to solve the problem.

4.3. Third commissioning

Location:	Montiglio Monferrato, AT, Italy
Heat source:	Air
Heat pump:	Ochsner GMLW 60
Thermal power:	60 kW
Cycle:	Reversible
Duties:	Heating
Cx Type:	Initial Cx

This plant, located in a residential building in Montiglio, 50 miles from Torino, is different from the previous cases for its dimensions. A 60kW HP (Figure 32 a and b) may have more compliance with respect to small-medium HPs; for this reason, this commissioning was followed by two specialized technicians, arrived directly from the Austrian Ochsner center.

The building is a restored house with a single big apartment of about 70k cubic inches: as reported in Annex 40, a large building with a complex heating system requires a high level of Cx, although the level of risk could be low, because this is a holiday estate.

The existing heating plant consists in wall radiators; for this reason, the heat pump cannot be switched in cooling cycle although it could work in reversed cycle. The DHW production is made by a separate boiler; the heating tank receives hot water by the HP, by the solar collectors and, in case of necessity, also by the boiler.

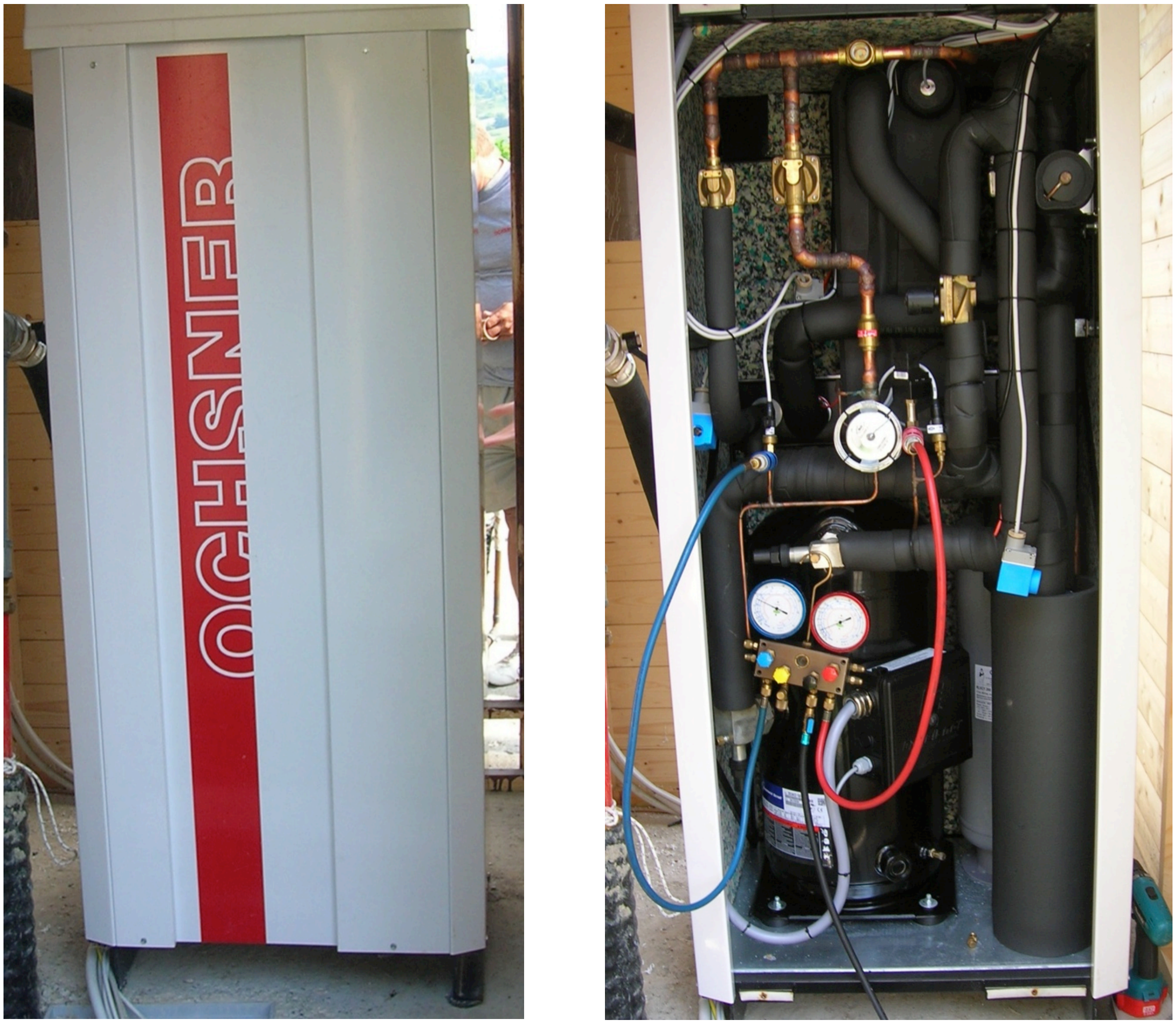

Figure 32. Ochsner GMLW60: a) In usual working conditions; b) During the testings

Figure 33. The three-channel heating circuit

Apart from representing an overview of the little wood cabin that contains the HP and of the three-fans evaporator, Figure 34 shows a good example of well coordinated work: the commissioning agent completed the check in list while the technicians made the welding of the expansion valve between HP and evaporator.

Figure 34. Plant overview

4.3.1. Start up

Two days were planned for the Montiglio start up and in the early afternoon of the second day the plant was correctly running. In the first day, the weldings were concluded in the morning and the testings in the afternoon, at the same time the check in list was filled; the second day was spent to simulate heating condition, defrost cycle and to fill the commissioning report.

After the first day, 26 liters of R407c were already in the plant; in the second day, the nominal charge of 32 liters was reached and exceeded.

4.3.2. Problems and modifications

Along the two days, all incurred problems were successfully solved.

- The solar collectors were fully working thanks to the irradiation of a sunny summer day, keeping the tank temperature at 45-50° C (about 120° F). The testing simulation has to start from 25-30° C (about 80° F) so some tricks were necessary to reduce the temperature: the heating system was opened and the plant was started in reverse cycle.
- The ice formation was frequent during the first simulations, but this is quite common when the refrigerant charge is not yet completed or the fans are not working.
- A fastidious inconvenience was an apparent sub-dimensioned pressure heat of the pump between the HP condenser and the tank (8,5m according to the project). After an analysis of the main critical points that produce a concentrated pressure drop, the filter resulted clogged increasing the losses. This problem could be avoided with a more accurate plant cleaning by the installers.
- Initially, the compressor starting stops after few seconds; tuning the soft starter, the technicians were able to stabilize the starting. Finally, the problem was completely solved realizing the main protection on the electrical panel worked at 32A, a little more than the current in steady working conditions. The right protection should work around at 60A.
- The check in list also permitted to see some lacks on the plant, such as the cable between control unit and boiler and the electrical protections on the fans; the intervention of the electrician that made the works, who has to be available during the start up, solved the problems.
- The position of the external temperature sensor (Figure 35) was incorrect, since it was too close to the evaporator airflow. It was moved to an other side of the little wood cabin that contains the HP.

Figure 35. The wrong position of the external sensor

- After the start up, the external wood cabin has to be insulated. The thermal insulation is mandatory and, in particular in winter, its lack can reduce the performance, while the testings were conduced in summer, feeling less this contribution.

4.4. Fourth commissioning

Location:	Heliant, Torino, TO, Italy
Heat source:	Air
Heat pump:	Ochsner GMLW 14 Plus
Thermal power:	14 kW
Cycle:	Reversible, Vapor Injection
Duties:	Heating, DHW, Cooling
Cx Type:	Ongoing Cx (Continuos Cx)

Figure 36. Ochsner GMLW 14 Plus and two heating storage tanks

The previous startups and commissioning cases are managed by the firm “Heliant”, Italian Ochsner distributor, chaired by Ing. Vavalà. An interview about his work and his idea of the Italian HP situation is available at the end of this dissertation. The Heliant central in Torino is heated and air-conditioned by an HVAC powered by an Ochsner GMLW 14 Plus, shown in Figure 36. It is composed by two large rooms at the first level, four offices at the second level, two locals as thermal and electric central, with a total of about 3000 heated squared meters (33k squared inches), while the storage area is not heated.

The plant feeds a 2-channel heating circuit, composed by a channel of radiant floor and a channel of wall radiators. The HP is also matched to a gas boiler and to an additional tank, to produce DHW.

Figure 37. Heliant thermal plant

4.4.1. Ongoing commissioning

The initial commissioning and the start up of the plant were already done previously this work; however the plant manager, and owner at the same time, constantly monitors the plant, taking also digital surveys. These data, which will be examined in the Chapter 5, are taken by a datalogger linked to the onboard sensors of the HP and by daily reading of the power meter.

To reach the air internal quality saving energy, the HP is set in two working modes:
- A comfort mode, in which the internal temperature should reach 20° C
- A reduced mode, in which the internal temperature should reach 19° C

It works in comfort mode:
-Monday: from 4am to 6.45pm
-From Tuesday to Friday: from 5.45am to 6.45pm
-Saturday: from 5.45am to 2pm
On Sunday and during the other time periods, it works in reduced mode.

However, during the analysis of data, the distinction is made with respect to working and non-working hours, independently of the operating mode of the HP, from 9am to 7pm.

5. EXPERIMENTAL ANALYSIS

5.1. Daily consumption data

These data represent a list of energy consumption values and components behavior. The following parameters are known:

- Cumulative energy consumption;
- Cumulative hours and times of compression starting;
- Provided thermal energy;
- Cumulative times of defrost cycle and required energy;
- Average indoor and outdoor temperature;
- Cumulative of thermal resistor working hours and starts.

It is easy to obtain the values in the period knowing the cumulative data. Furthermore, the survey is done at different hours and some days miss but it is possible to convert the data in a standard period of 24 hours.

BEWARE

This operation is valid, however we must be careful. For example, if a datum taken during the evening is followed by an other one taken the next morning, the period of time refers only to nighty conditions, when the external temperature is lower and the compressor could work more. The daily average could have a very high compressor start number as result, but this is not completely true.

In addition, if a survey is referred to a certain time of the day, it takes into account all the events happen between this moment and the previous survey. This feature has to be considered during the following analysis.

5.1.1. Advantages

-Knowing the COP is one of the most advantages of this type of commissioning

-It represents a whole season

-It gives results on different levels of detail (daily, monthly, seasonal)

-It doesn't require expensive instrumentation.

-Some days can miss without compromising the results

5.1.2. Disadvantages

-It is a manual reading, so it requires patience and constancy

-As all long term surveys, the results are not immediately available

-Survey at different times of the day could give unreliable average values

-It permits to see some problems during a day, but it doesn't allow understanding the reasons

-Some malfunctions cannot be seen

5.1.3. Time plots

In the two graphs below, showing respectively monthly and daily data, it is possible to see how these give two different informations.

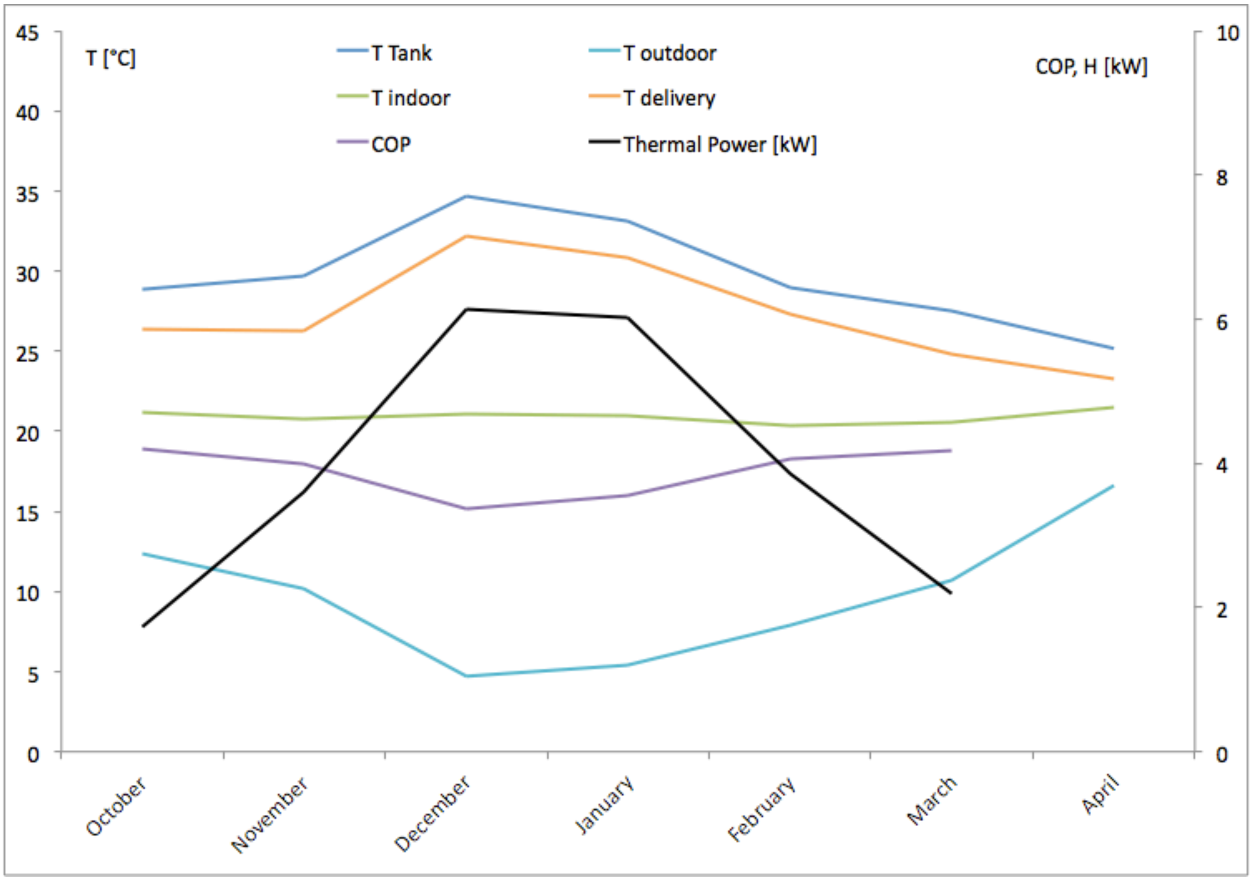

Figure 38. Monthly average data on a time plot

Figure 38, which contains the monthly average values, doesn't show information for the commissioning, since it is rare to find malfunctioning with this level of detail, while it is useful for a first quick analysis of the studied plant, especially when the commissioning (for example a retro-commissioning) is done for the first time and the plant or the project are not known. In fact it gives an idea of the region climate (external temperature), of the seasonal performance of the heat pump (COP and thermal power), of the plant (temperature in the tank and delivery of the circuit) and the final result in terms of indoor temperature.

In this case, the Heliant plant is located in a mild cold climate, it uses a high performances HP with the COP below 4 (EER=14) only during the coldest winter months; the average internal temperature seems to respect the project and the regional standards.

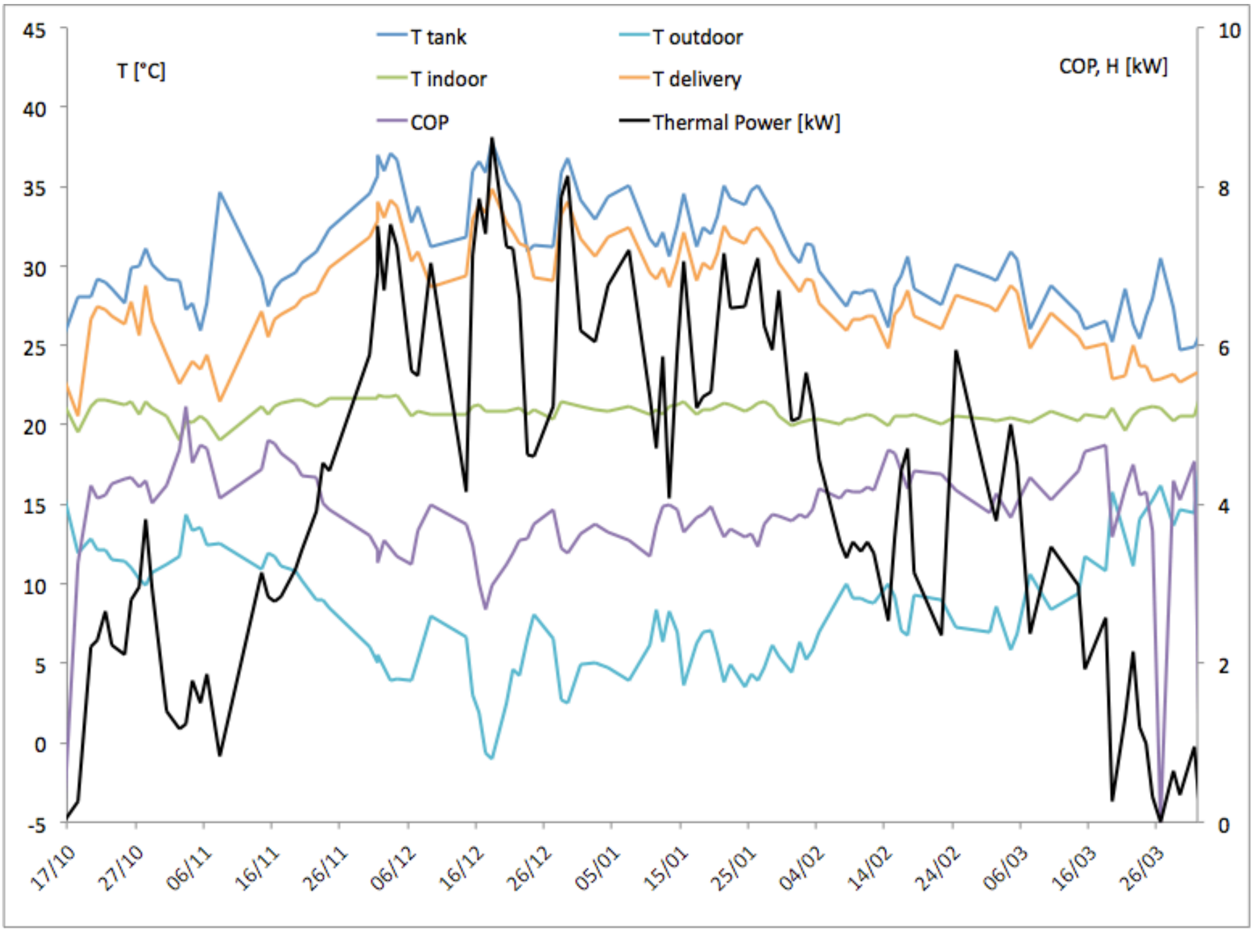

Figure 39. Daily data on a time plot

This second graph, in Figure 39, with the same parameters but with a higher level of detail (daily), shows more information in the short period, losing a global trend: this is the reason because both graph are useful.

Speaking about the external temperature, in this case, it doesn't represent the climate as before, but it represents the daily weather, in which the average temperature can drop below 0°C. Unfortunately this is the higher level of detail for this type of commissioning and it is not possible to know the minimum external temperature.

Analyzing individually 175 blocks of data may be long and useless, while this graph permits a rapid visual analysis. During the winter season, there are particular days in which a datum reaches the maximum or the minimum or something unusual happens. The Cx should be concentrated for these cases, which can be easily found observing the peaks on the graph.

Principally, the critical days are located on peaks of maximum thermal power, minimum internal temperature and minimum external temperature. These peaks not necessarily coincide. For instance, in the graph above, the days with minimum internal temperature are October 18 and March 21, while the minimum external temperature day is December 18. However a limit of this kind of Cx is that it is not possible to analyze what happens during these days, unless these are matched with an other kind of data, as we will done after.
Furthermore, it is possible to see the correlation between COP and external temperature (without considering the cases in which it goes to zero, when the HP doesn't work). This will be analyzed in the section dedicated to the characteristic curves.

5.1.4. Compressor and defrost cycles

An other way to find the critical days is to analyze the compressor behavior. Also, compressor start and defrost cycle number can be studied together, since they are correlated each other. In addition, the external temperature can be compared to understand if there is an inverse proportionality between this and the cycle number.
Looking at Figure 40, the plot of defrost cycle copies the compressor starting trend, in particular in the coldest period of winter, when both start several times during a day. In the warmest periods, the late fall and the early spring or in general when temperature is about 10°C or higher, there is not ice formation on the fins so the defrost doesn't start, also if the compressor works from one to five times a day.
The general trend of compressor starting seems being similar to the reverse of the external temperature; however, more in detail, the peaks don't coincide. The reason is probably that the average external temperature doesn't really represent the whole range of temperature of the day. Secondly, there are other reasons linked to the number of starts, such as the internal and external gains and losses.

Thanks to the same graph, we can observe the peaks and discuss these. There was a very cold period with respect to the average, between December 17 and 18. On the other hand, the compressor started many times around the December 1 and 2, December 21 and January 15. However, January 15 represents one of the cases to pay attention: in fact this data analyze a nighty period from 17PM and 9AM: during this night the compressor started 21 times so the daily average results 31.

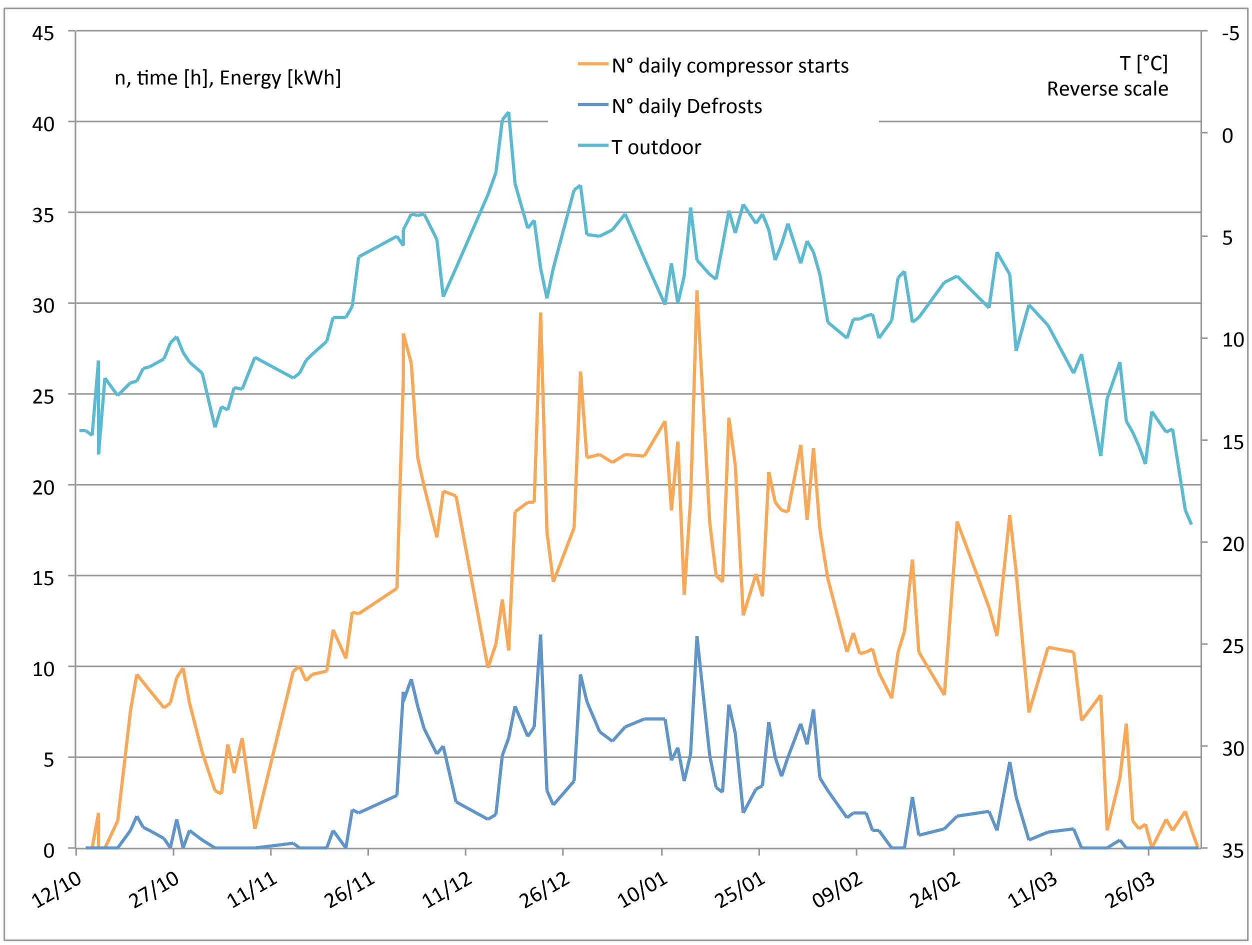

Figure 40. Compressor starts, defrost cycles and outdoor T on a time plot

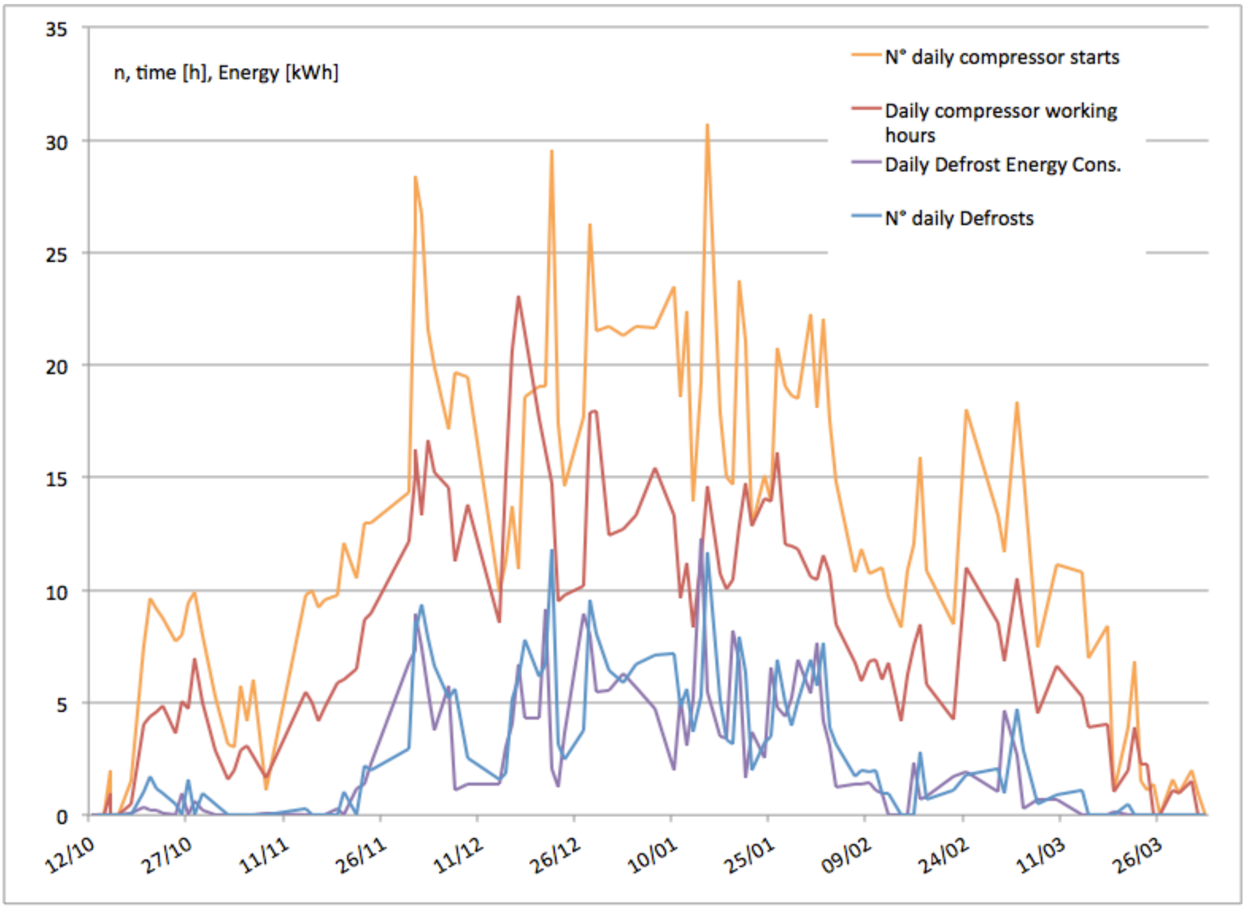

Figure 41. Compressor starts and working hours, defrosts and required energy on a time plot

5.1.5. Thermal resistor

The analysis of thermal resistor behavior can be quickly done with these data. The cumulative of working hours and number of starts are given. For this plant, a graph is not necessary, since the thermal resistor works only two days in the whole season. In particular, it starts five times and works for only two hours between December 17 and 18, the coldest days.

Heat pump equipments are usually not recommended in very cold climates, in fact the plant has to avoid the operating of thermal resistor and, furthermore, the COP decreases with low external temperature, as we will see in the next graph. Two hours of functioning during the year mean that the heat pump is a right choice for the Torino climate and the plant is not sub-dimensioned.

5.1.6. Characteristic curves of the HP

Previously, the examined graphs have in common the time x-axis, however the data have often been compared with the external temperature behavior and not with the time. A good way to represent this relation is to put the external temperature on the x-axis, as in Figure 41. It is necessary to observe the graph cannot be a continuum line but it will be plot using scattered points. Then, the linear behavior can be approximated with a trendline.
BEWARE: The zeros are considered to create the thermal power trendline while are not taken into account for the COP trendline, in fact they represent an error of the COP definition.

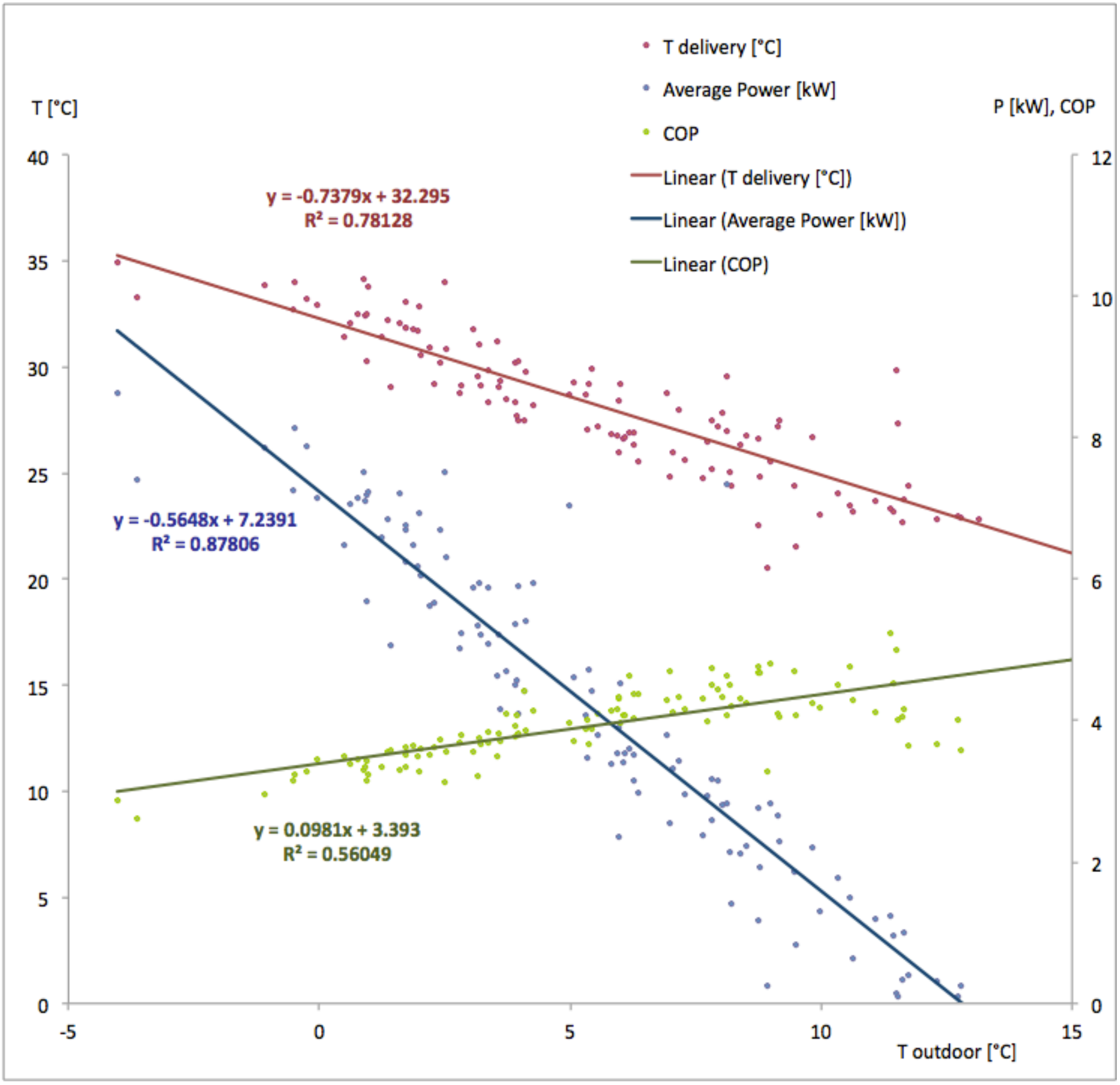

Figure 42. Characteristic curves of the HP

The trend of theoretic definition of COP, according to Carnot, as seeing in the Chapter 2, should represent a hyperbolic curve, which is well evident in Figure 43.

$$COP\max_{heating} = \frac{T_H}{T_H - T_L} \qquad (2\text{-}5)$$

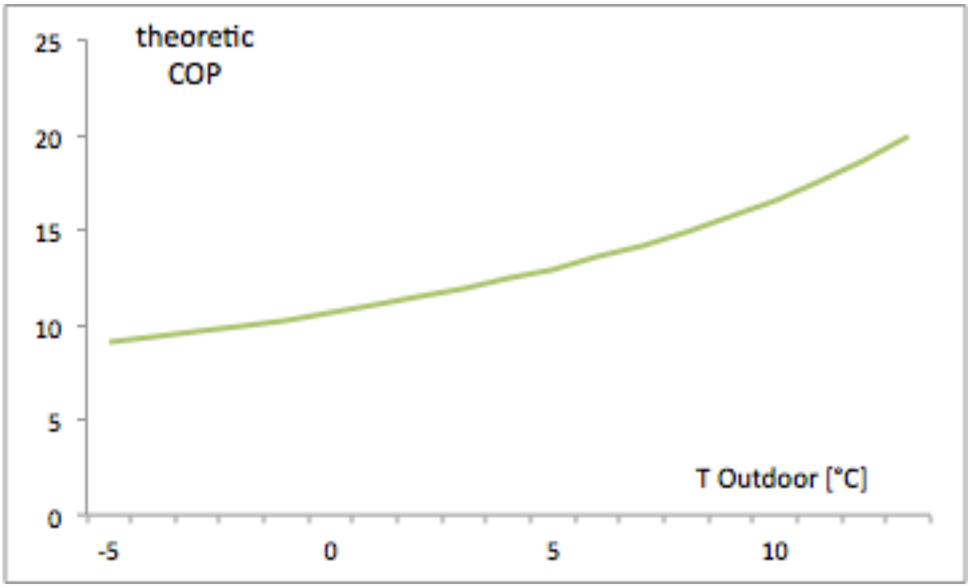

Figure 43. Theoretic COP in winter temperature range

However, it can be also approximated with a straight line without committing a big error, in particular in the part far from the asymptote, which corresponds to the temperature of hot side. For this plant, the linear trendline is about:

$$COP = 3.4 + 0.1 \cdot T_{outdoor}(°C) \qquad (5\text{-}1)$$

in a range between -5°C and 13°C.

This model means the heat pump has an average COP (EER) of:

2.9	at	-5 °C	(10.0	at	23 °F)
3.4	at	0 °C	(11.6	at	32 °F)
3.6	**at**	**2 °C**	**(12.3**	**at**	**36 °F)**
3.9	at	5 °C	(13.3	at	41 °F)
4.1	**at**	**7 °C**	**(14.7**	**at**	**45 °F)**
4.3	at	10°C	(16.7	at	50° F)

The installed HP, an Ochsner GMLN 14 PLUS, should have a COP (EER) of

3.9	at	2 °C	(14.0	at	36 °F)
4.5	at	7 °C	(16.2	at	45 °F)

at a heating water outlet equal to 35 °C (95 °F), while the experimental data are conducted at different temperatures. This difference doesn't permit to make a perfect comparison; however, it is possible to say that these results represent a very high COP for an air-water HP.

5.2. 5-minute temperature data

On the same plant, eight parameters are registered every five minutes, obtaining a series of 50575 sets of data, representing 176 days.

1. Internal temperature;
2. External temperature;
3. Temperature in the tank;
4. Temperature in the delivery circuit;
5. and 6. Inlet and outlet temperature in the HP;
7. and 8. Inlet and outlet temperature in the evaporator.

5.2.1. Advantages

- Automatic data survey
- A high level of detail
- It represents a whole season
- Possibility to obtain indirect information
- Complementary with the "Daily consumption data"

5.2.2. Disadvantages

- As all long term surveys, the results are not immediately available
- Lack of power and pressure data
- It doesn't permit to calculate the COP
- It requires eight temperature sensors with an interface and an acquisition instrument
- The post processing could need a good performance computer (one million data)

5.2.3. Internal temperature distribution

The primary goal of an HVAC system is to guarrantee a minimum internal temperature during the whole season. The designer, according to the regional standards, defines a project internal temperature; then, the occupant can modify it on the remote control. The ongoing Cx verifies if and when this minimum is satisfied.

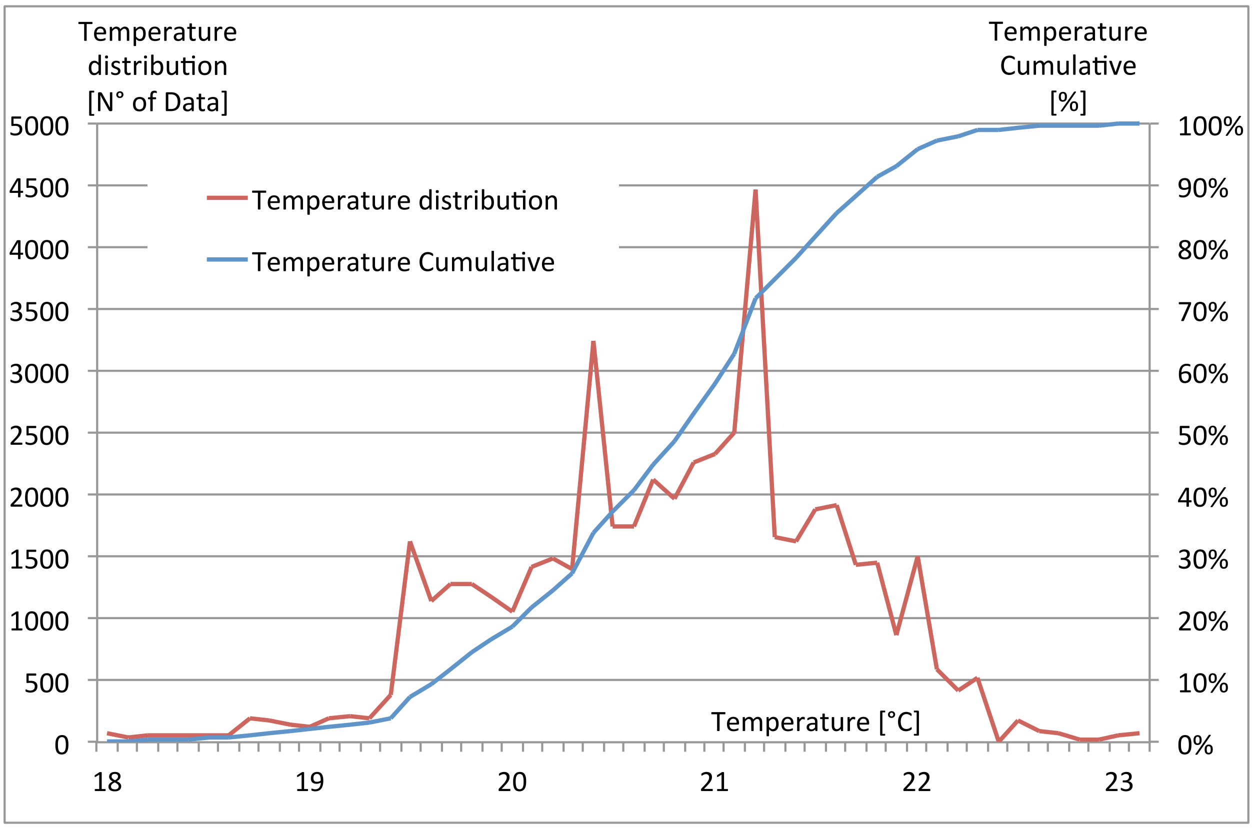

Figure 44. Internal temperature distribution

Analyzing Figure 44, the average temperature is 20.8 and the standard deviation is 0.80.

From the cumulative series, it is possible to read the probability to have a minimum temperature:

- In the 100% of data, the temperature is higher than 18°C (64.4 °F)
- In the 98% of data, the temperature is higher than 19°C (66 °F)
- In the 81% of data, the temperature is higher than 20°C (68 °F)

The analysis of whole seasonal internal data is useful to understand the behavior of the building and of the plant in general and the temperature is verified in each moment. However, the offices are occupied only five days a week and in the daily hours.

Making a filter on the whole data, the new distribution in Figure 45 is obtained considering only working hours.

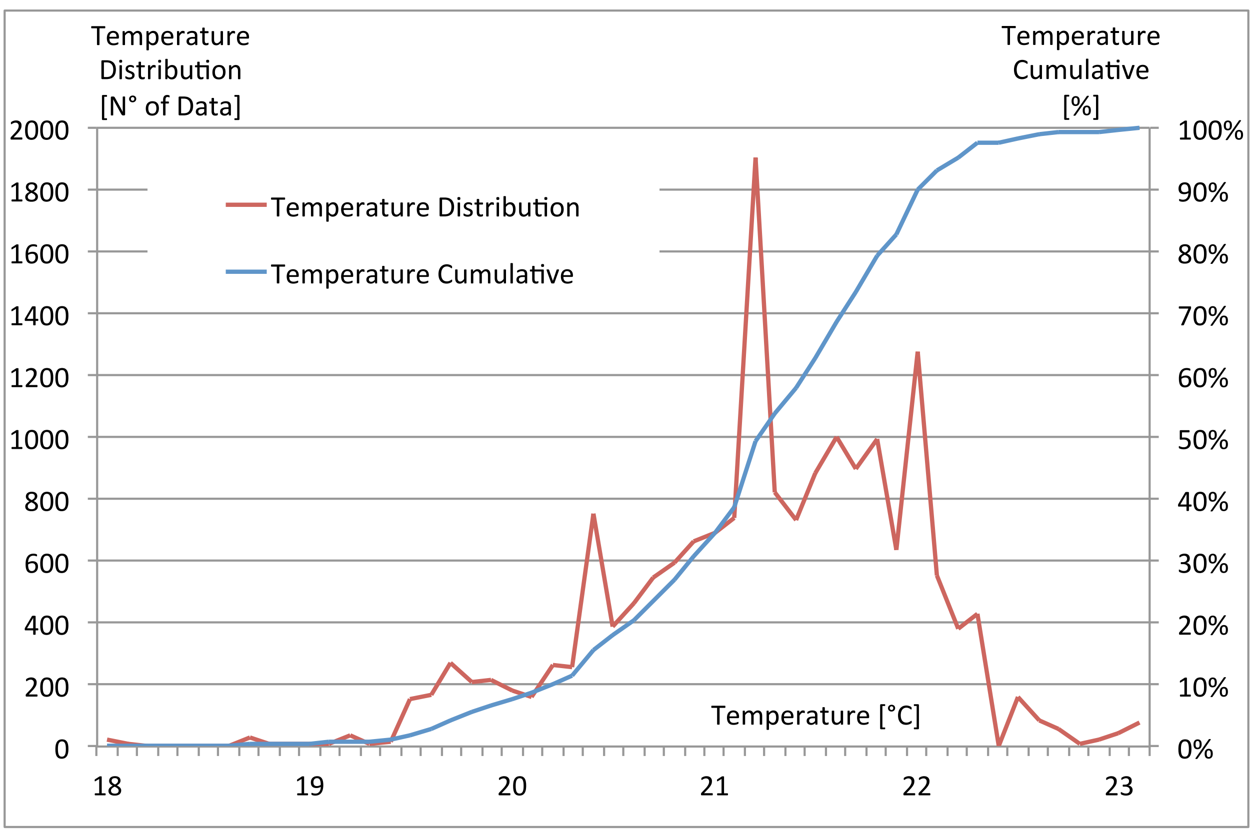

Figure 45. Internal temperature distribution (working hours)

Looking at the graph, it is easy to see that generally the internal temperature is above 19.5 °C (67 °F) and the peaks at the lower temperatures seem reduced.

The average temperature is 21.2 and the standard deviation is 0.74.

Reading the probability to have a minimum temperature:

- In the 100% of data, the temperature is higher than 18°C (64.4 °F)
- In the 99.4% of data, the temperature is higher than 19°C (66 °F)
- In the 98.1 % of data, the temperature is higher than 19.5°C (67 °F)
- In the 92.3% of data, the temperature is higher than 20°C (68 °F)

Each value is improved with respect to the previous analysis and the minimum internal temperature (20° C in comfort mode) is largely satisfied.

At the opposite, it could be interesting to evaluate if the temperature during the non-working hours is not excessively high in order to reduce the energy consumption, which is the second purpose of the Cx, after satisfying the internal conditions. Using the opposite filter, new distribution and cumulative curve are obtained and plotted in Figure 46.

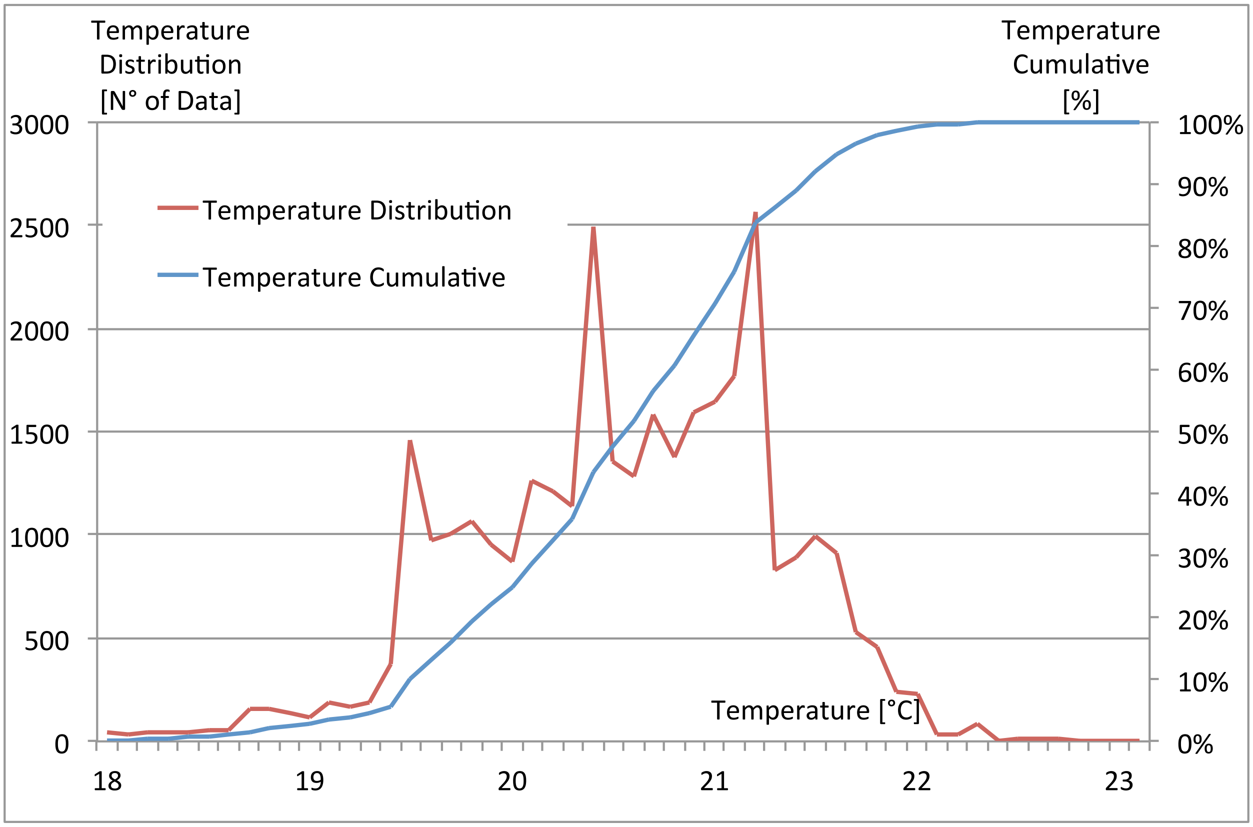

Figure 46. Internal temperature distribution (non-working hours)

Few data are in the range between 22°C and 23°, while the peaks from 21°C to 22°C are strongly softened; considering the thermal inertia of the building that blocks a rapid drop of the temperature, better results cannot probably be obtained.

The average temperature is 20.6 and the standard deviation is 0.75

Reading the cumulative curve:

- In the 100% of data, the temperature is lower than 23°C (73.4 °F)
- In the 99.4% of data, the temperature is lower than 22°C (71.6 °F)
- In the 70.6% of data, the temperature is lower than 21°C (70 °F)
- In the 25.6% of data, the temperature is lower than 20°C (68 °F)

The internal temperature distribution shows useful probability information, but loses the correlation with the external temperature. As done with the daily consumption data, a scattered point graph can be made with respect to the external temperature, with more accurate detail, since it contains more than 50k points, filtered between working and non-working days. See Figure 47.

Figure 47. Relation between internal and external temperature

It doesn't appear an evident correlation between internal and external temperature, so it is possible to say the internal temperature is almost independent from the external temperature. Furthermore, during the non-working hours, the lower temperature is more difficult to see than on the distribution graph.

5.2.4. Internal temperature "heat maps"

The previous graphs concentrate the entire internal temperature information from October to April in a single plot. This permits to have a global idea of the behavior and to verify the main goals of the commissioning, but both miss the time history. In order to keep the time function, the internal temperature can be plotted as a line graph in the time, but the level of oscillation and detail don't permit to plot more than a couple of days. The "heat maps"[3] can represent a period of more than a month in a single graph, keeping separated in two axes the day and the hour of the day. They can be considered as a tridimensional graph, using a color shade as the temperature third axis.

The blue color is associated to 18° C, the yellow to 20° C and the red to every temperature higher than 22.5° C (considering the winter season and being sure that the maximum temperature is 23.2° C; in climates or buildings, in which the internal temperature can go beyond 25° C during winter and the cooling is required, the black color can be used); the shades represent the intermediate temperatures.

A correct "heat map" should be:

- blue during the non working days (including the previous and the next nights);
- yellow during the nights between two working days;
- red (or at least yellow) in the working days, showing an alternate horizontal red band in the center of the map; each anomaly is easy to notice.

Each following map, from Figure 48 to Figure 53, has this general behavior, without big anomalies; however, comparing the six graphs each other, it is possible to see that, in December,

[3] Heat map is used in inverted commas to avoid a confusion: the term "heat" don't refer to any form of thermal power, but refers to the colors from blue to red of the graph, as a thermal map

January and February, the coldest months in Torino, the temperature is lower than in the other months during the working hours. Often, in the first two hours of the morning, the temperature is lower than 20° C; this is not a surprise, as seen in the distribution function: the 8% of the internal temperature during the working hours is lower than 20°C. Also, the behavior in the first two months is less regular than in the rest of the season, probably due to some parameters that were not yet well set.

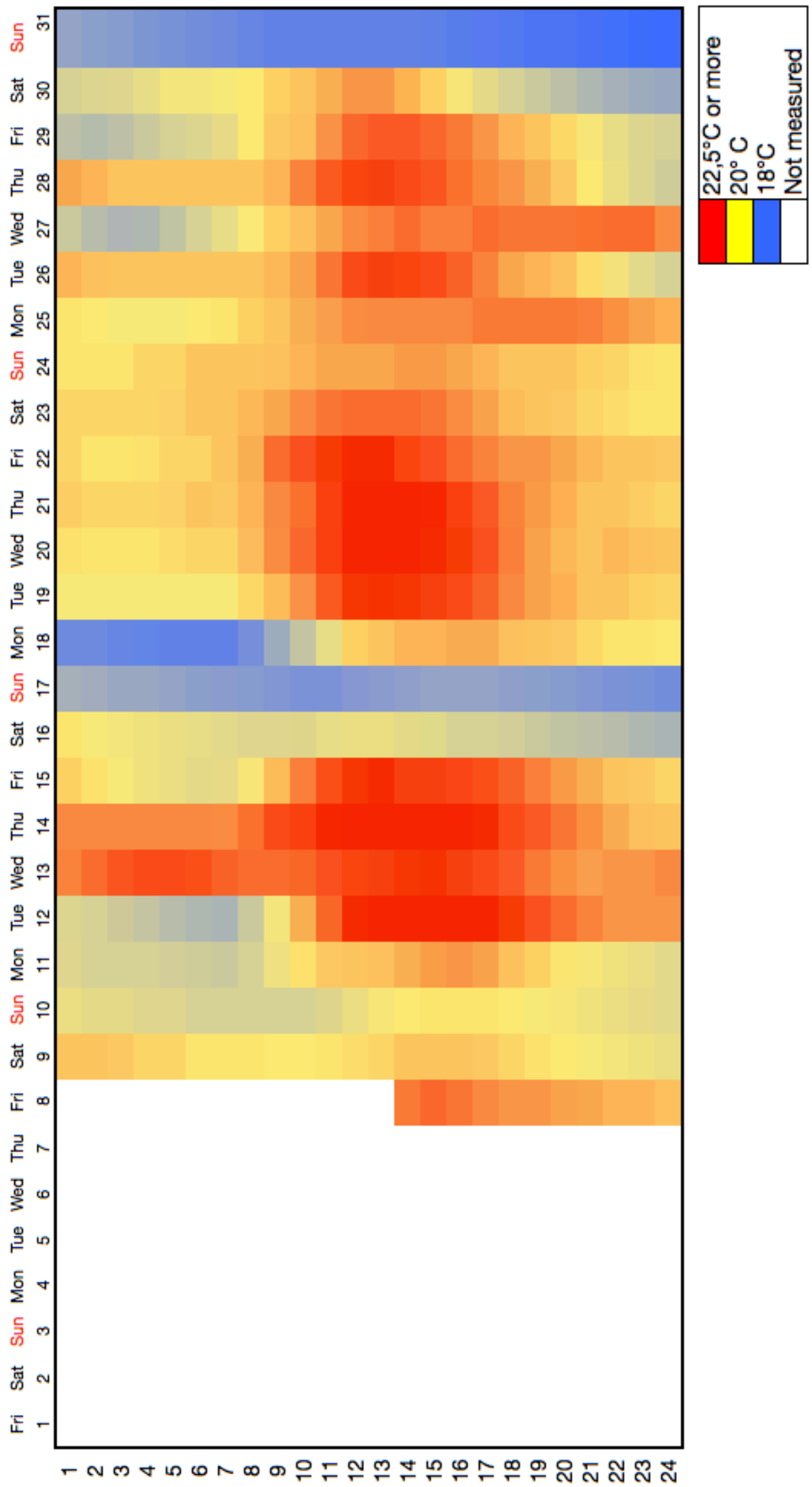

Figure 48. October 2010 internal temperature “heat map”

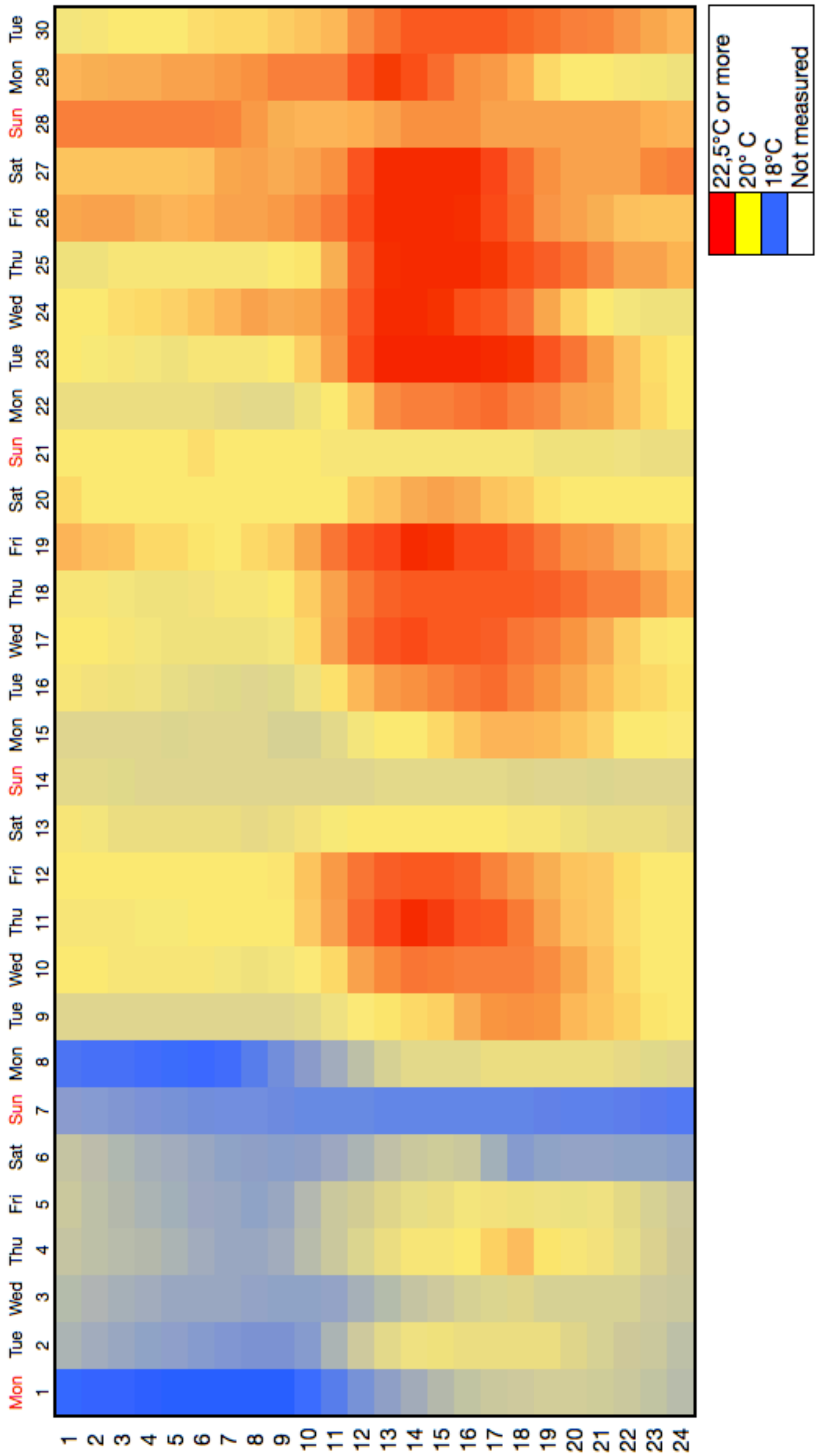

Figure 49. November 2010 internal temperature “heat map”

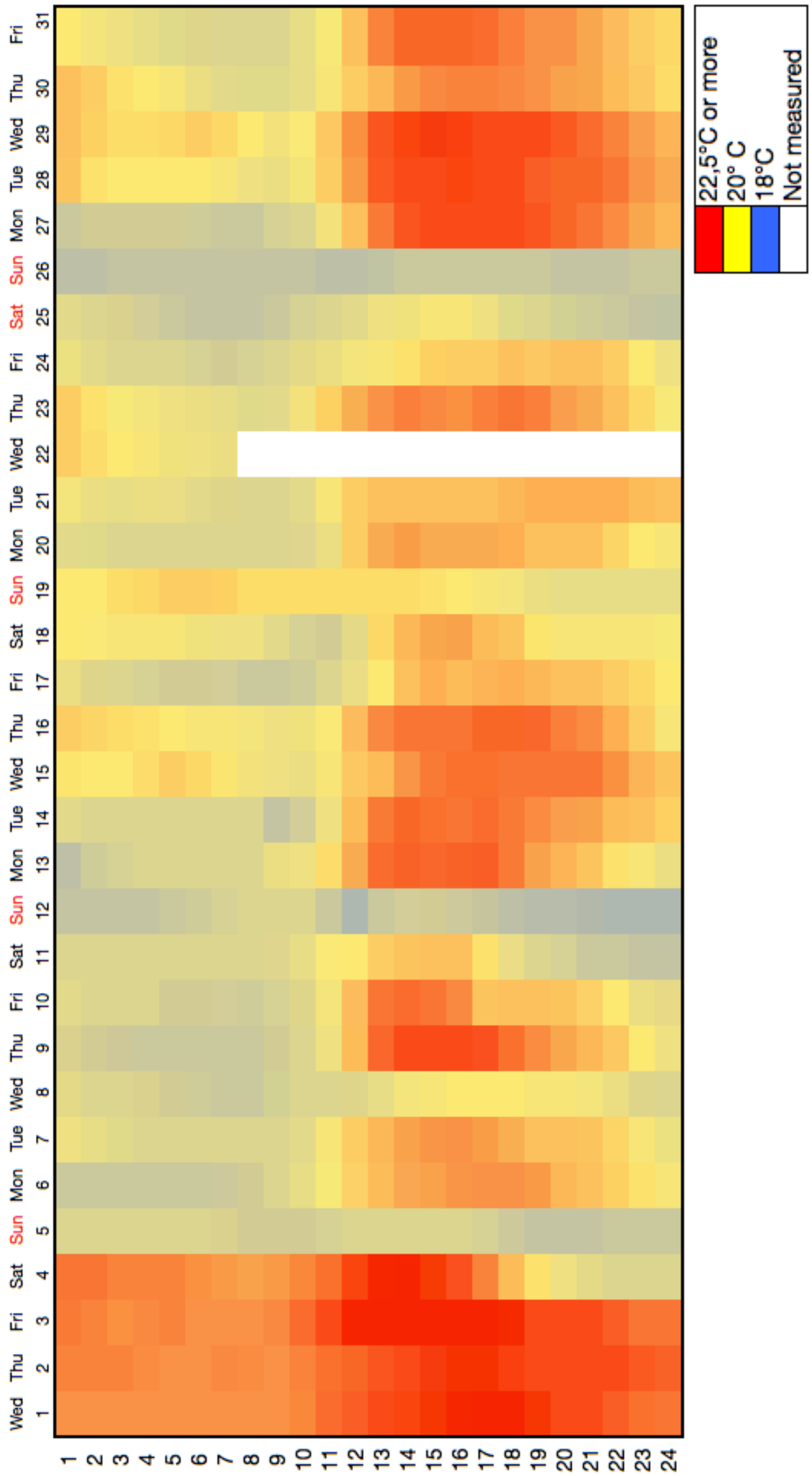

Figure 50. December 2010[4] internal temperature “heat map”

[4] On December 22nd, the datalogger was used on an other plant

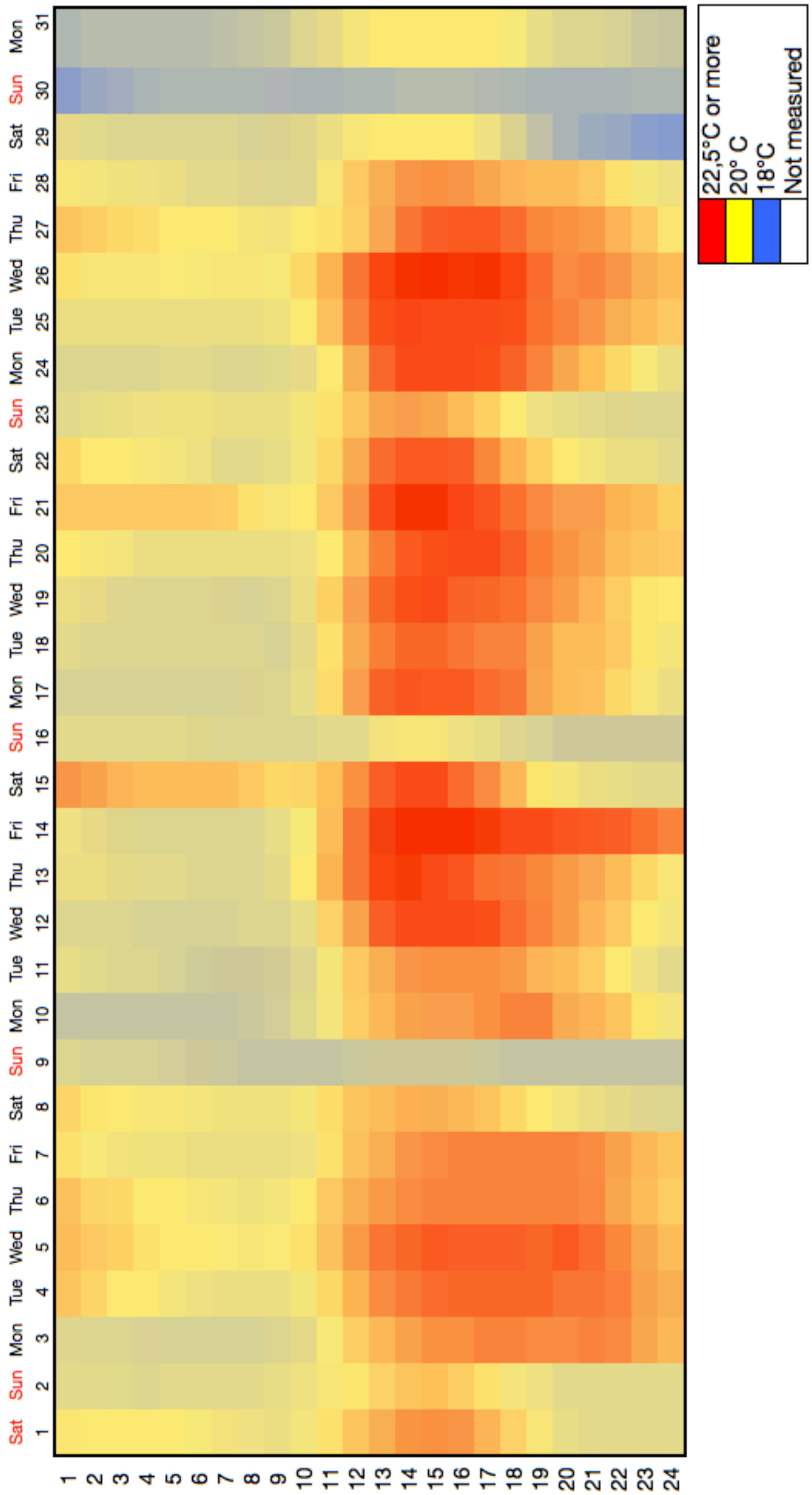

Figure 51. January 2011 internal temperature “heat map”

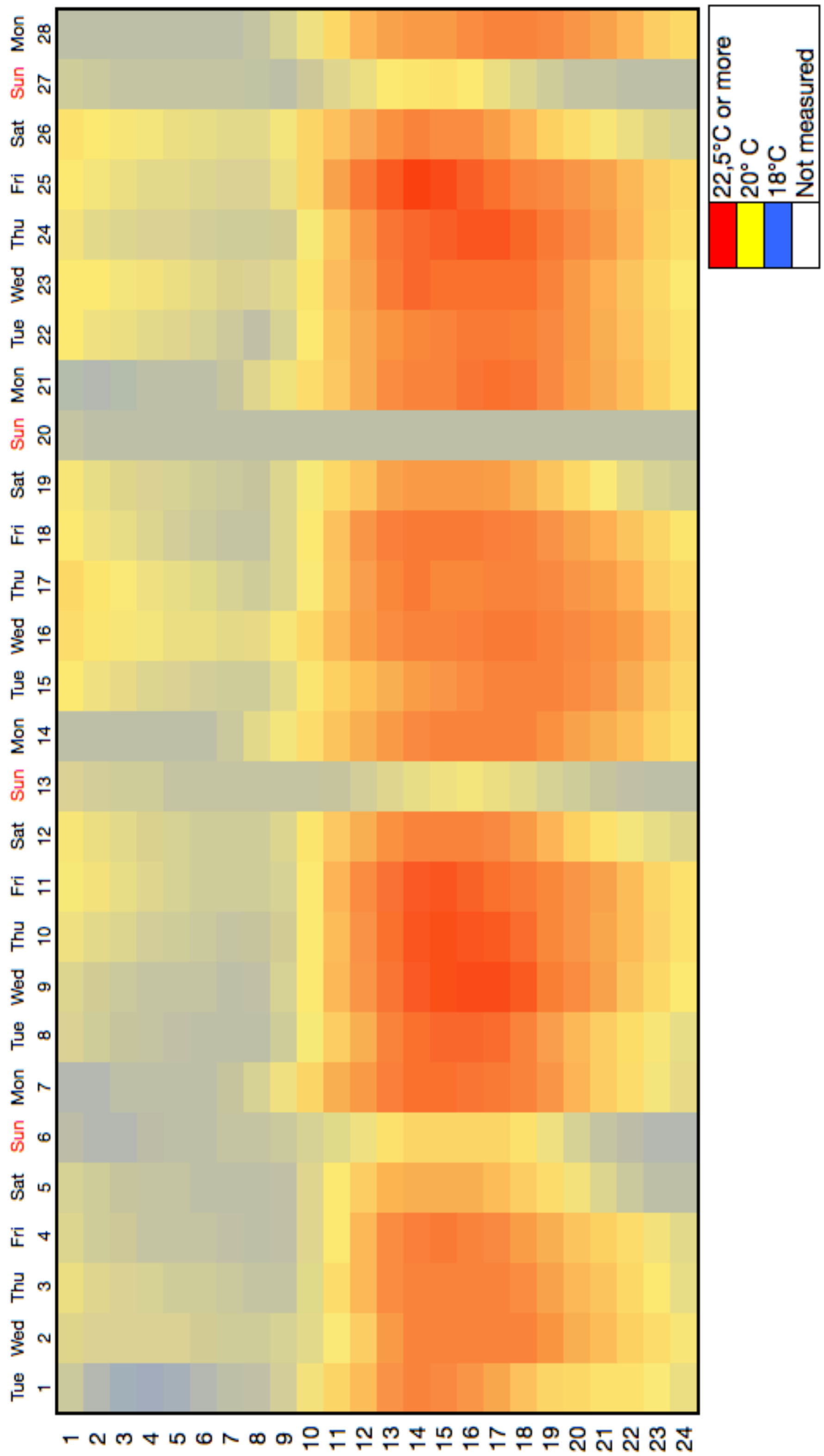

Figure 52. February 2011 internal temperature “heat map”

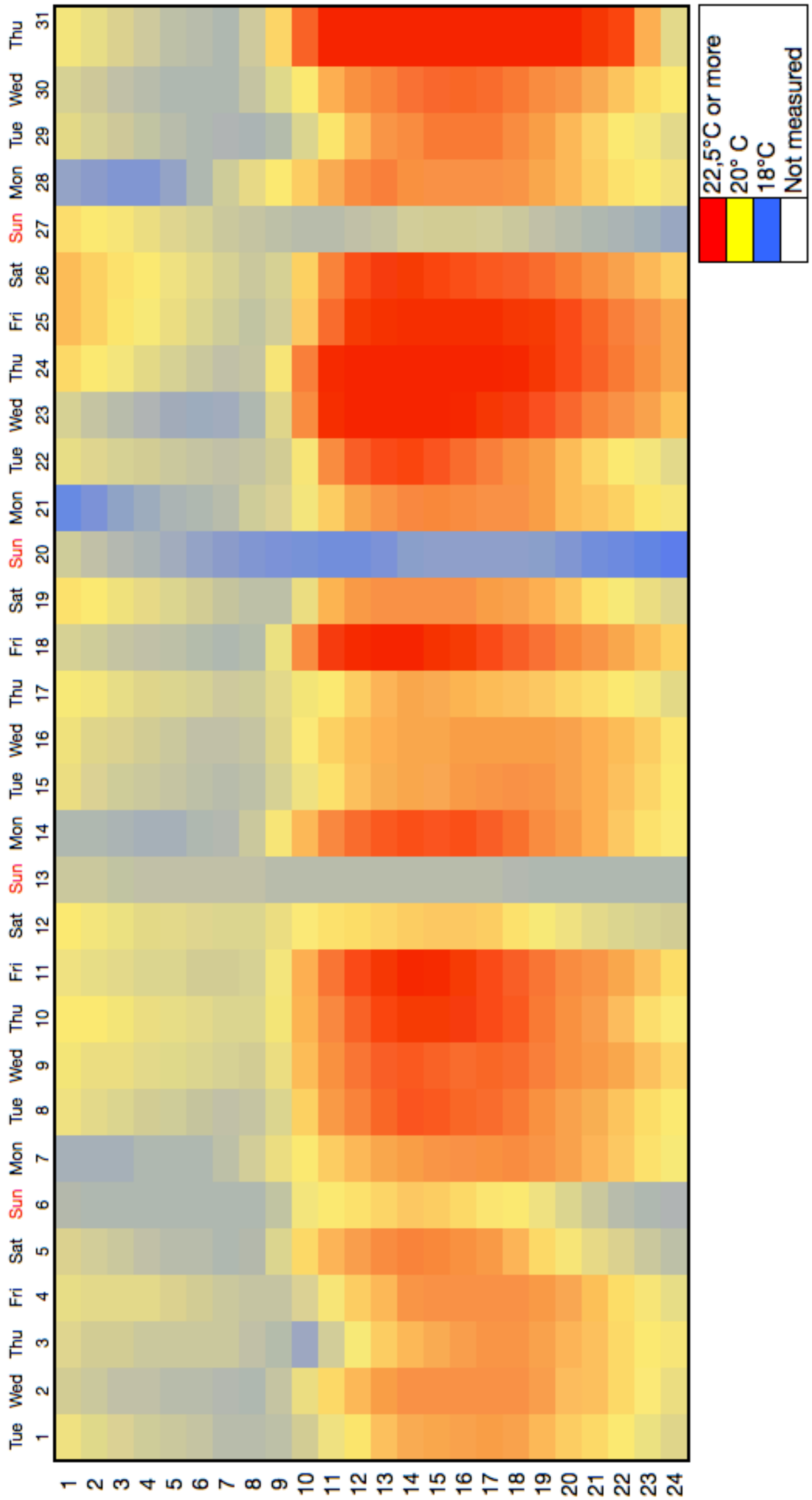

Figure 53. March 2011 internal temperature “heat map”

5.2.5. HP outlet temperature

As done for the internal temperature, a graph between outlet temperature of the HP and external temperature can be useful. The HP is set to give an outlet temperature of 45°C (113 °F) at an external temperature of -8°C (18 °F) and an outlet temperature of 20 °C (68 °F) when the external temperature is 20 °C. The trend of all data matches the project curve, in a band of about 5 K, with some points that don't respect the trend. The difference between working and non-working hours is well evident in Figure 54.

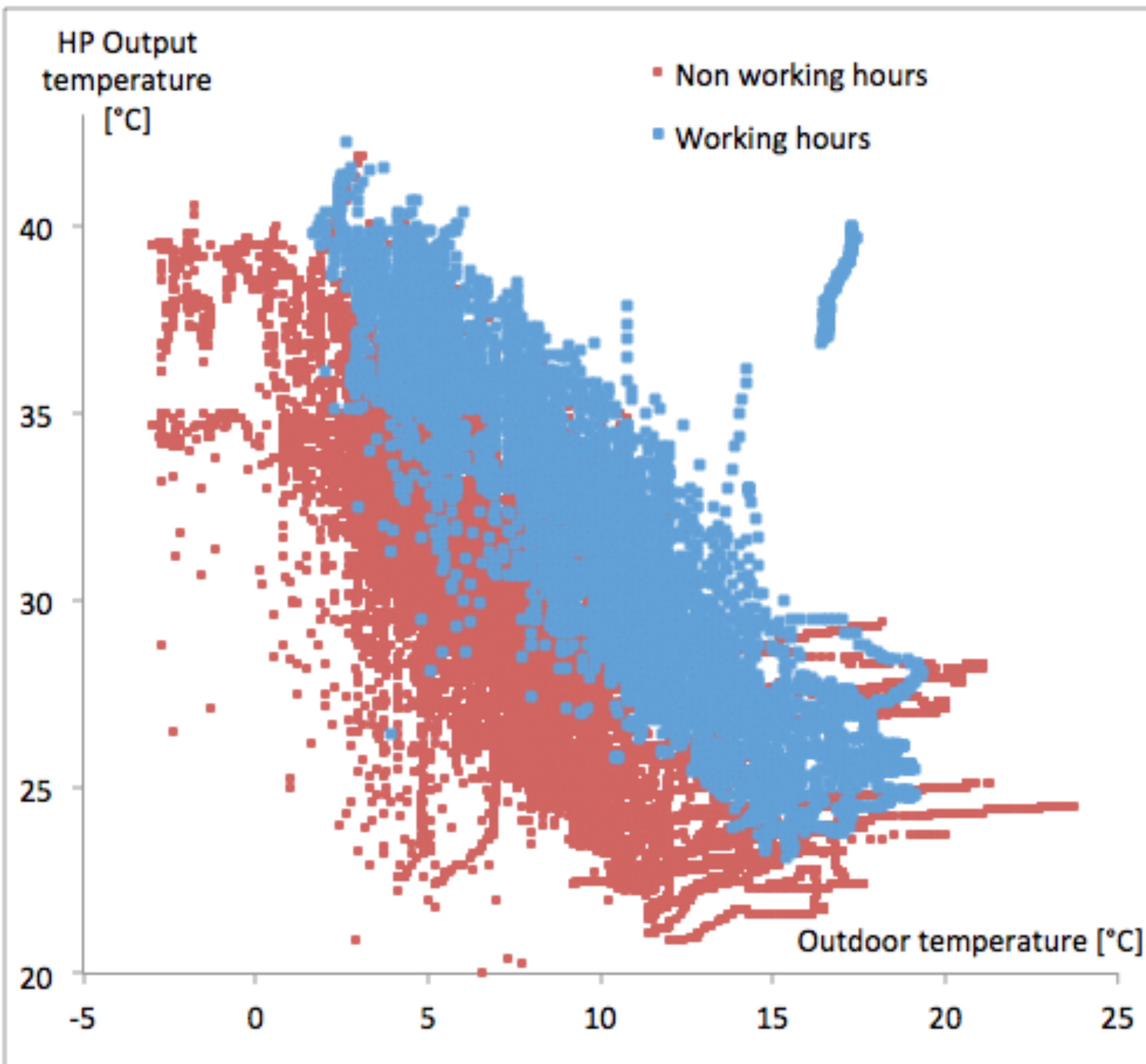

Figure 54. Relation between HP outlet temperature and external temperature

5.2.6. Critical days analysis

The “Daily consumption data” shows the critical days, however in that analysis it is impossible to understand what happened during those days and why. Now, using the 5-minute data, those ones could be examined. Summarizing:

-October 18, 2010: Lowest internal temperature

-December 1, 2010: High number of compressor starts

-December 18, 2010: Lowest external temperature and thermal resistor cycles

-December 21, 2010: Highest number of compressor starts and defrost cycles

-January 15, 2011: High number of compressor starts and defrost cycles

-March 21, 2011: Lowest internal temperature

The data are plotted on a period of 48 hours, trying to take into account 12 hours before the critical day and 12 after this one or, in some cases, the previous or the next day.

5.2.6.1. First analysis

(from 12am October 17 to 12am October 19)

First of all, in case of low internal temperature, it is important to understand if the plant was working or not. In this type of survey, there is not apparently a datum that shows directly if the plant was working; however, plotting the temperature on a time chart, it appears at once the behavior of the plant including the compressor cycles. Looking at Figure 55 and 56, it is possible to see the same data on different temperature scales.

The internal temperature, usually above 20 °C (68 °F), started to slowly decrease during the day of October 17. On October 17, a non-working day (Sunday), the compressor started only once and this is confirmed also by daily data; the compressor cycle permitted to slow down further the temperature decreasing. For the 2010-2011 winter, October 18 represented the first day of intense work of the plant, since the compressor started three times in the morning. Thanks also to the high external temperature of this autumn day, the internal temperature rose to 22° C (71 °F) in seven hours and defrost was not necessary. However, the temperature at 9am was still lower than 20° C at the work restart. According to the plant manager, the anomalous peaks of the circuit temperature in the last hours of the graph were due to an irregular work of the boiler, which was not yet well set for the heating season.

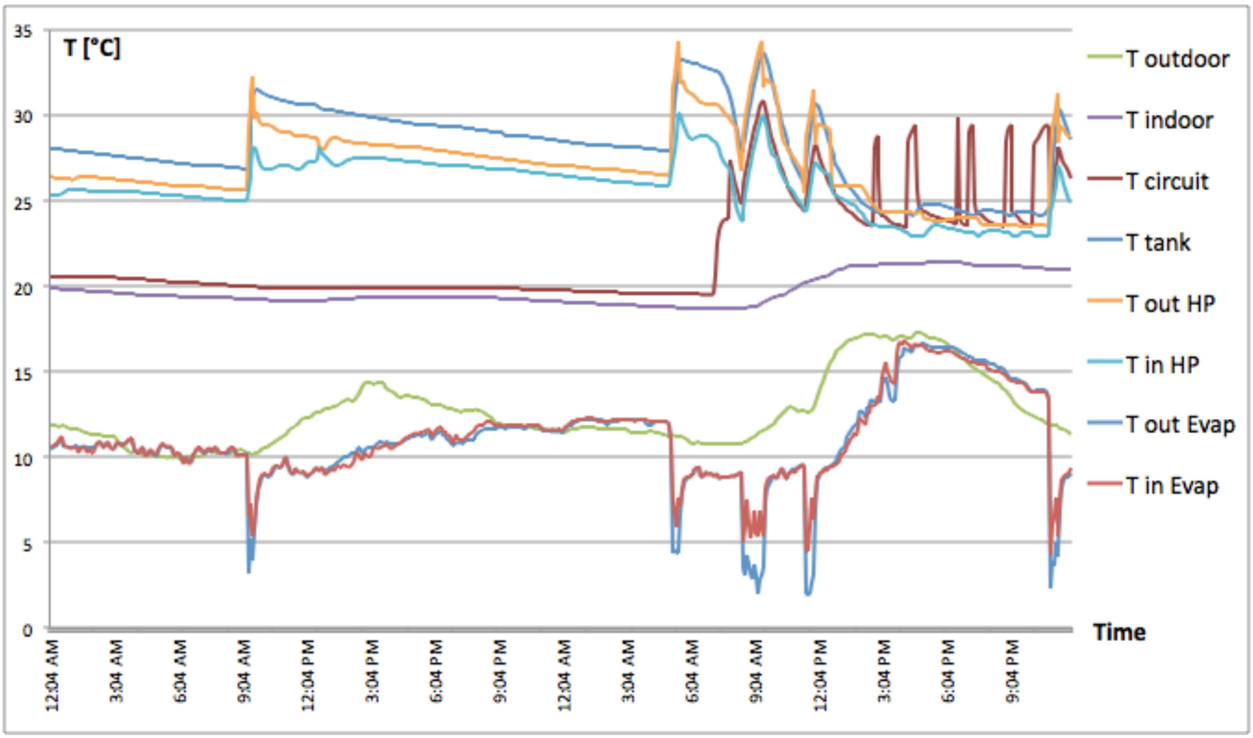

Figure 55. Data time plot from October 17 to 19

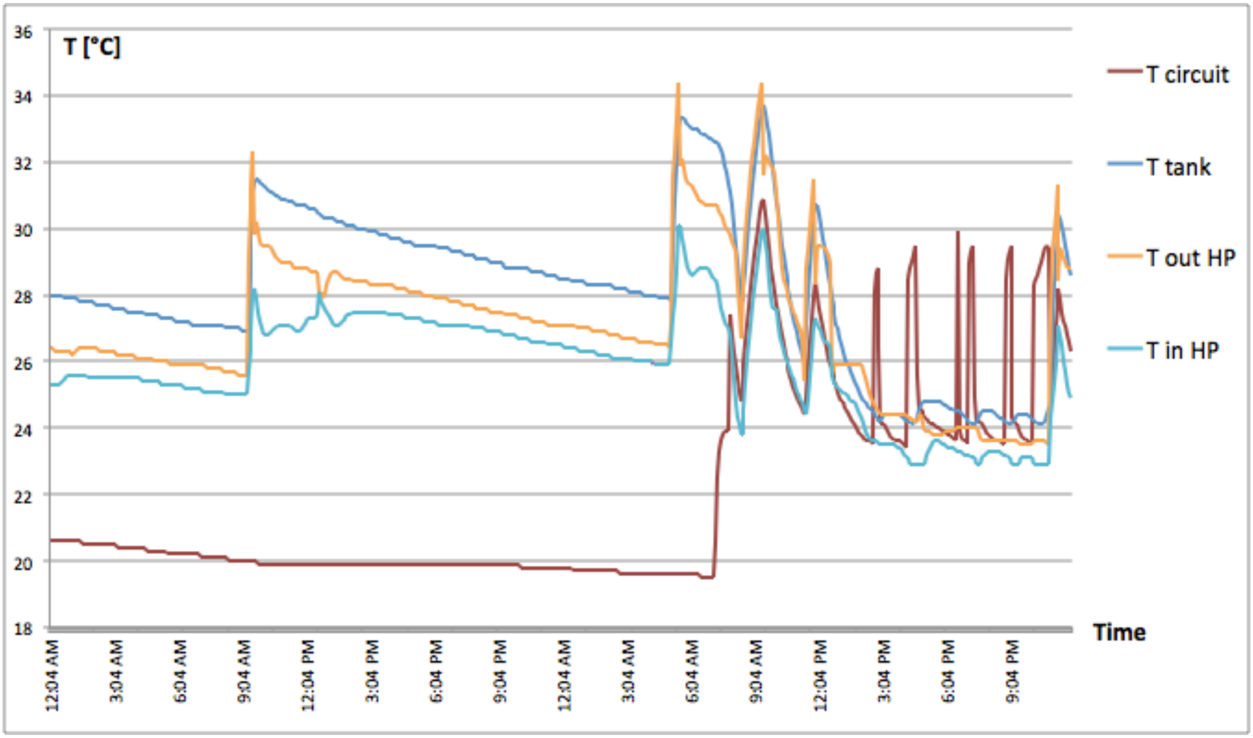

Figure 56. Data time plot from October 17 to 19 (High temperatures)

5.2.6.1. Second analysis

(from 12am December 1 to 12am December 3)

This 2-days period has 15-16 compressor working hours per day, in fact it is possible to see in the graph that only in the middle of the day (from 10am to 16pm) the compressor didn't work. Despite that, there was not a large amount of defrost cycles, which start only when the outlet temperature in the evaporator was below -5° C (23° F). In Figure 57 and 58, there is a large gap between the night external temperature and the daily one, but the internal temperature was always guarranteed, being higher than 20° C also during the night.

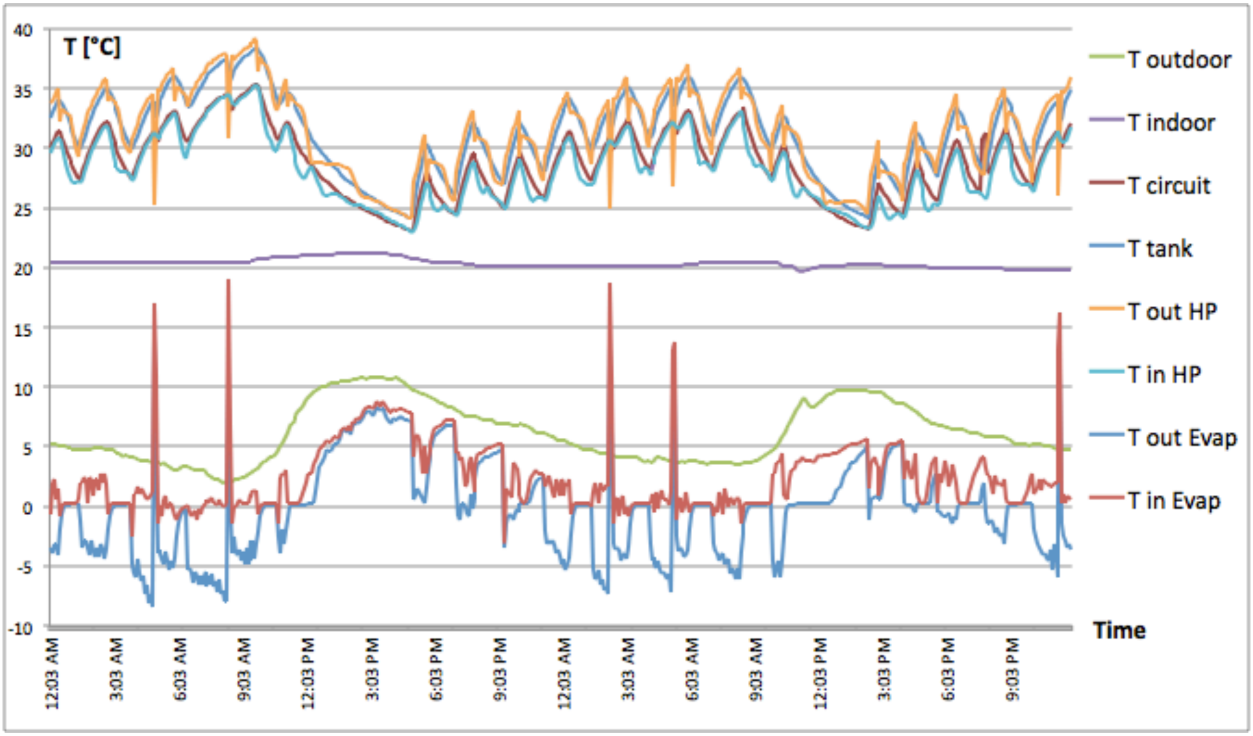

Figure 57. Data time plot from December 1 to 3

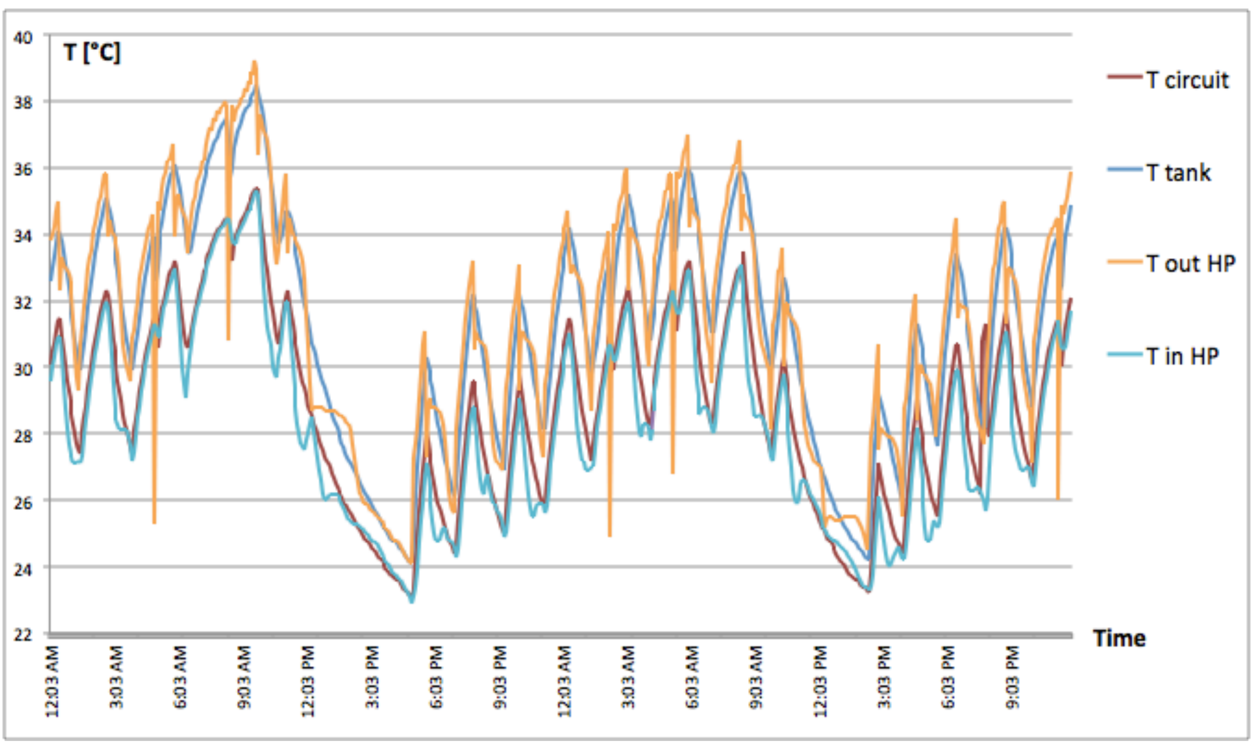

Figure 58. Data time plot from December 1 to 3 (High temperatures)

5.2.6.2. Third analysis
(from 3pm December 16 to 3pm December 18)

This 48-hours period represented the coldest one in that winter, with the temperature firmly below 0°C (32 °F) during two consecutive nights and just shy of some degrees above 0 °C during the middle day.

Looking at the outlet temperature of the HP, in Figure 59 and 60, the compressor seems to work nonstop during the period; the daily consumption data confirm this impression, registering 23.1 working hours a day.

It is important to look at the shape of the circuit temperature peaks. In the days seen before, they were triangular, with a period of compressor working followed by a similar drop time; in this case, the shape is flat or constantly growing while the drop seems immediate. This happened only in those days and it shows how the compressor was working hard.

However, working at its higher power, the HP was not able to reach its goal, so the thermal resistor intervened two hours. Thanks to this combined action, the internal temperature was higher than 20 °C (68 °F) during the whole period.

There was a heavy and constant intervention of defrost cycle around the clock, since the evaporator inlet temperature reached often values closed to -15 °C (5 °F). A particular behavior is visible in the first defrost cycle: the cycle lasted more than usual and the inlet temperature of the pump dropped strongly (it is usually constant while the outlet temperature goes down). This probably happened because the pump was working in reverse conditions, both dissipating heat and consuming energy. About one hour was necessary to re-establish the usual working condition, but meanwhile the tank was able to guarantee the temperature in the circuit.

Figure 59. Data time plot from December 16 to 18

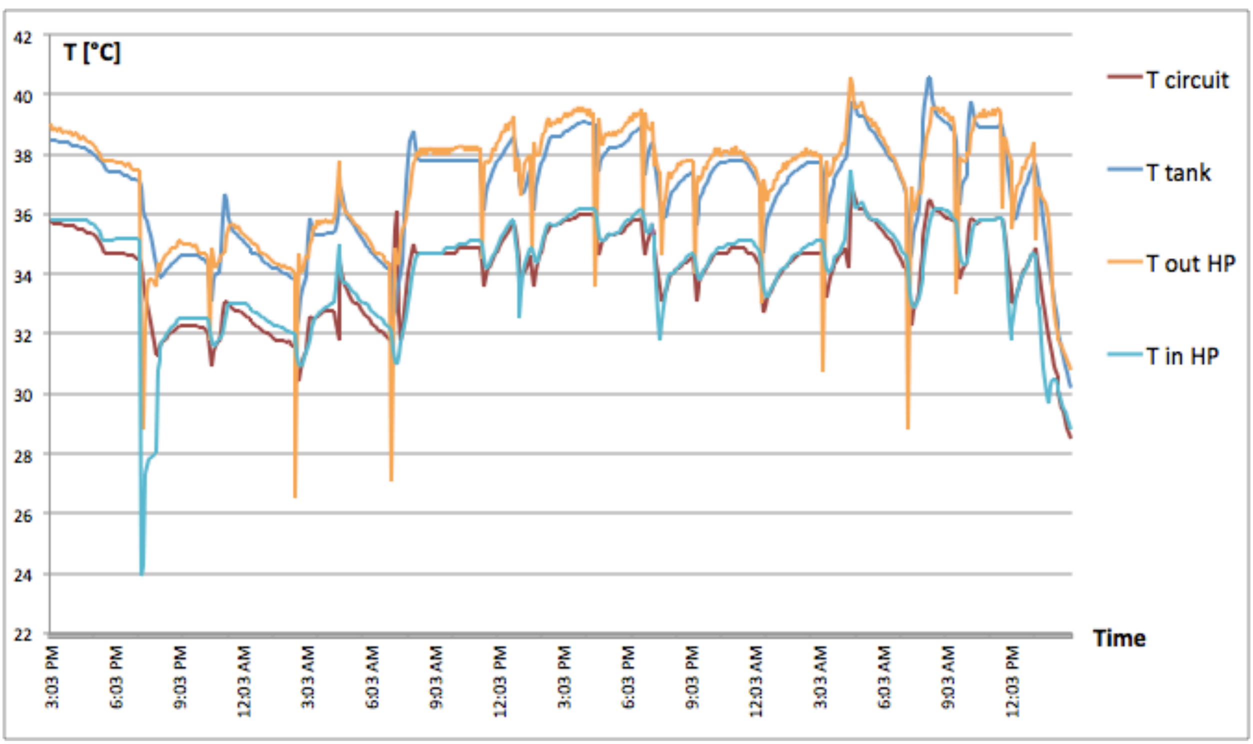

Figure 60. Data time plot from December 16 to 18 (High temperatures)

5.2.6.3. Fourth analysis
(12am December 20 to 12am December 22)

The following graphs show the day with the highest number of compressor starts, according to the "Daily consumption data": 30 starts in a day with 15 hours of work; we could say the average cycle is represented by 35/40 minutes of compressor working followed by 10/15 minutes of non working, repeating itself each 50 minutes. Looking at Figure 61 and 62, the real situation was more complex, with some longer single peaks, which contain two or three starts.

Thanks also to the quiet external temperature, the defrost cycle usually reached 15 °C (59 °F), and it happened with a high frequency in particular during December 21.

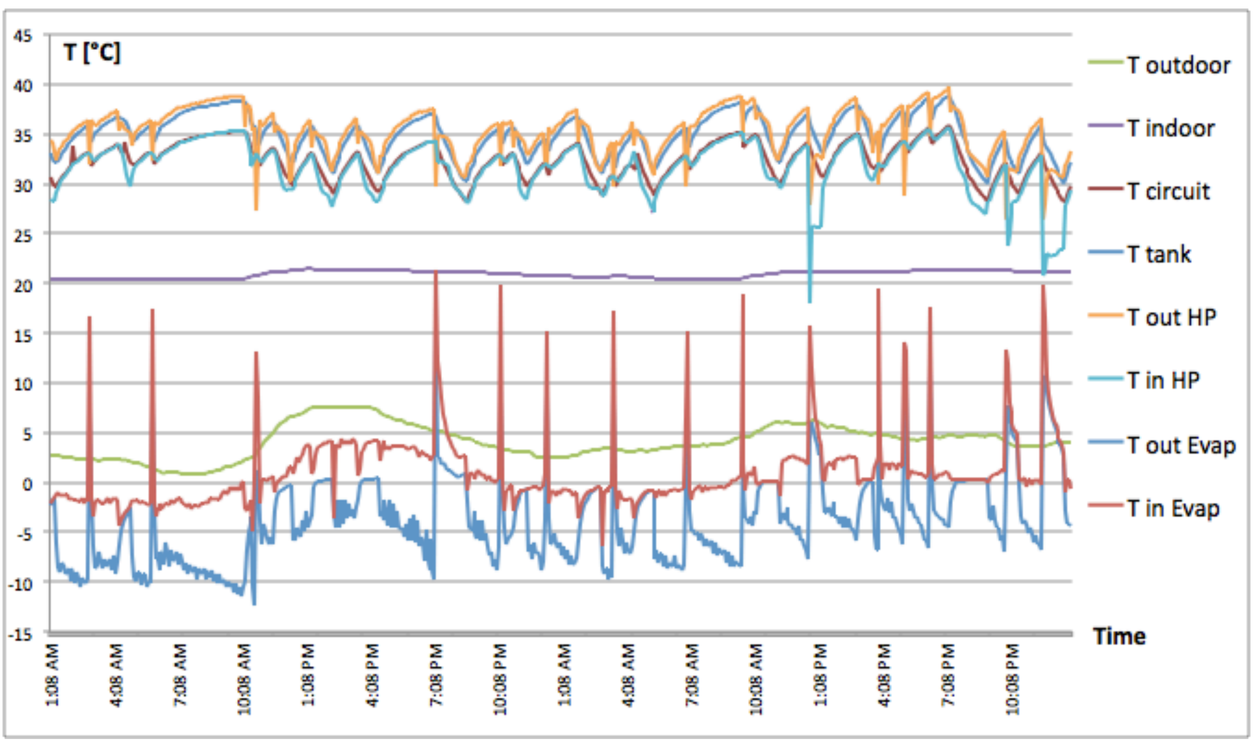

Figure 61. Data time plot from December 20 to 22

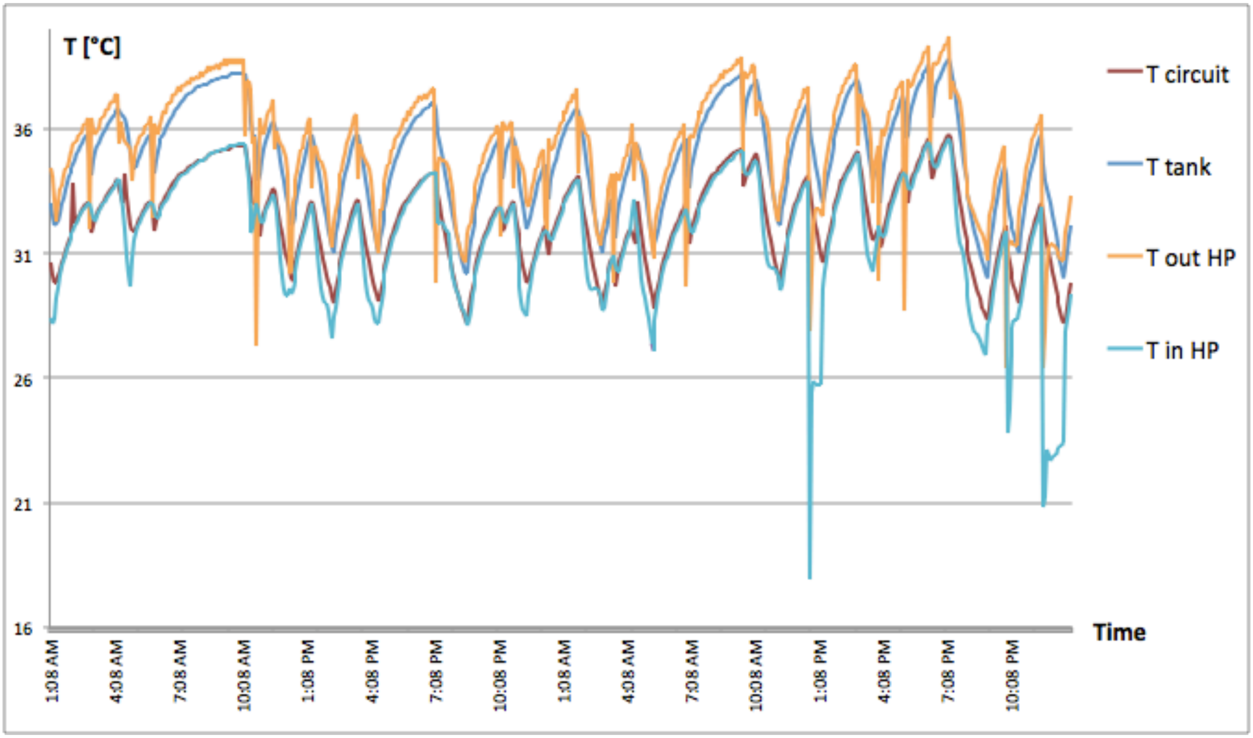

Figure 62. Data time plot from December 20 to 22 (High temperatures)

5.2.6.4. Fifth analysis
(12pm January 14 to 12pm January 16)

This case is similar to the previous one, with a huge compressor intervention (30 cycle/day and 15 hours/day) except for the middle of the day when the heat pump didn't work for 6 hours, guaranteeing (and increasing) the internal temperature using the heat in the tank and probably thanks also to the solar irradiation. The number of defrost cycle was proportional to compressor starts.

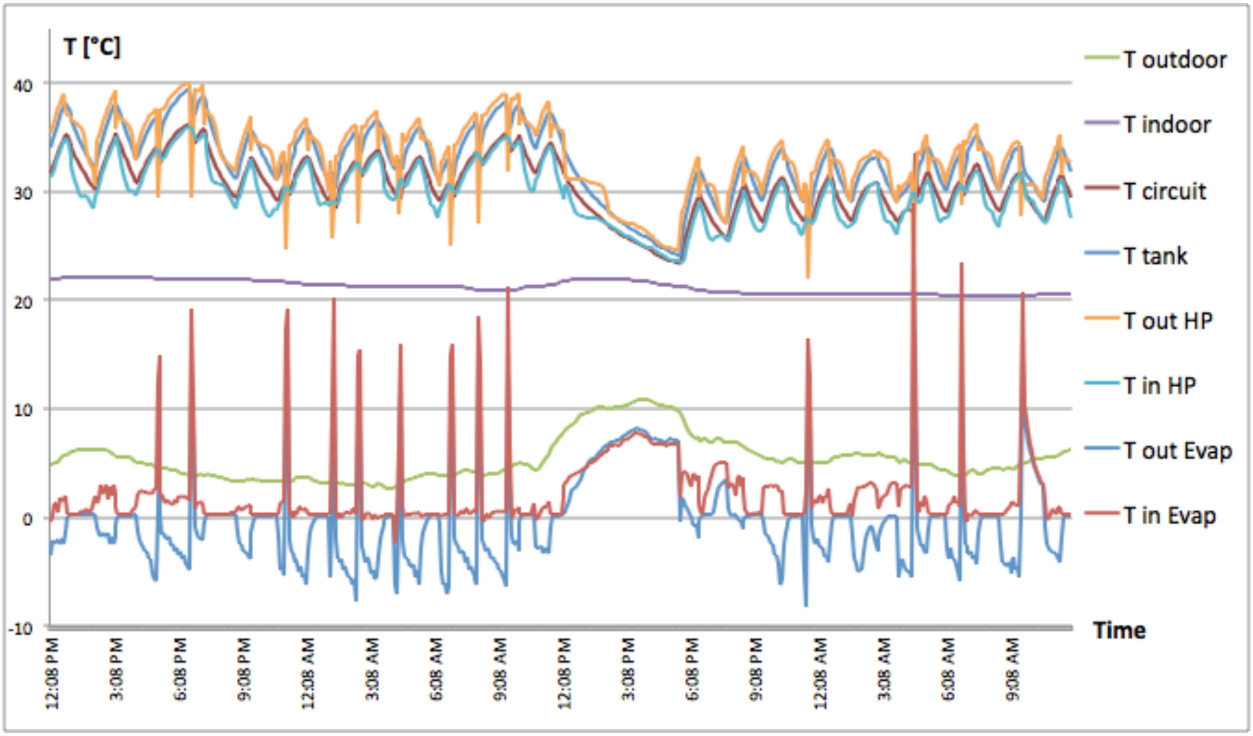

Figure 63. Data time plot from January 14 to 16

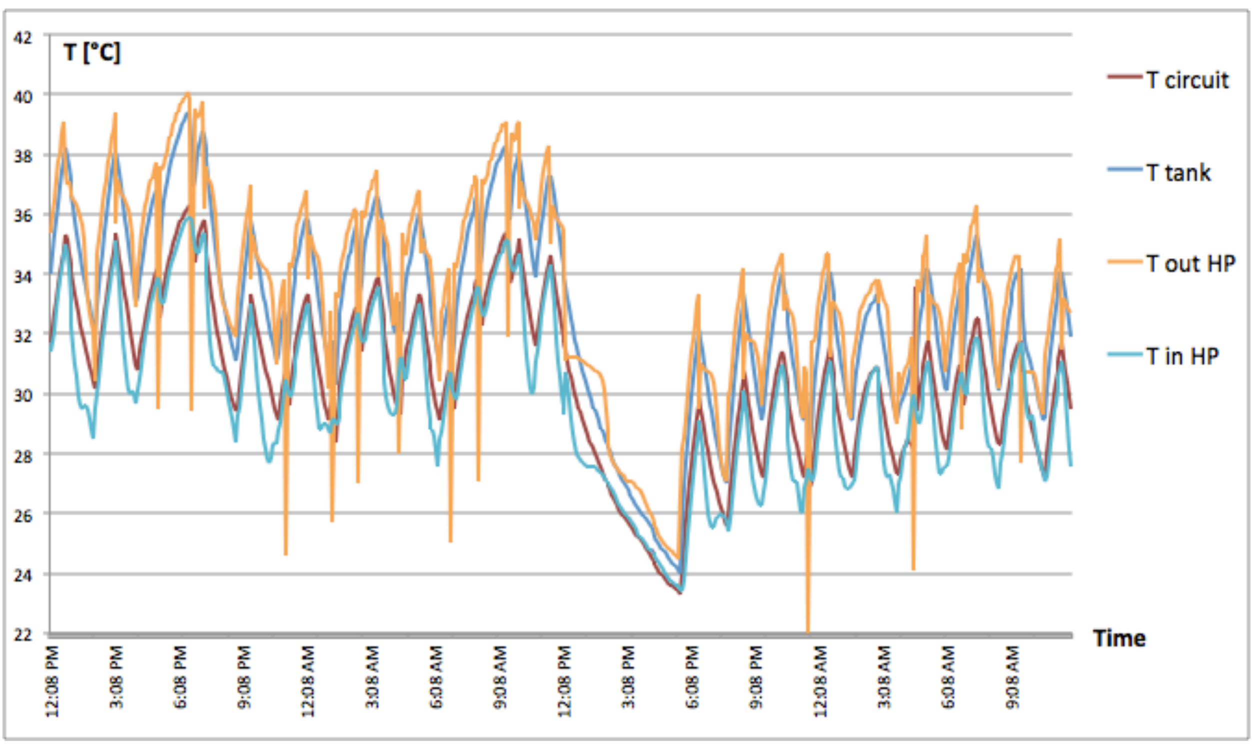

Figure 64. Data time plot from January 14 to 16 (High temperatures)

5.2.6.5. Sixth analysis
(12am March 20 to 12am March 22)

During the approaching spring days, the plant reduced its work to few interventions during a day as seen before in the fall days; this produced a slow internal temperature drop, which is unacceptable below 18°C (64.4 °F). Taking into account March 20 was a Sunday and this is an office application, the temperature started to increase during Sunday night and, at the work restart on Monday 9am, the temperature already reached 20°C (68°F).

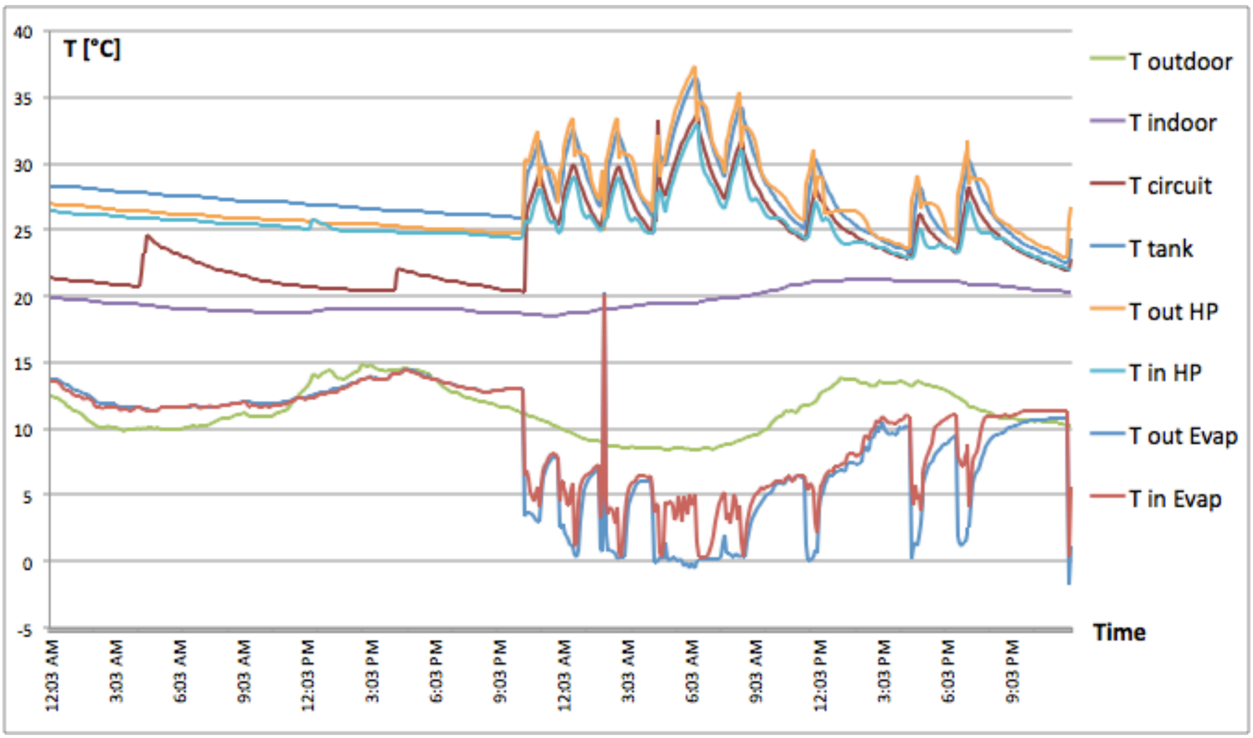

Figure 65. Data time plot from March 20 to 22

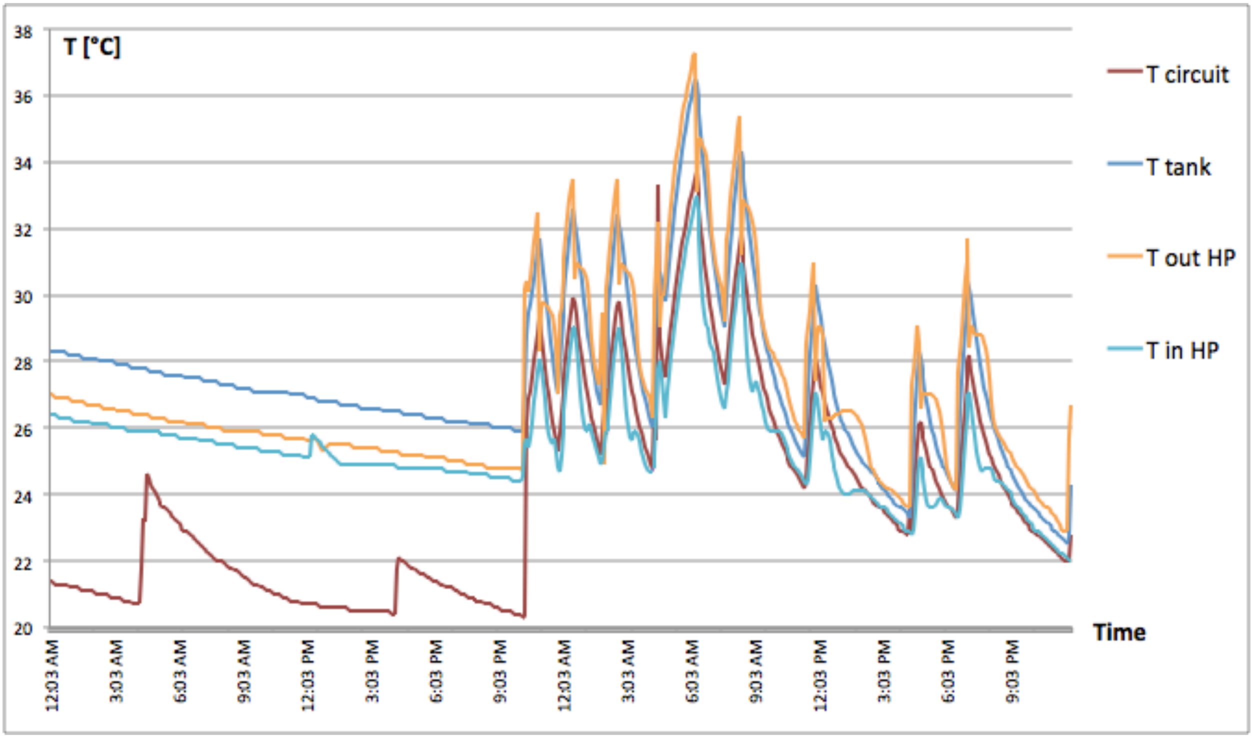

Figure 66. Data time plot from March 20 to 22 (High temperatures)

5.3. 15-second electrical data

During the start up of the Rivalta plant, some electrical probes (Figures 67-68-69) were mounted on the HP electrical panel and interfaced to a computer by the Dent Elite Pro (Figure 70), a three-phase power recorder and data logger.

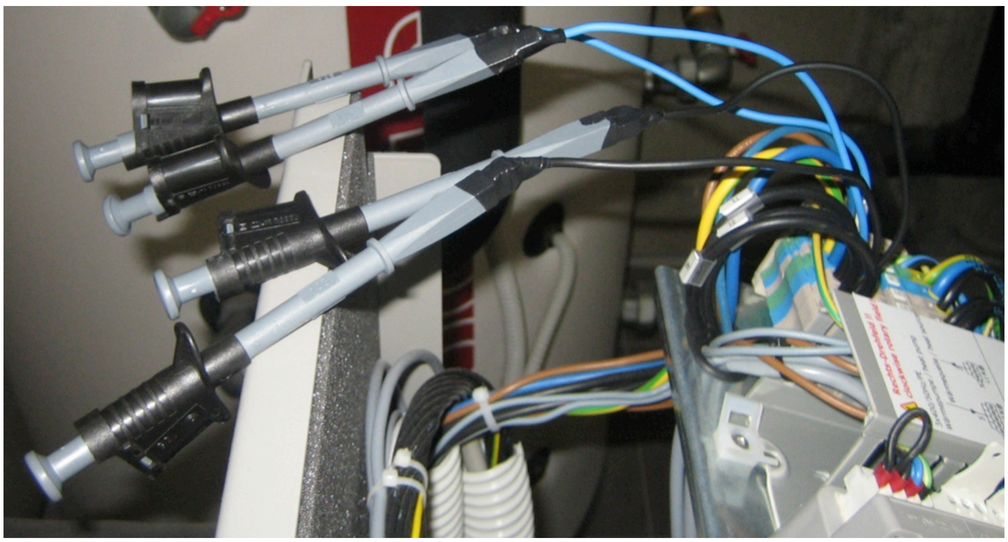

Figure 67. Electrical pincer probes connected to the HP electrical panel

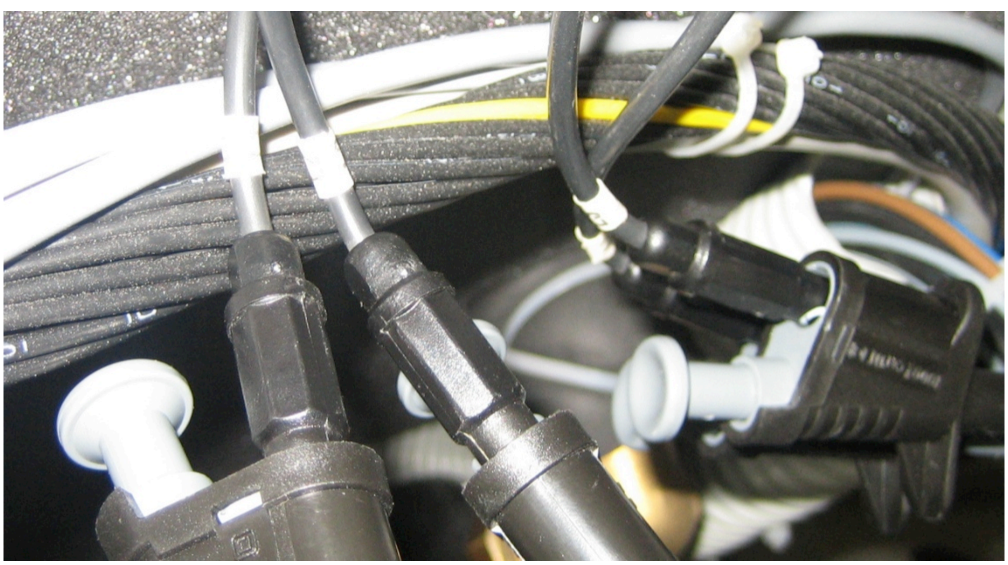

Figure 68. Electrical pincer probes connected to the interface

Figure 69. Dent clamp-on probes

Figure 70. Dent Elite Pro on work

The following parameters are known:

- Voltage (but it is not analyzed since it is almost constant)
- Average values in the 15-second period:
    - Current
    - Real Power
    - PF
- Maximum values in the 15-second period and exact time (in a 3 seconds range) in which it happened:
    - Current
    - Real power
    - Apparent power
    - PF
- Energy consumption in the period

5.3.1. Advantages

- Quick survey (two hours of recording and 15 minutes for mounting it)
- It permits to know the Power Factor, unlike a common electricity tester
- It can be used in different phases of plant life (start up, working condition, malfunctions)

5.3.2. Disadvantages

- If it is not matched with other sensors, it is limited to only electrical parameters
- Expensive instrumentation (the interface, the probes and the software cost about 1500$)

5.3.3. Time plots

In function of time, the four main parameters are plotted: average current and real power, maximum apparent power and power factor. In two hours of testing, five different cycles started: in order to increase the time detail, they are separately plotted.

BEWARE

In the following plots, the average value of the apparent power is unknown, unlike real power and current; despite that, we choose to plot the known maximum apparent power and the average real power together. In practical terms, the difference between the maximum value and the average one is significant only in the transitory periods, such as the starting. This is the reason because sometimes the apparent power plot has a pick that the real power has not or has a trend different to the current, otherwise similar (remember that the voltage was almost constant).

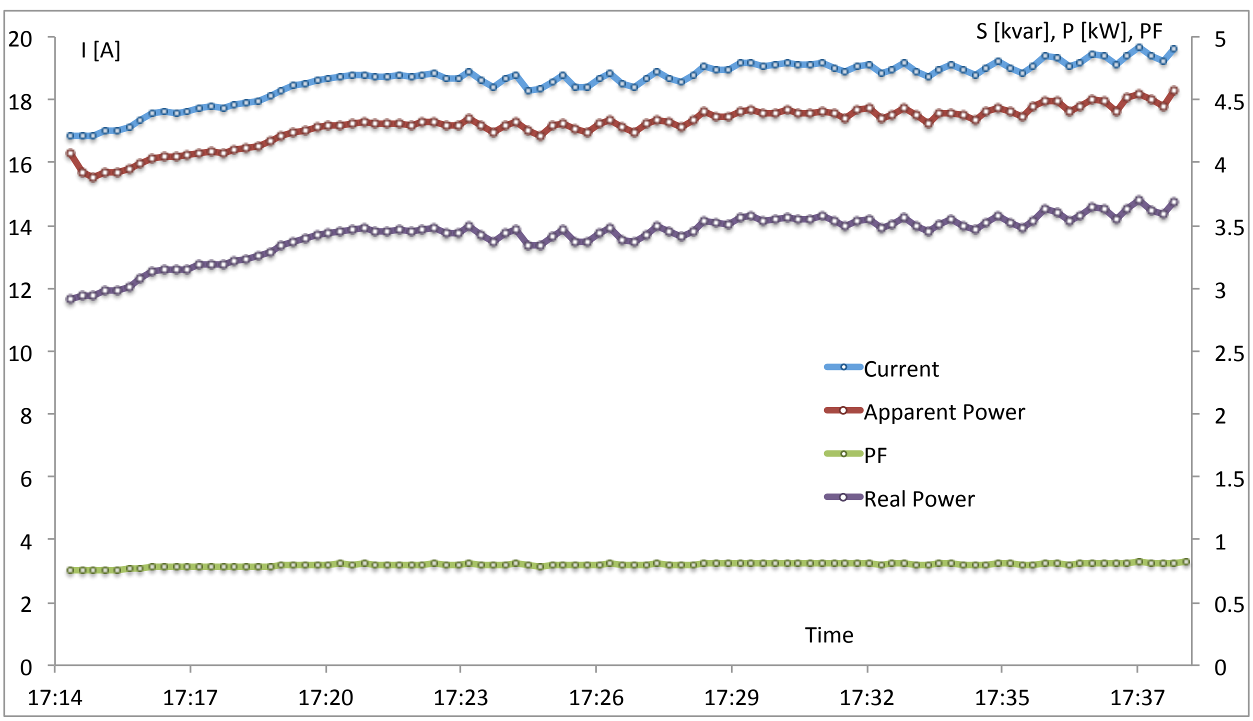

Figure 71. Time plot of the first starting

The first graph in Figure 71 shows the plant on its first running, starting in heating conditions and working for about 25 minutes. The soft starter worked correctly: the current during the compressor starting was not higher than the average working current while the maximum apparent power was a little higher only in the first ten seconds. The working current started between 15A and 16A and increased to 17A; at that moment, it began to oscillate with an average period of about 1min15sec (the time of 5 oscillations). The oscillating power/current is usual in the first starting attempts of a new plant, since the refrigerant charge had to reach the working level (unknown by the project) and the refrigerant had to fill each component.

Figure 72 represents the defrost cycle, which is usually responsible of a huge electrical (and heat) consumption of the plant; consequently, it is necessary reducing and optimizing the necessary length of the cycle.

Two attempts lasted respectively 3 minutes and 5 minutes; in particular, the second attempt was composed by two current oscillations that went beyond 20A.

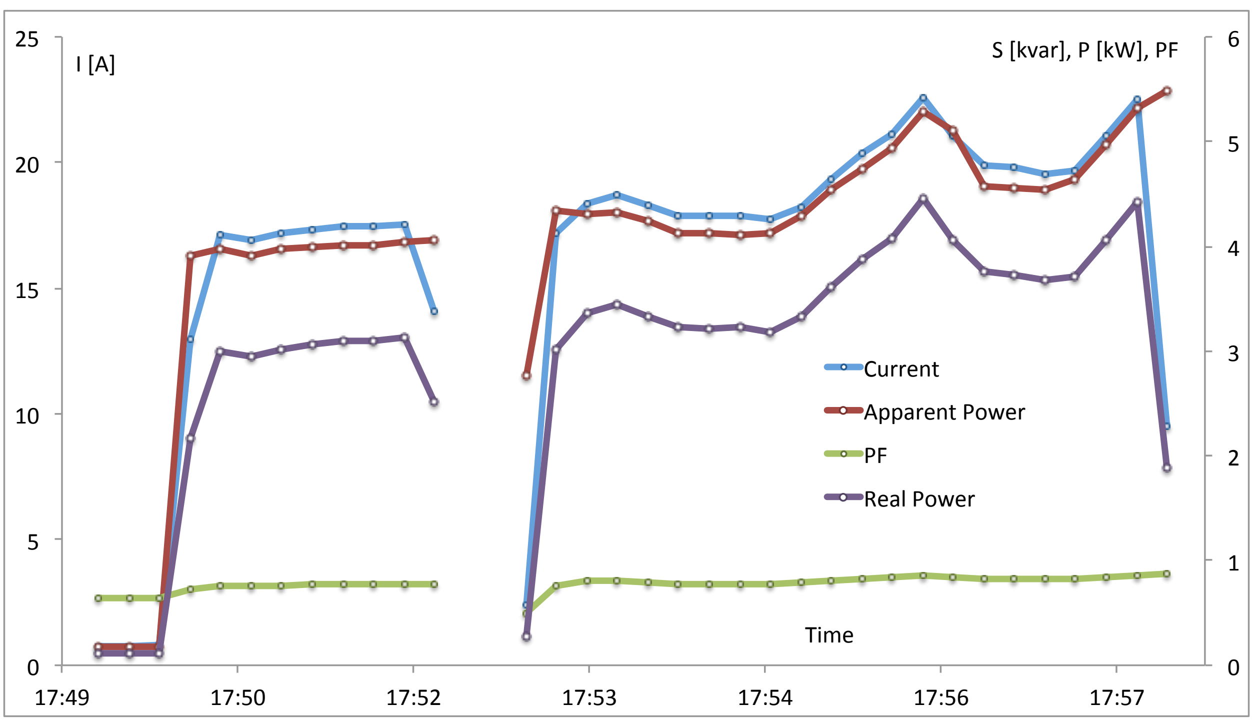

Figure 72. Time plot of the second and the third startings

With respect to the first graph, the fourth starting, which lasted again 25 minutes, was more stable also in the short period: the oscillations didn't totally disappear but they were strongly reduced, as represented in Figure 73. After an initial peak due to the compressor starting at an acceptable current, about 18A, which is not higher than the working current, it started working regularly at 17A then rose slowly until 18A.

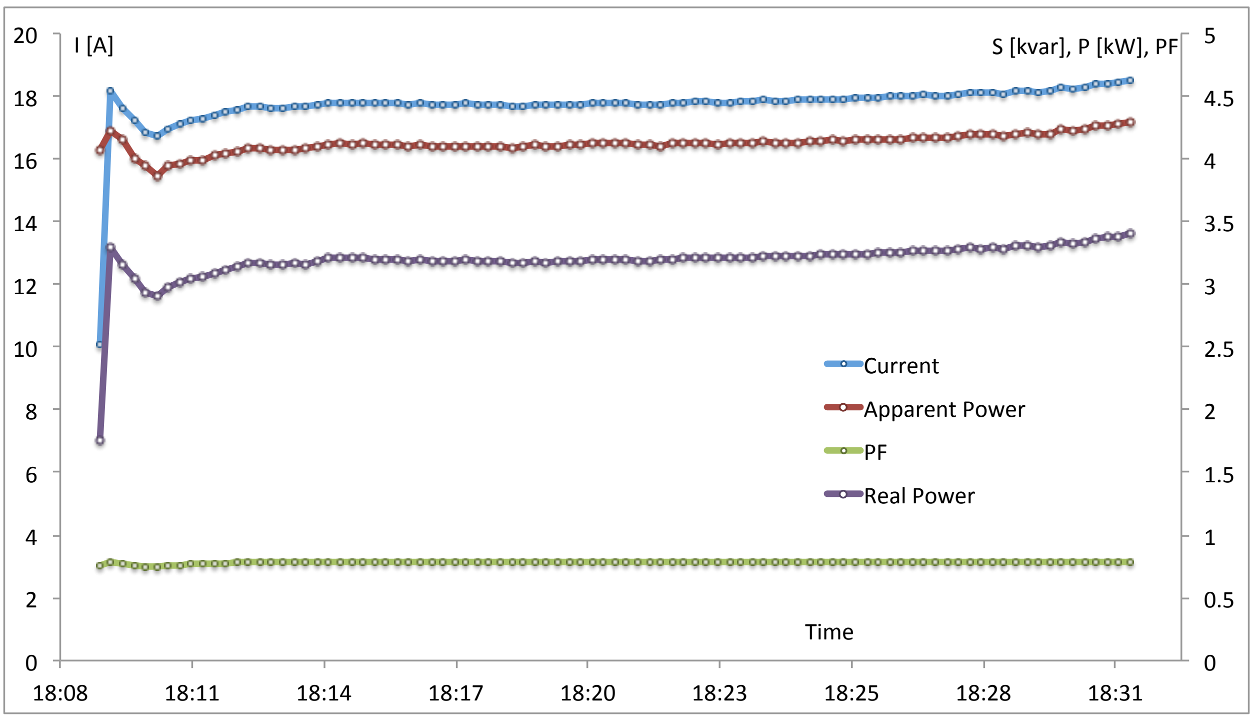

Figure 73. Time plot of the fourth starting

The last testing, shown in Figure 74, probably represented the usual behavior in the plant life, after a transitional initial testing time. There were not initial peaks or oscillations during the working condition: current, powers and power factor were stable. It lasted only few minutes because no more information was necessary.

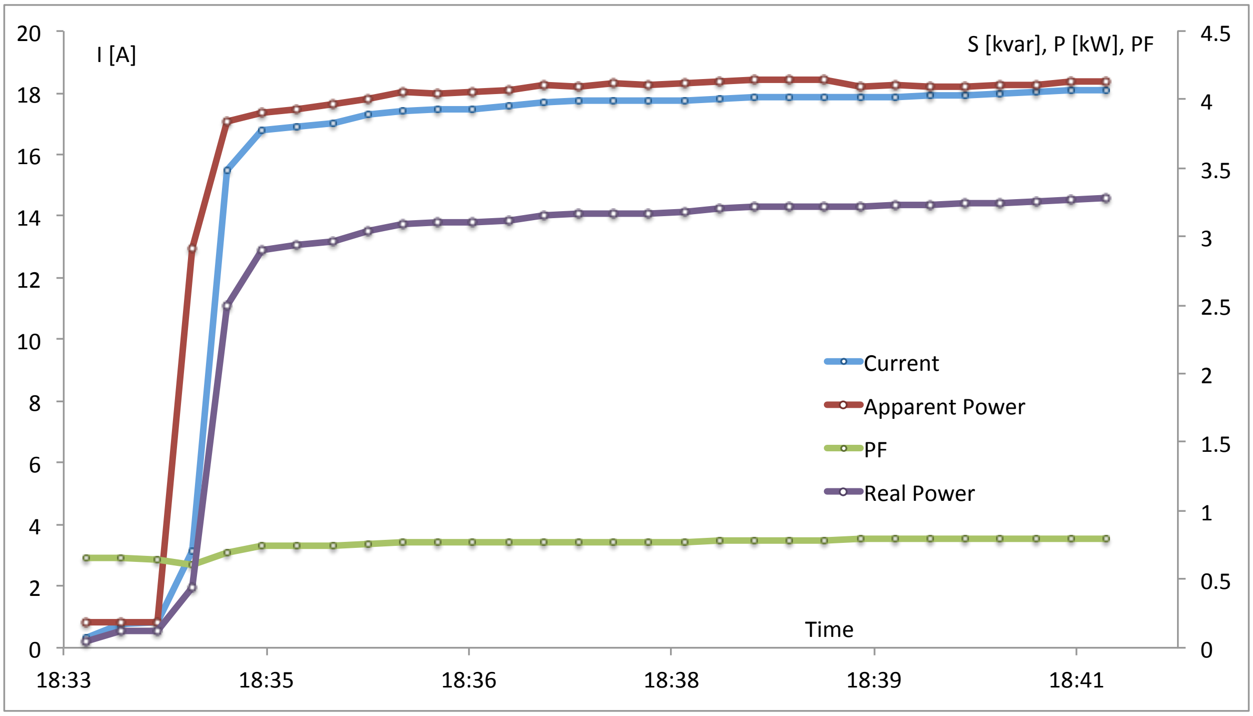

Figure 74. Time plot of the fifth starting

5.3.4. PF analysis

One of the most important parameters we obtained in this analysis is the power factor or PF, which is calculated by this equation:

$$PF = \frac{P}{S} \qquad (5\text{-}2)$$

Of course, the analysis doesn't give a unique value but a value changing in time as power changed, and it is in function of other parameters. In the previous graphs, the PF is analyzed in function of time; however, this solution permits to do few considerations, apart from an idea of the average value and stability information. So, the idea is to compare it with one of the other three parameters analyzed. The choice to plot it in function of the apparent power permits at the same time to know the behavior with respect to the current, because the voltage was almost constant. The points due to the initial transitory period are not considered.

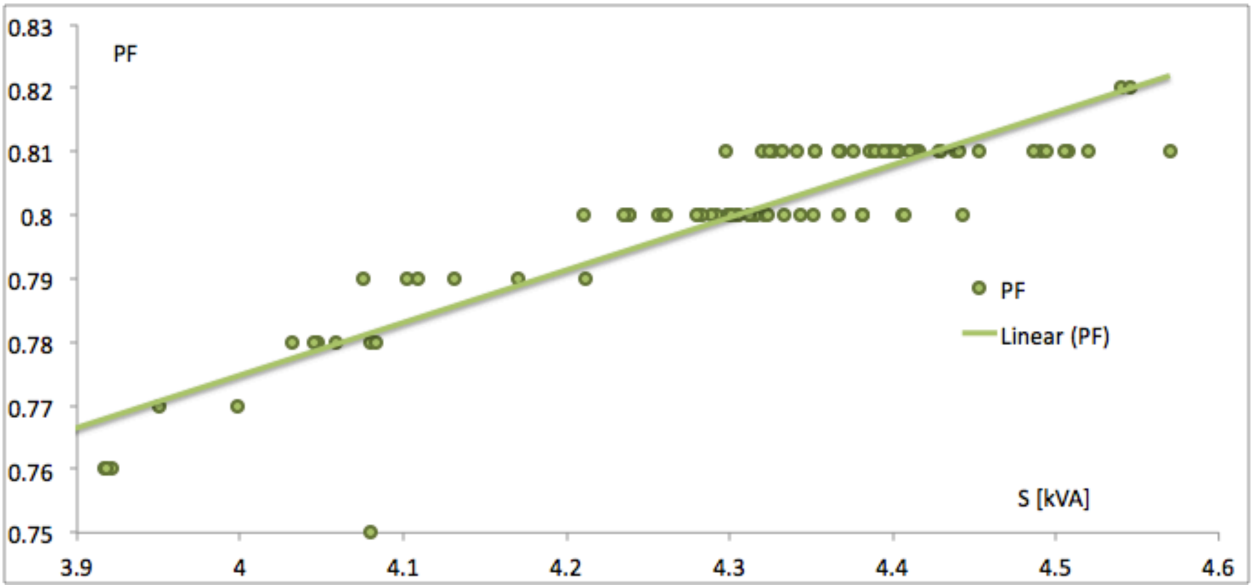

Figure 75. PF plot of the first starting

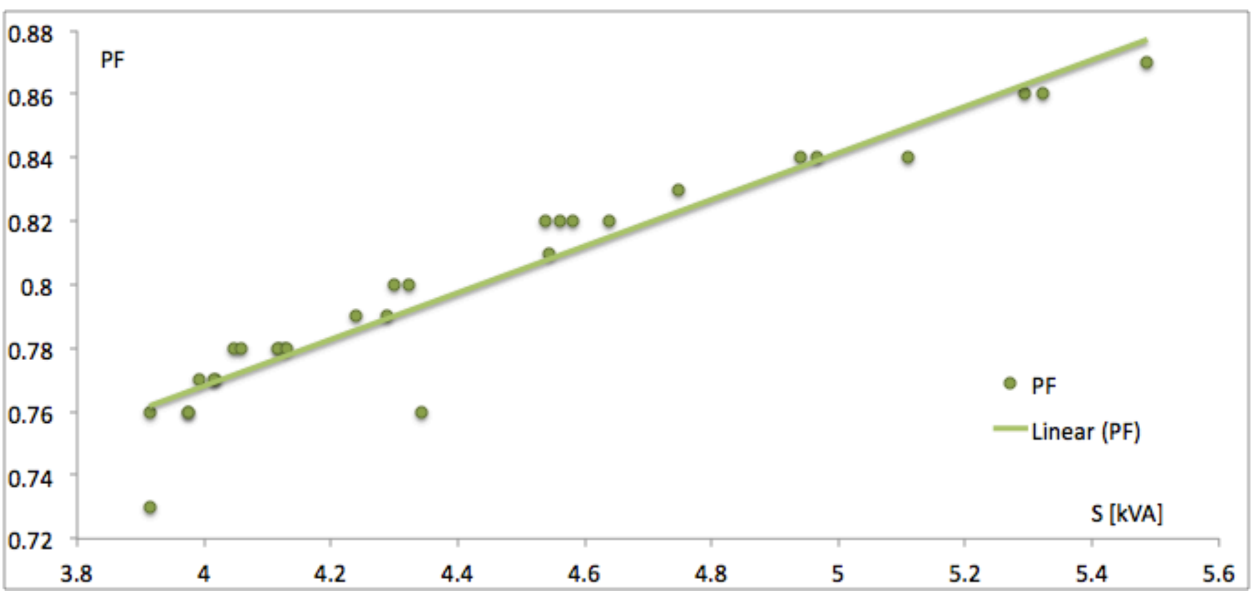

Figure 76. PF plot of the second and the third startings

In the second situation (Figure 76), correspondent to a defrost cycle, the apparent power was not stable and varied in a large range of value, so also the power factor changed a lot in function of this one. A linear trend line matches accurately these two parameters on the whole range.

In the Figure 77, the power factor tended to concentrate in a region between 0.78 and 0.79 when the apparent power was between 4 and 4.3 kVA.

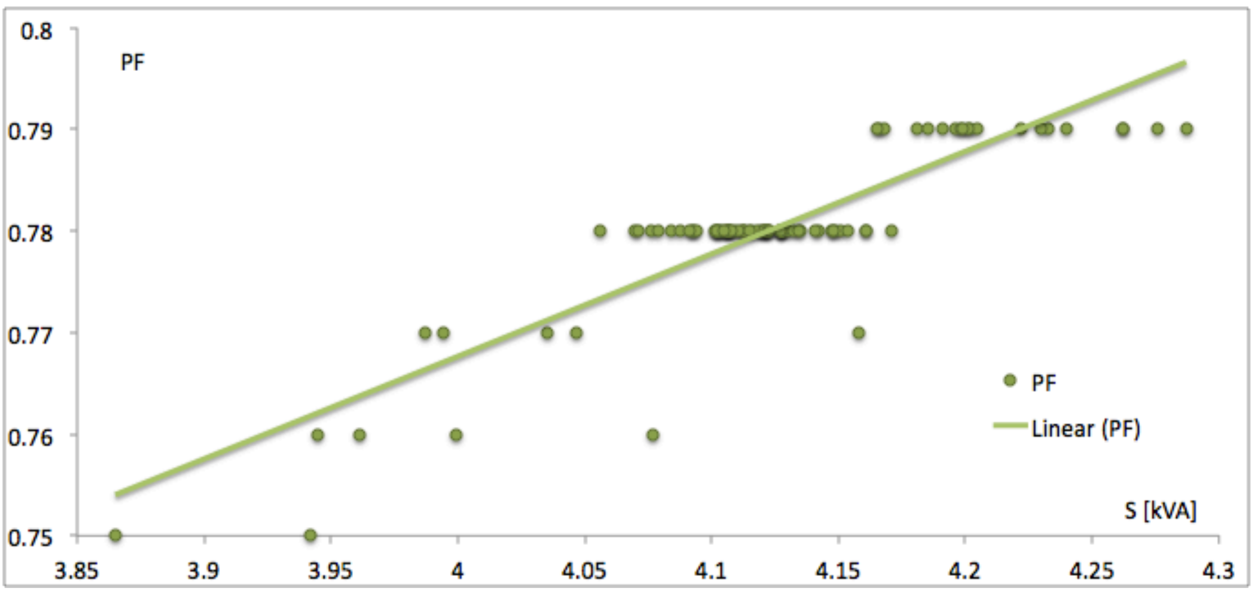

Figure 77. PF plot of the fourth starting

In the last graph (Figure 78), it is possible to see the range of stable working conditions for power factor and apparent power, respectively between 0.77 and 0.79 and between 4 kVA and 4.2 kVA. This means a real power between 3.1 kW and 3.3 kW.

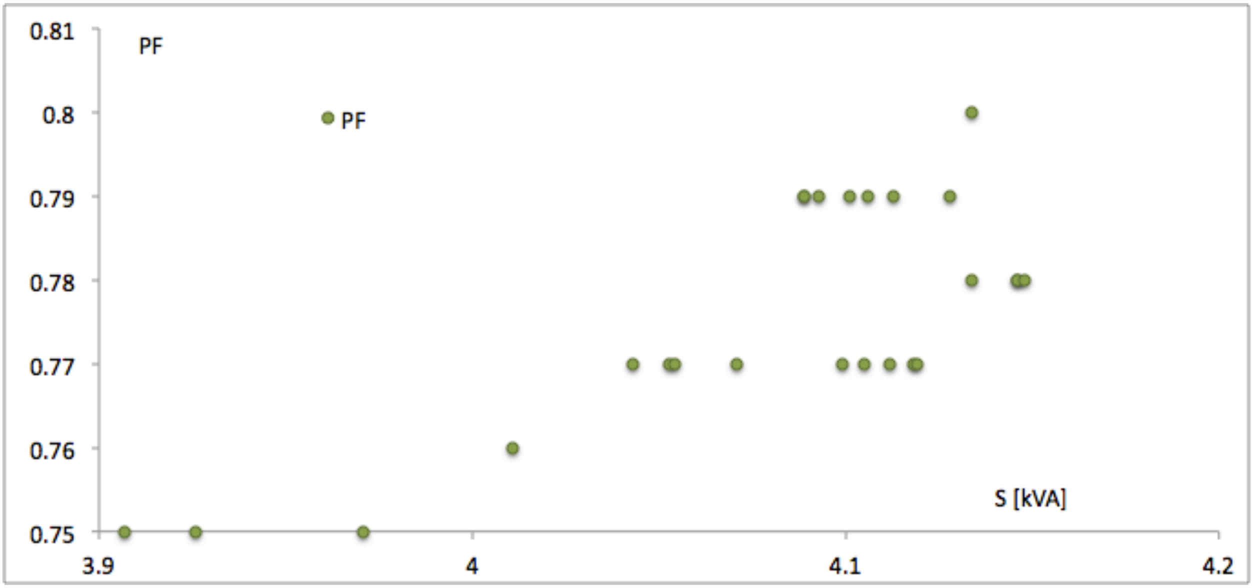

Figure 78. PF plot of the fifth starting

The graphs above show also a linear trend line: this is not the primary purpose of the analysis, but the proportionality of the two data is so evident to suggest plotting it. However, in some cases, a band instead of the line should be the right solution. In the last graph, which represents the stable condition, the line is not represented because the PF is concentrated in a short range of results.

6. AIR-AIR HEAT PUMPS

6.1. VRV systems

This work analyzes in detail heat pumps using water as fluid in the heating/cooling circuit, in terms of start up, commissioning and performance. A parallel field in HVAC systems is represented by air-air heat pumps, which use the same thermodynamic cycle and similar components but different technologies.

One of the best technologies, introduced in Japan in the 80s and in Europe and North America in the 90s, is called VRV, which means “Variable Refrigerant Volume”, consisting in an external air evaporator and a multiple system of internal heat pumps. The success of this technology was also due to the introduction of the heat recovery in 1992, which permits to save useful heat from air before changing it, especially in plants where heating and cooling systems can operate together at the same time. In the previous cases, the ventilation was not analyzed, being separated for the heating and cooling system, while the heat reclaim ventilation (HRV) works as a complement for the VRV system, so they must be analyzed together. In some cases, VRV and HRV can be a single system.

6.1.1. Energy advantages

- Heat recovery
- No water consumption
- Variable compressor load using an inverter
- Reduced transportation heat losses
- High performance since the first day
- Alternated defrost cycle (the heating doesn't stop)
- Free cooling
- Simultaneous heating and cooling in different area

6.1.2. Installation advantages

- A thermal or equipment room is not required
- Modular system
- Easy transport, also at high levels
- Simple electrical plant, with daisy chain without polarity
- Possibility to remove and relocate the plant

6.2. Examined case

Location:	Contacta, Torino, TO, Italy
Heat source:	Air
Heat pump:	Daikin[5] VRV system
Thermal power:	34.2 kW (nominal of VRV system)
Cycle:	Reversible
Duties:	Heating, Cooling, Ventilation
Cx Type:	Continuos Cx

Figure 79. External face of the building

[5] Daikin is a Japan-bases multinational corporation, leader in the air conditioning field.

The plant we briefly analyzed and visited, of which the main commissioning will be done in the next months, is located at the higher level of a 5-floors building (Figure 79) in Torino. The project is followed by Ing. Toniolo and the plant was started in April 2011, servicing a large call center room, an office, a smoking room, a lecture hall and a break area, for a total volume of 1880 m^3 (66k cubic inches).

The high internal gains, due to an average value of 130 employers and working computers and solar irradiation on three sides of the building, made necessary a huge cooling system, operating during a large time in the year. A built-in centralized fan coil system was present, but the energy manager decided to not use this and to install an independent heating system, in order to reduce the annual costs and to have an easier and better range of setting. The choice of reversible heat pumps was the best solution, also considering the saving of space in the rooms, indeed choosing air-air VRV system permits to mount the internal units and the piping, with ventilation and lighting systems, in the false ceiling; while the external units are located on the flat roof, just a level up the rooms. Furthermore, the call stations are irradiated by the sun in different periods of the day, since there are windows on east, south and west side, so the possibility to use both heating and cooling cycle in the middle seasons has advantaged the VRV choice (obviously only if the splits have not the evaporator in common).

We are sure that a photovoltaic system on the roof, for instance mounted as overhang, could be a winning investment, considering the HVAC system uses only electrical energy and principally during the day; however, Contacta rents the place so it is not sure to reach the payback time before it will leave; while, in case of necessity, the VRV system can be rapidly disassembled and moved.

The Contacta plant uses principally fifteen Daikin FXFQ-P cassette type units (Figure 81), as VRV system, and four Daikin VKM100 air exchangers and humidifiers, as HRV system. The VRV units, used in four different sizes, from 3.2 kW to 6.3 kW of nominal thermal power, are split in eight independent lines, regulate by as many remote controls, five in the main call center room and three in the other rooms. Each VKM takes clean air from outdoor and foul air from indoor through air intake grills (located near the windows) and it provides, recovering totally heat, new clean air to the rooms by two or three 60cm squared diffusers and ejects the foul air. Every VKM is controllable by a dedicate remote control in a convenient place of the served area.

Remembering the high internal heat gains, the HRV system gives an important contribute in terms of free cooling, especially the first hours of the morning. In addition, two concealed ceiling units, Daikin FXSQ-P, are mounted: a FXSQ100P (Figure 82) matched in series with a heat recovery system, a Daikin VAM100, provides air conditioned through five 60cm squared diffusors in a block of the call center room while a smaller FXSQ40P is the only VRV equipment in a lecture room.

Figure 80. Daikin outdoor unit

Figure 81. Ceiling mounted cassette Daikin FXFQ-P

Figure 82. Concealed ceiling unit Daikin FXSQ100P

6.2.1. Operation sequence

The setting of the HVAC system in function of the time and the season permit to combine the intervention of VRV system in heating or cooling mode with the work of the HRV system, which can also work in heat recovery or free cooling. The system can work in automatic mode, setting the goals in terms of internal temperature during the day, or can be manually programmed, hour by hour. Let's analyze the suggested operation sequence in a working day from 8am and 8pm.

In winter (or when the daily external temperature is lower than 20° C):

1. Heating and ventilation: during the hours before the work restart, the internal temperature of the rooms has to be risen to 20° C by the VRV in heating cycle, since there are not internal gains; after it continues to work in the morning and in the afternoon only in the coldest days.
2. Ventilation and heat recovery: during ventilation, the heat is kept by the recovery; thanks also to internal gains, the recovery can permit to stop the heating system for the rest of the day.

In the middle seasons (or when the daily external temperature is about 20° C)

1. Ventilation: in the morning usually only the ventilation works.
2. Free cooling: because of internal gains, the internal temperature rises. The free cooling can cool down the internal temperature, without the use of VRV system.

In summer (or when the daily external temperature is higher than 20° C)

1. Free cooling: during the hours before the work start and in the morning, if the external temperature is still lower than 20° C, the free cooling is sufficient to cool the rooms.
2. Cooling system and ventilation: in the middle of day, high internal gains and the irradiation from the completely-windowed south side make mandatory the use of VRV cooling system.

A call center could be used 24 hours a day, with a lower number of working stations. In summer nights, free cooling is probably able to completely solve the air conditioning; while in winter, a massive intervention of the heating system (lower internal gains and lower external temperature) could be necessary, however the recovery of the heat stored during the day can reduce the consumes.

6.3. Ongoing Commissioning

As done for the other cases in this work, the plant has to be monitored during its work also after the start up. In the large list of advantages due to the commissioning (see Chapter 1), two of these can be directly measured and quantified: the indoor air temperature and the energy consumption.

6.3.1. Internal air temperature

The Cx has to respect the needs of owners and occupants, for these reason they should actively participate to the Cx, in particular in a initial meeting; the satisfaction and the comfort of the employers influence its behavior at work, in particular in a call center, in which the mood and the kindness of the operator represent the quality of the service, apart from the proficiency. For this reason, the energy manager suggested a higher internal temperature in the first hours of the morning, when usually the employers feel the temperature colder than it is.

A survey should be done in different parts of the office, considering the different exposure of the rooms and the different type of VRV system. Also, the air humidity has to be surveyed.

The analysis of internal temperature data should be as done in the Chapter 5, plotting:

- A distribution and a cumulative
- A graph in function of the external temperature
- The "heat maps"

6.3.2. Energy consumption

A digital power meter, the Powerlogic PM 710, was installed on the electrical panel, measuring 4 channels, among which the HVAC electrical circuit as a whole. It permits to know and to survey:

- Real time RMS (Current, Voltage, Frequency)
- Power (Real, Apparent, PF)
- Energy consumption

A standard survey can be done on the energy consumption, for example each month or week, while, in case of malfunctioning, the real time data can be useful.

7. INTERVIEW

with Ing. Raffaele Vavalà, president of firm Heliant, Italian Ochsner distributor

7.1. Heliant

When was Heliant born?

Heliant was born in 1997

In which field does Heliant work?

We started with the idea of working in the renewables, since Heliant is an ambitious name that means "Sunflower" in Esperanto.
Since 1995, we began to work with solar collectors plants, relatively not much diffuse in those years; these didn't permit us to do full time work, so they were matched with plant maintenance, electrical systems, etc. When we entered in the photovoltaic field (stand alone PV, then grid-tied PV), all non-renewable activities were quitted. In the PV field, we are also distributor of marine lamps.
Then, we entered in the thermal plants sector, initially with Rotex, afterwards with other brands, including Ochsner.

Who works in Heliant?

We are two partner and we trust to external collaborators.

Which is your environmental and energy vision?

Our basis idea is concreteness. When we started to work in this field, we immediately understood the energy consumption and pollution problems. The training courses we offer are very important for the energy conservation.

7.2. Ochsner distribution

Why do you choose Ochsner?

At the beginning, we had a first-rate collaboration for some plants, when we still worked mostly for Rotex. With the Rotex contract ending, we struck up an exclusive rights contract with Ochsner, as Italian distributor.
We love the brand because it represents a little firm, which still offers the possibility to dialog with the producers, the developers and the owners, who are very open at suggestions.
Ochsner offers a product that maximizes performance and reliability, therefore it fulfills the Heliant policy.

What does it mean to be the Italian Ochsner distributor?

To be the Italian Ochsner distributor entails the commercial management, with the need to reach a minimum of annual sales, in order to obtain a positive balance sheet. Furthermore, it must deal the assistance, the customer search and the training. Also, we have to find the assistance centers along the national territory: this is not easy because of the high level we demand.
The customer training is the last but not the least step, because HVAC plants are usually more difficult to use than traditional boilers and those have a different behavior.
We have a lot of job to do with respect to real rewarding sides, but this is certainly a long-term program.

How is your national net planned?

The target is to succeed to have a whole net of specialized installers, who are followed by us about the training. Their choice must be oriented on the product, without quality saving.
We have not wholesalers, in order to guarantee a short direct path between the final installation and us.

How is your marketing plan?

First, we do a local marketing, so installers and partners are Ochsner promoters at the same time. Second, the word-of-mouth advertising is also important. Also, we receive a lot of interest from the web (our web site and forums).
We don't think about classic marketing because we don't aim to a large-scale policy and we prefer to talk directly to the customer.

7.3. Heat pumps in Italy

How do you see the Italian heat pump market?

The Italian market is still limited.
I premise that the HP definition is overused: this term should be narrowed down talking about only heating HPs. In this case, I guess a couple of thousand units are installed in a year in Italy.
In other European countries, the market reaches tens of thousand units in a year, so it is comprehensible there is a young market in Italy.

Have you some criticism about the Italian heat pump situation?

The COP calculation, its value and the applied rules are often different and doubtful.
Recently, I am worried about the incoming of some low-quality oriental products and the mediocre proficiency of some technicians, for this cause we often receive unreliable performance data. This is one the first reason because we claim reliability.

In general, where do you recomend an installation?

By economical considerations, a HP is successful everywhere the methane is not available; in fact the fuel oil is surely more expensive than the electric energy used by a HP.
Where the methane is available, the condensing boiler is the main competitor. In those situations, we consider advantageous the HP only if it is matched with a photovoltaic plant or if the owner

is available to a long-period investment (20-25 years). In this case HP wins thanks to a lower maintenance costs and a lower pollution.

Furthermore, buildings with a better insulation with respect to the average are surely more interesting for an HP installation.

Which advantages can heat pumps have with respect to biomasses?

HPs have a higher initial cost but their advantages are not only economical. Biomasses require periodic cleaning, constant charge, more frequent survey, while HPs work automatically, offering a better comfort level.

About emissions, the CO_2 value for biomasses is lower than for the HPs, but biomasses emit several pollutants that HPs don't produce.

Which is the best seller in Ochsner heat pump catalogue?

For sure, air-water systems are the best sellers, due to their easier installation and the lack of bureaucracy. The intermediate size between 10 and 20 kW is the most used, but machines until 60 kW are not rare. The context is residential, with a limited number of apartments.

We have done several quotes for large size commercial plants; however, in this sector, a low initial cost is fundamental and we are competitive in term of performance/cost but not in term of absolute cost, with respect to cheaper and lower quality equipment.

Do you prefer air or water as evaporator thermic source?

The air as thermal source is easier to manage but the project requires more ability to obtain good performance. However, the water is more variable than the air: the last one is always available and, except for the temperature, it doesn't change.

Water source plants have better performance but they need specific local characteristics, furthermore water well can have stability problem, corrosion phenomenum and it could deplete after some years.

In general, they are both valuable, so it is very important to evaluate each situation.

7.4. Startups and Commissioning

Who make the HP start up?

We are working with local technicians. We have not internal employees because we prefer collaborate with firms that have already experience in the field. I often take part to the start up but I would prefer, thanks to continuos training, the start could be self-followed by the installers.

Which should the right collaboration be with installers?

The relation should be in common interest. We have to sell our pumps, so we need installers. These must be proud of our product and promote this.

How is it possible to prevent a problem?

The installation must be perfect to respect our idea: the plants should work about 20/25 years without large maintenance. This could be possible only if the installation has followed every appropriate technical standard. We don't accept compromise solutions.

Why is it important to do the check-in list and the commissioning report?

There are two important thinks to verify. First, we must be sure that the installation respects our guidelines, which are composed by technical manual criterions and the information we give during the training courses. For instance: flows, paths, sensors, etc. The practical purpose is to guarantee the project performance.
Second, it photographs the plant at the start up moment, in order to have a reference for the following years, comparing the known initial situation. In case of necessity, it is useful also for the warranty.
We make a copy for the customer, one for the installer, one on the plant and one for the Ochsner center: this represents a common reference.

What kind of maintenance do you recomend?

A European code imposes a refrigerant testing for plants above a certain dimension; however, we acknowledged it but it is still few applied in the sector. We simply recomend an annual verify of the system conditions. On air-water plants, it is necessary a periodic evaporator cleaning, otherwise these HPs require low maintenance.

APPENDIX

BLACK AND WHITE GRAPHS

Some graphs in this work, if printed in black and white can result very difficult to read. In many cases, we suggest to print them in color if possible, in order to make easier the reading; otherwise, the same plots are here available optimized for the b/w print in the following pages. The figure number doesn't change respect with the original color figure.

Heat maps

Instead of using a 3-color scale (blue, yellow and red with shades; white for hours without information), it is used a 2-color scale, from white to black. Loosing a tonality, it is more difficult to read the graph; for this reason, we reduced the range of represented temperature from 18-22.5 to 19-22, where the total white refers to 19°C and the total black refers to 22°C.
White, which previously referred to the hours without information, cannot be used for that in this case, since it is already used for the temperature scale; so, the lack of information is represented with diagonal-up lines.

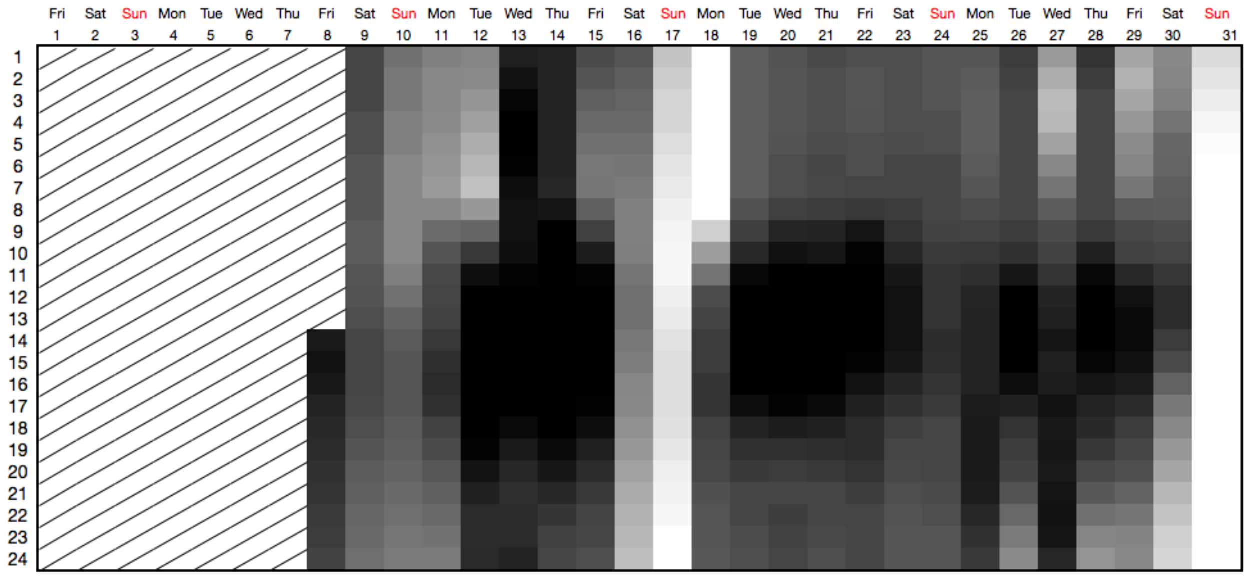

Figure 48. October 2010 internal temperature “heat map”

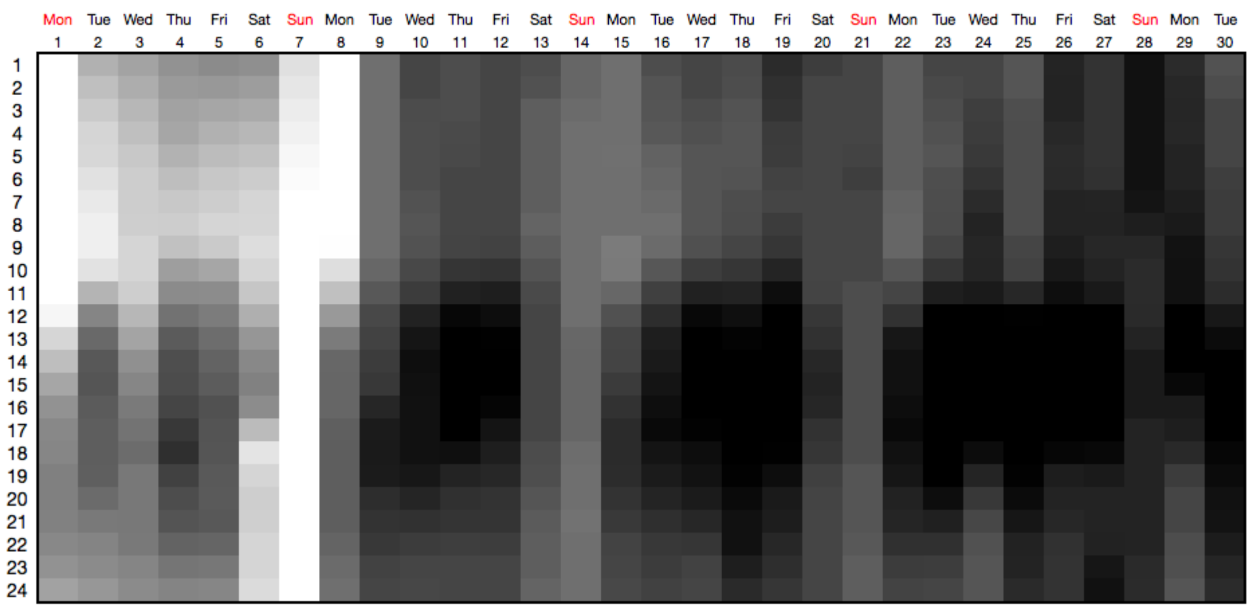

Figure 49. November 2010 internal temperature “heat map”

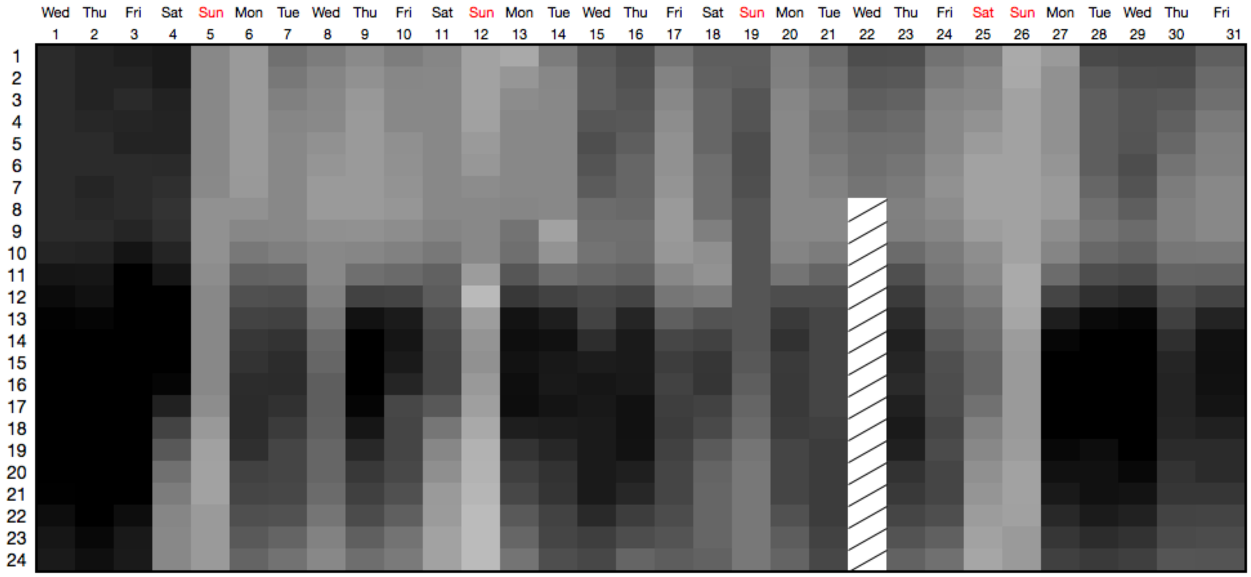

Figure 50. December 2010 internal temperature “heat map”

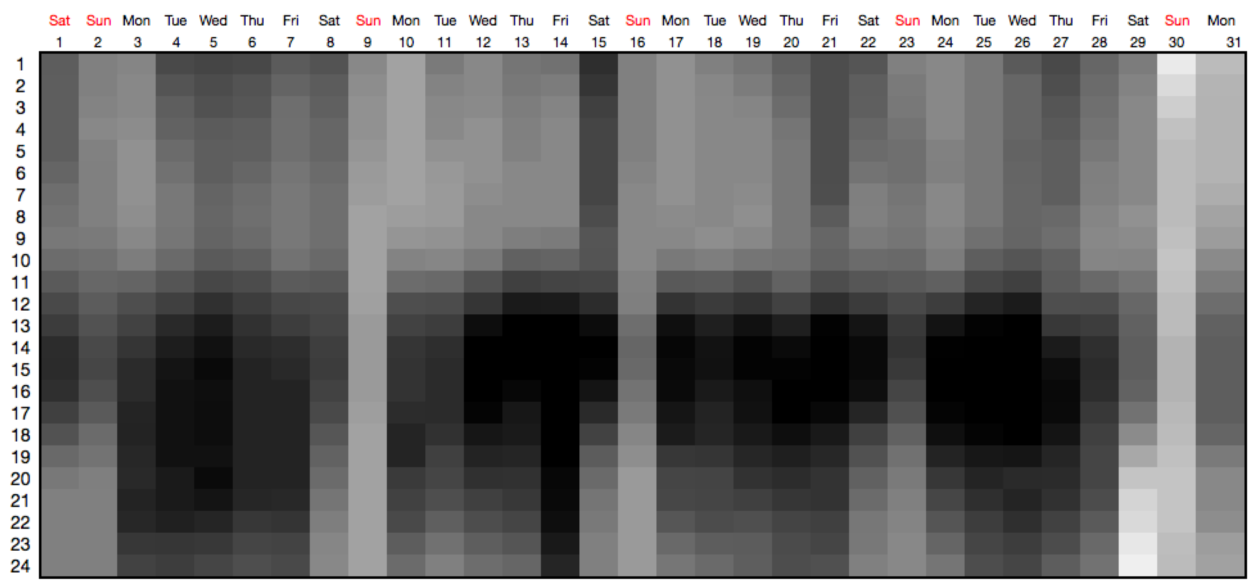

Figure 51. January 2011 internal temperature “heat map”

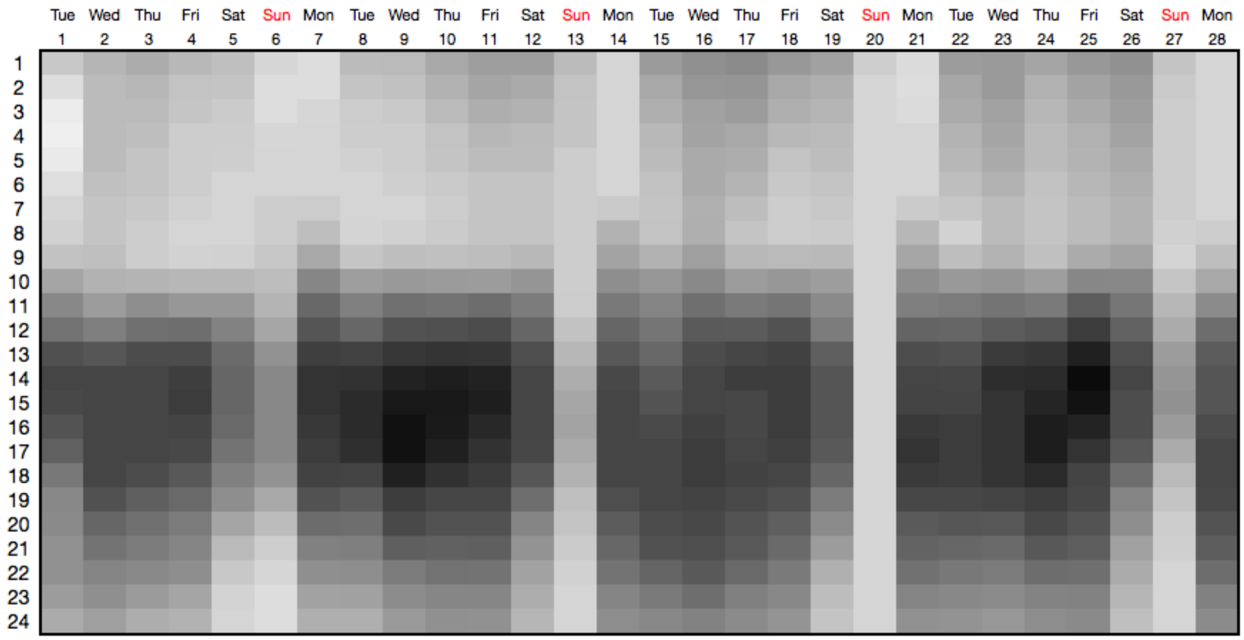

Figure 51. February 2011 internal temperature “heat map”

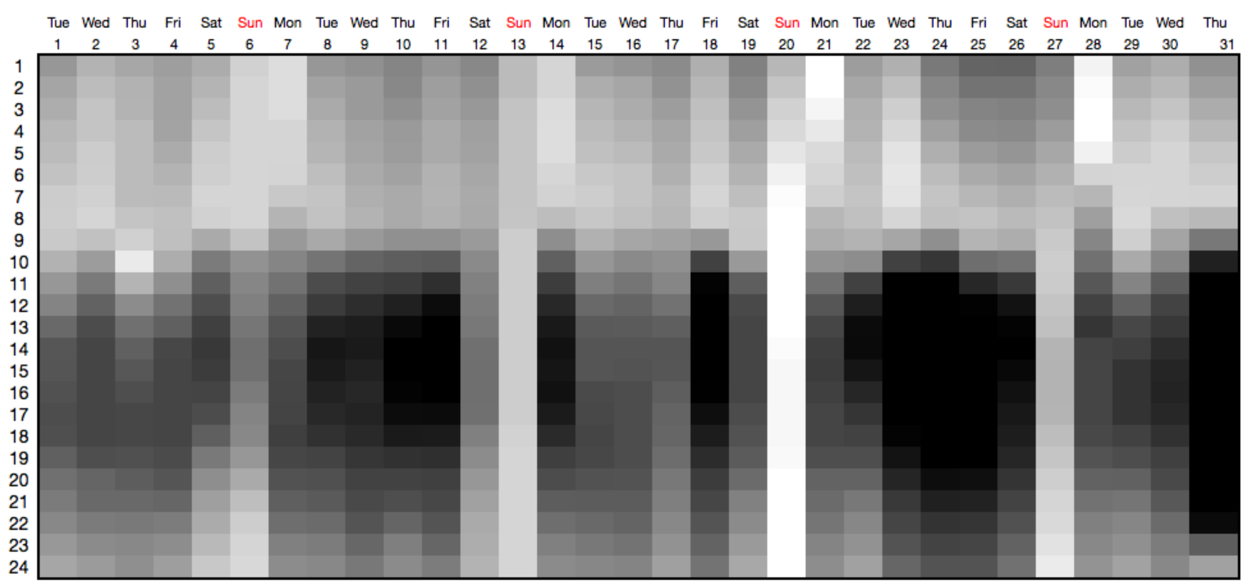

Figure 51. March 2011 internal temperature “heat map”

<u>Characteristic curves</u>

A higher contrast between non-working hour dots and working hour dots is created to improve the black and white print.

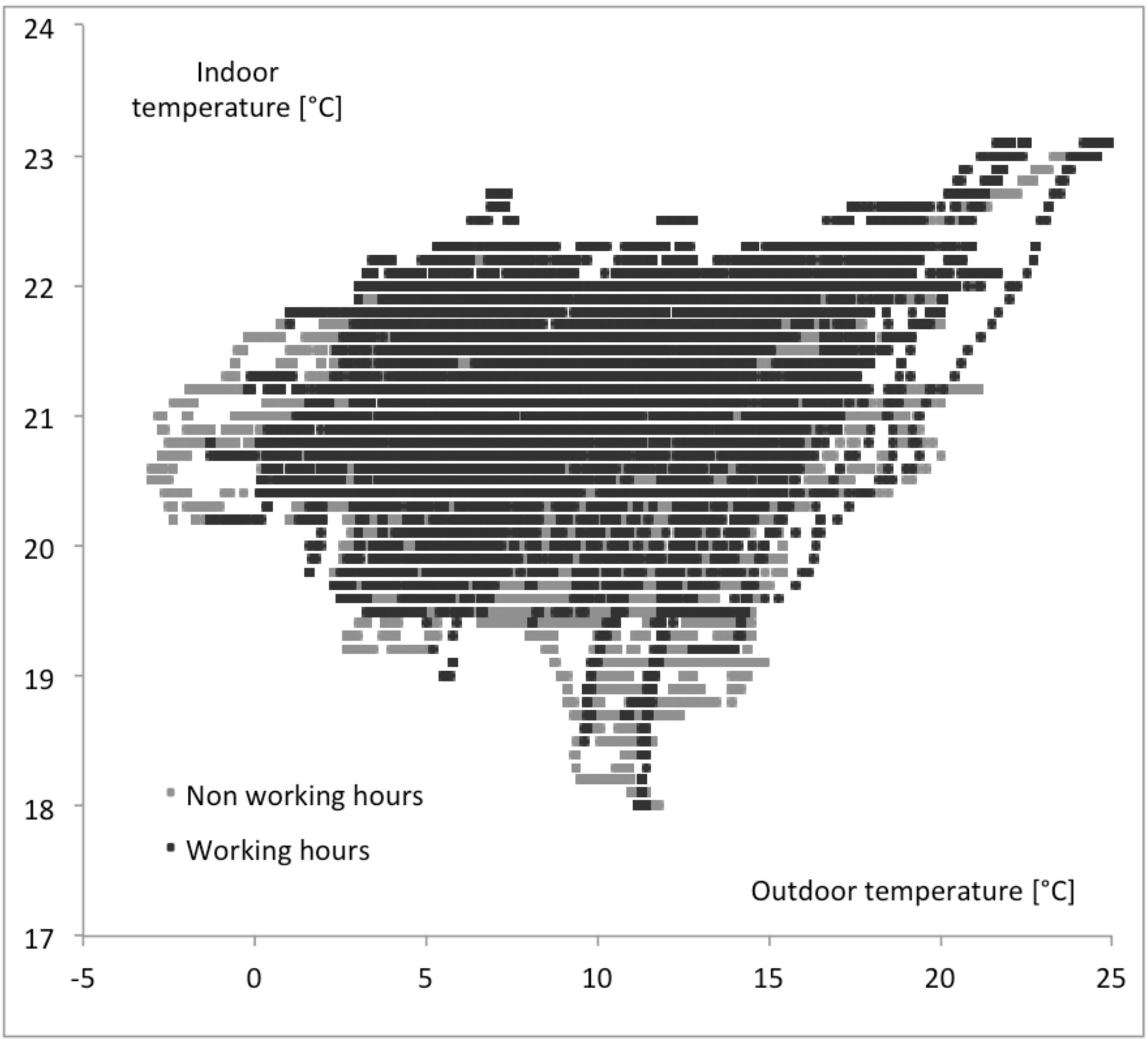

Figure 47. Relation between internal and external temperature

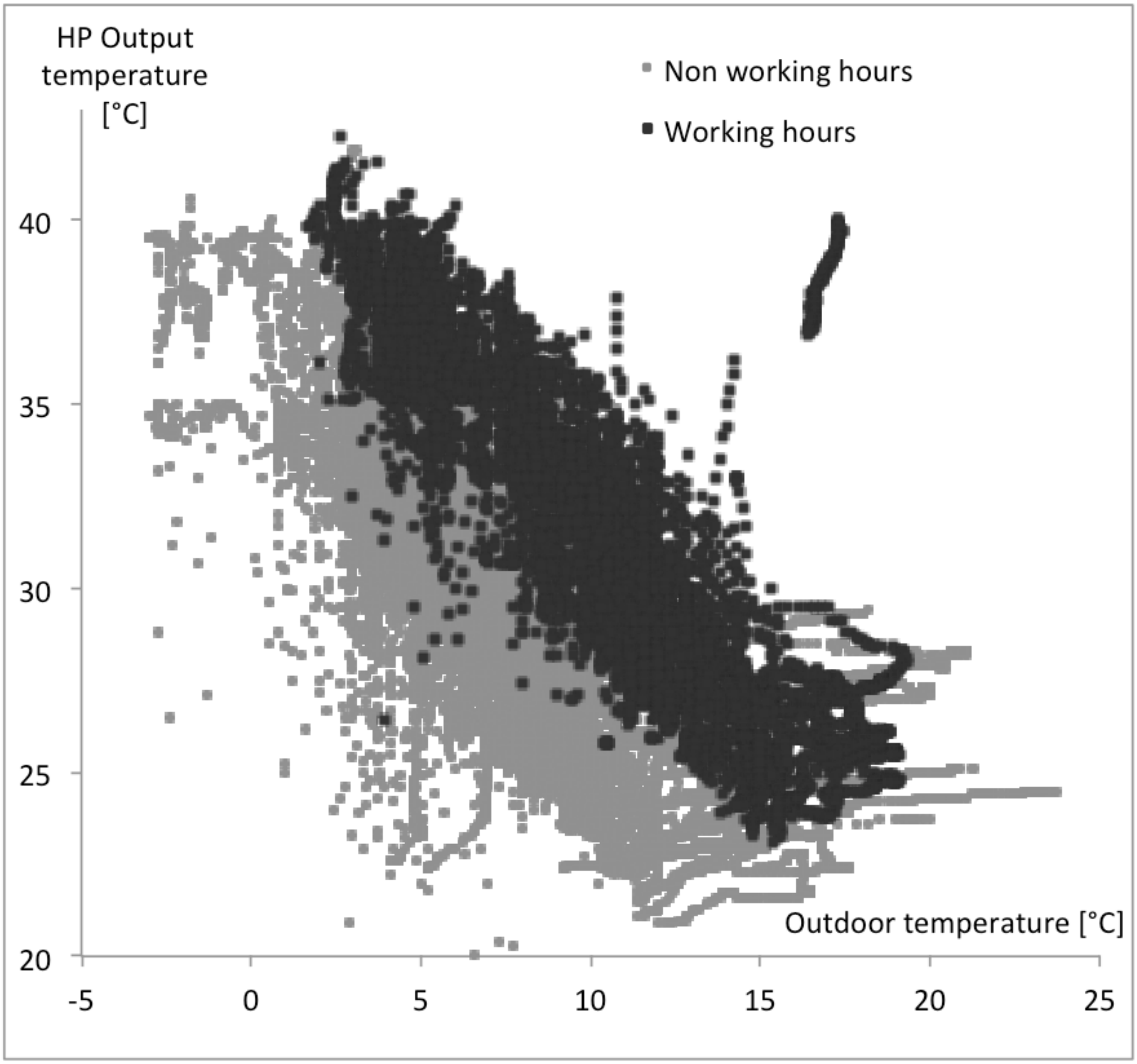

Figure 54. Relation between HP outlet temperature and external temperature

Critical days

Critical days graphs contain eight different informations; so, it is difficult to separate the lines in grey scale and we suggest to print these graphs in color. If this is not possible, here there are the b/w figures.

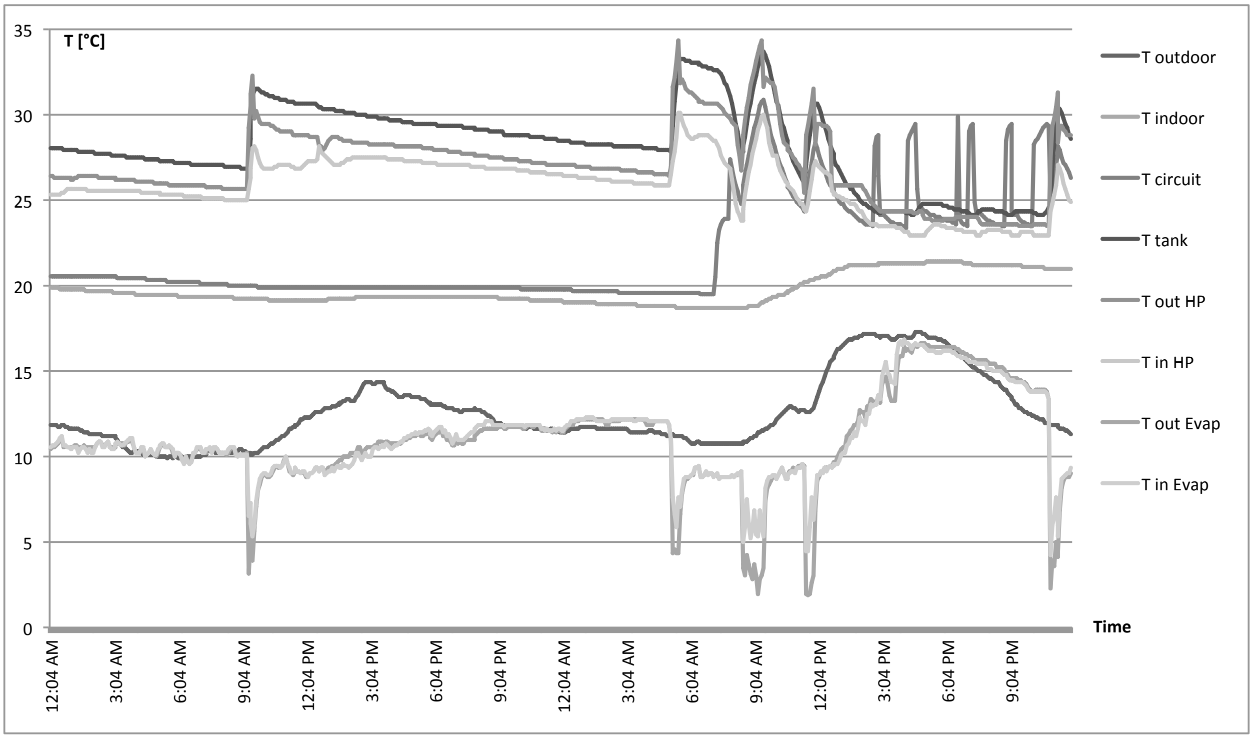

Figure 55. Data time plot from October 17 to 19

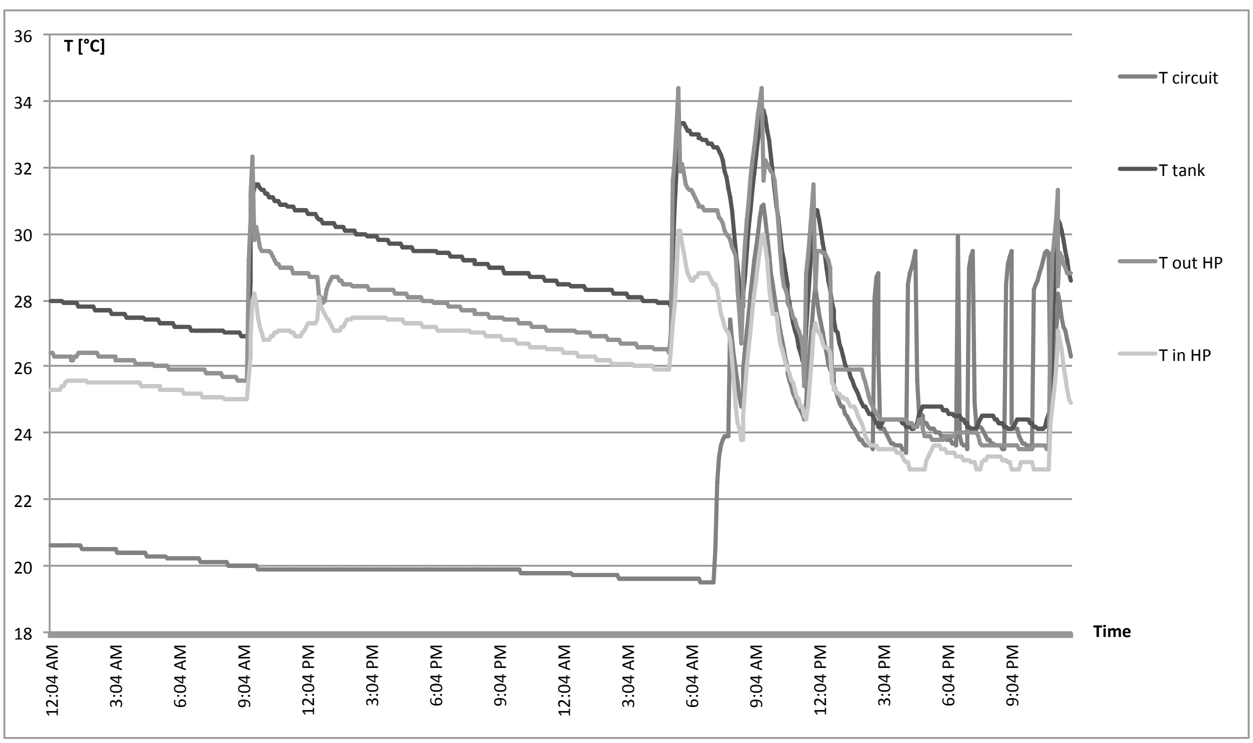

Figure 56. Data time plot from October 17 to 19 (High temperatures)

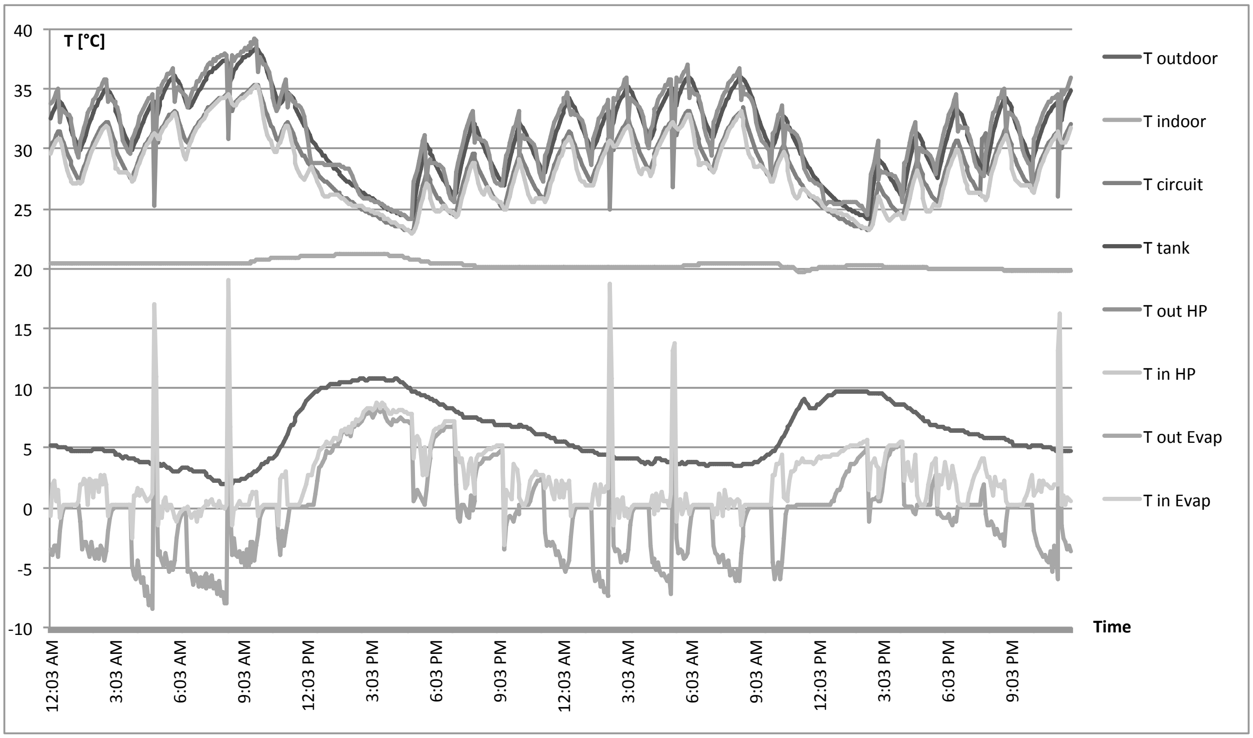

Figure 57. Data time plot from December 1 to 3

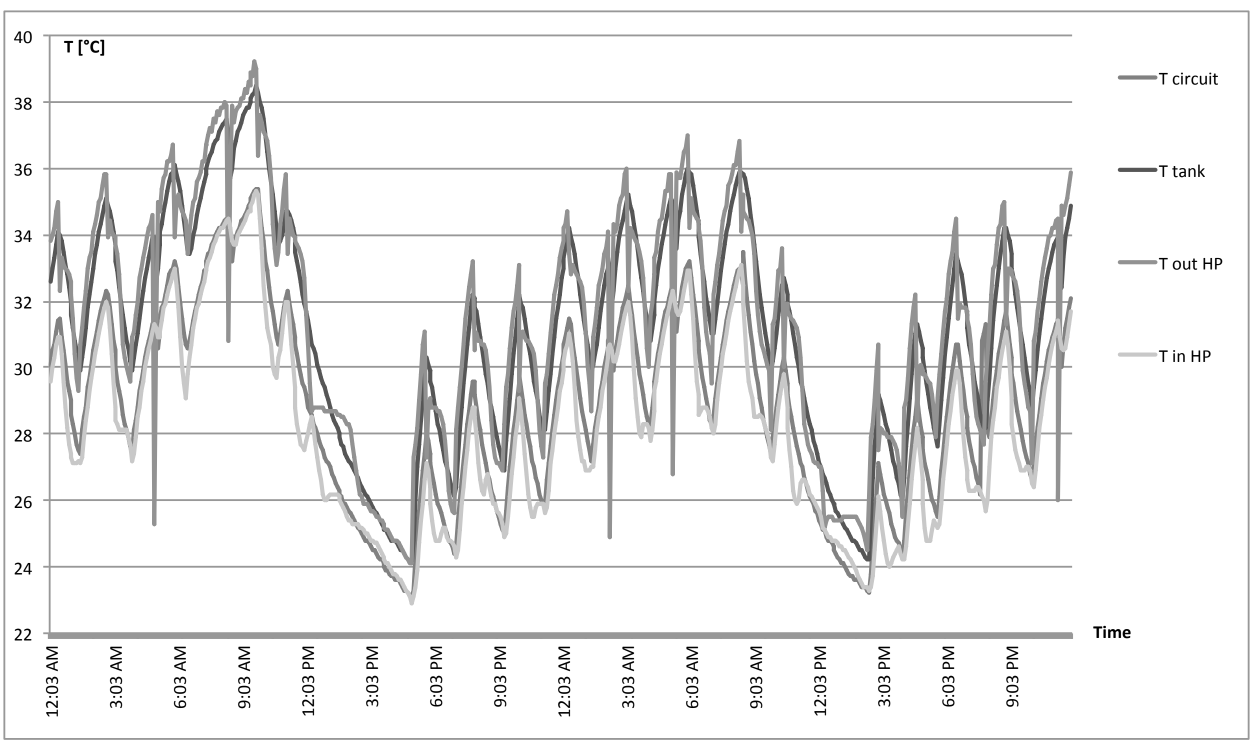

Figure 58. Data time plot from December 1 to 3 (High temperatures)

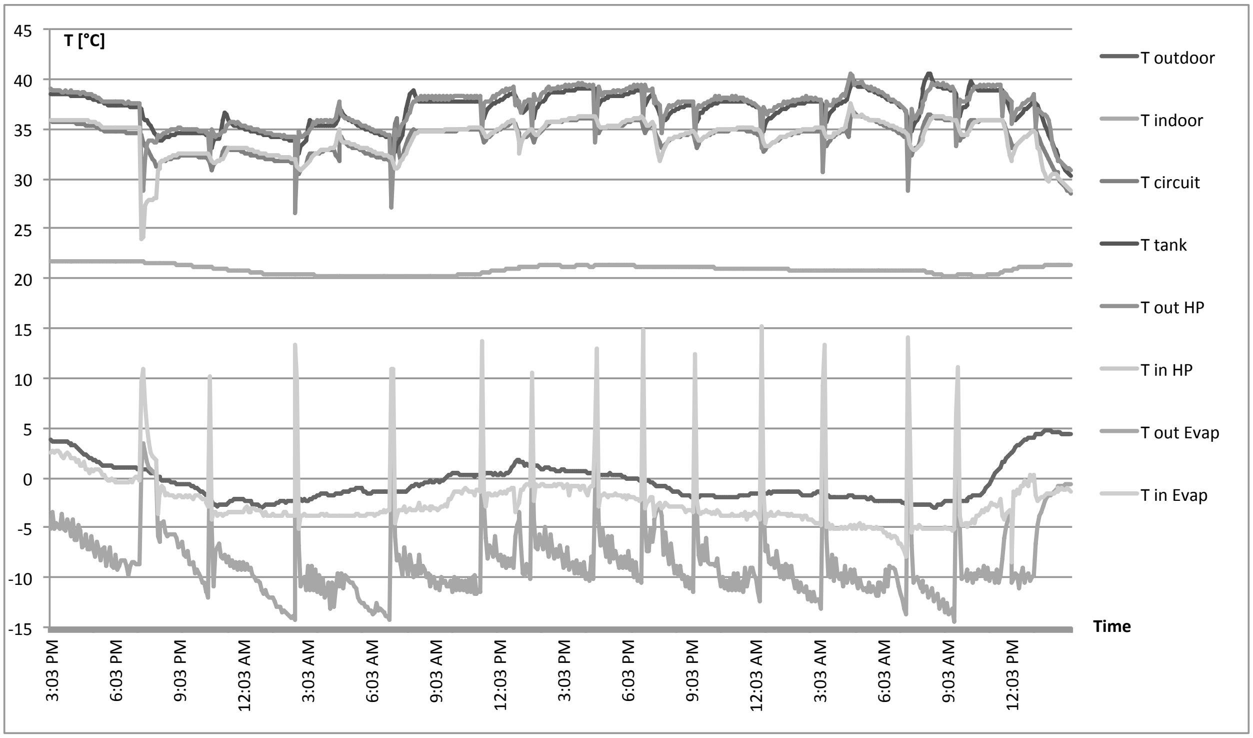

Figure 59. Data time plot from December 16 to 18

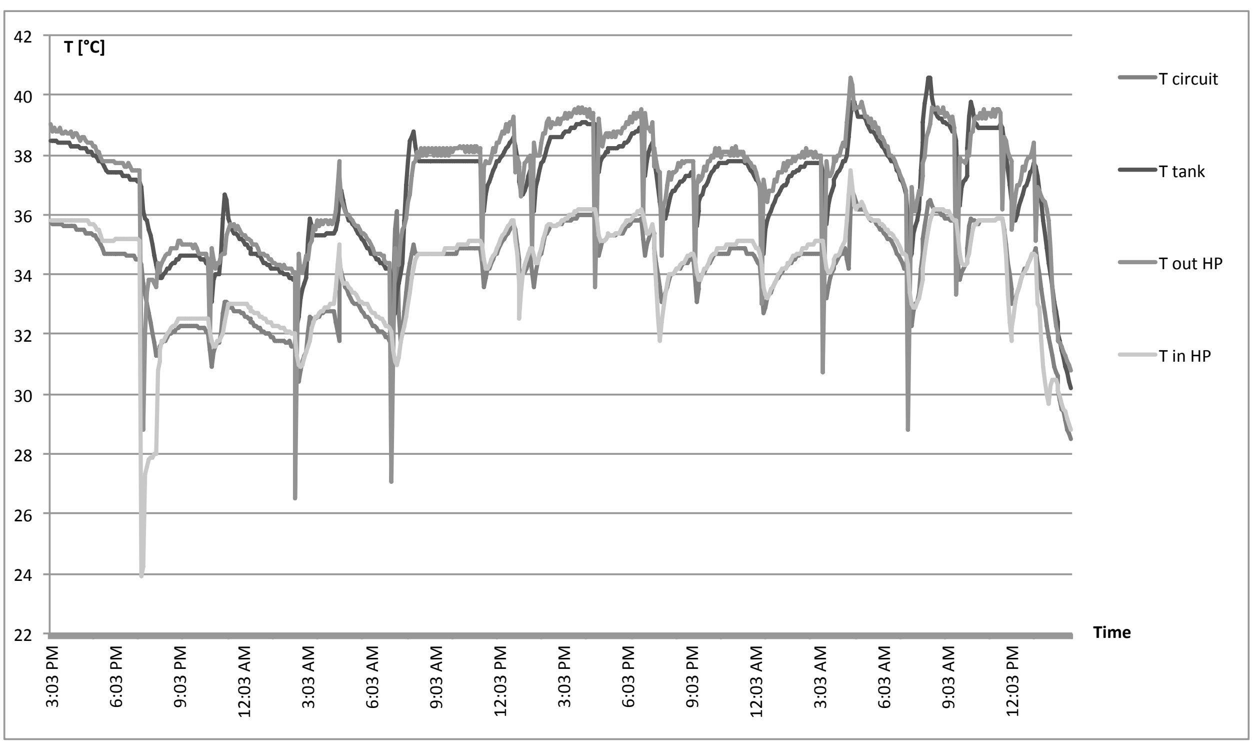

Figure 60. Data time plot from December 16 to 18 (High temperatures)

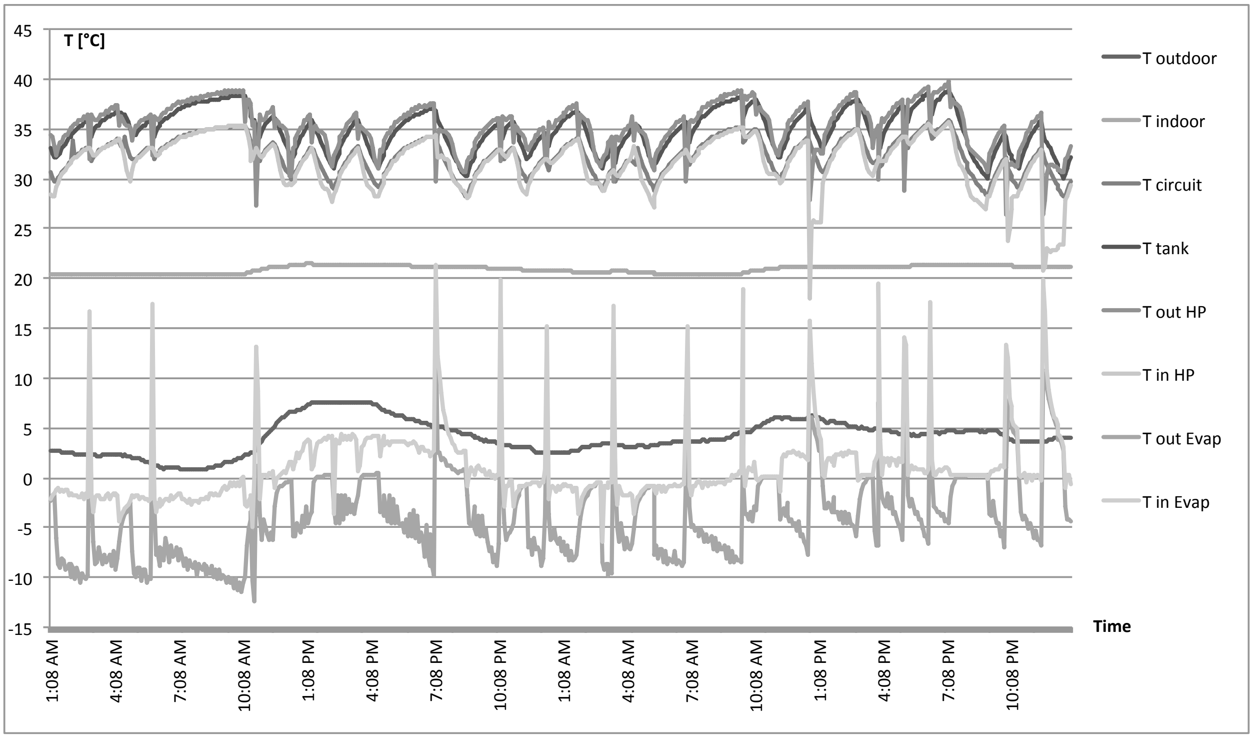

Figure 61. Data time plot from December 20 to 22

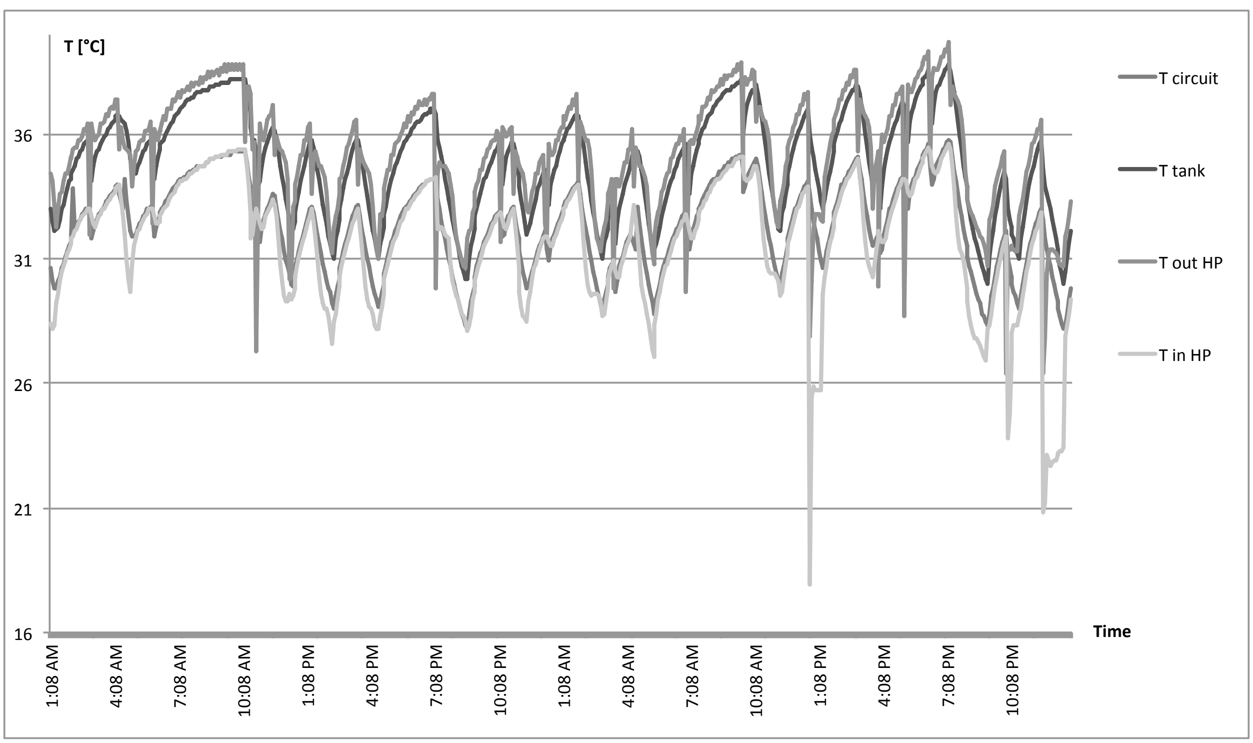

Figure 62. Data time plot from December 20 to 22 (High temperatures)

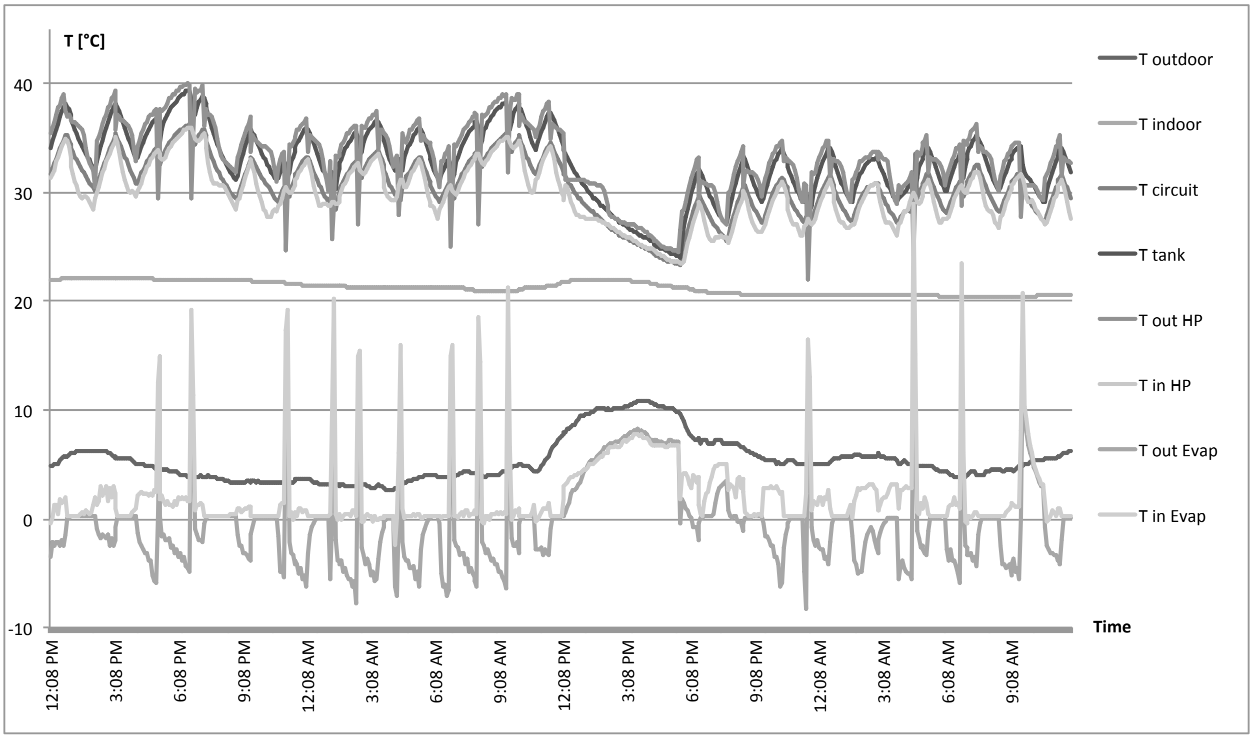

Figure 63. Data time plot from January 14 to 16

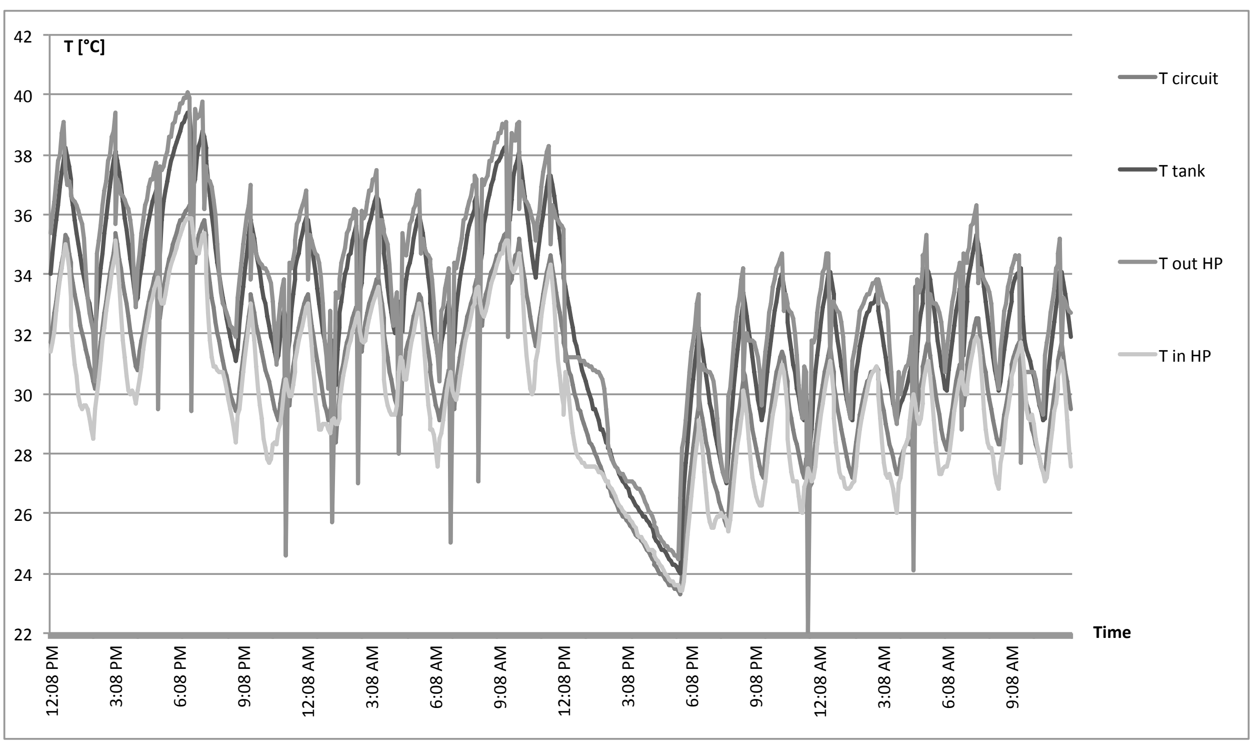

Figure 64. Data time plot from January 14 to 16 (High temperatures)

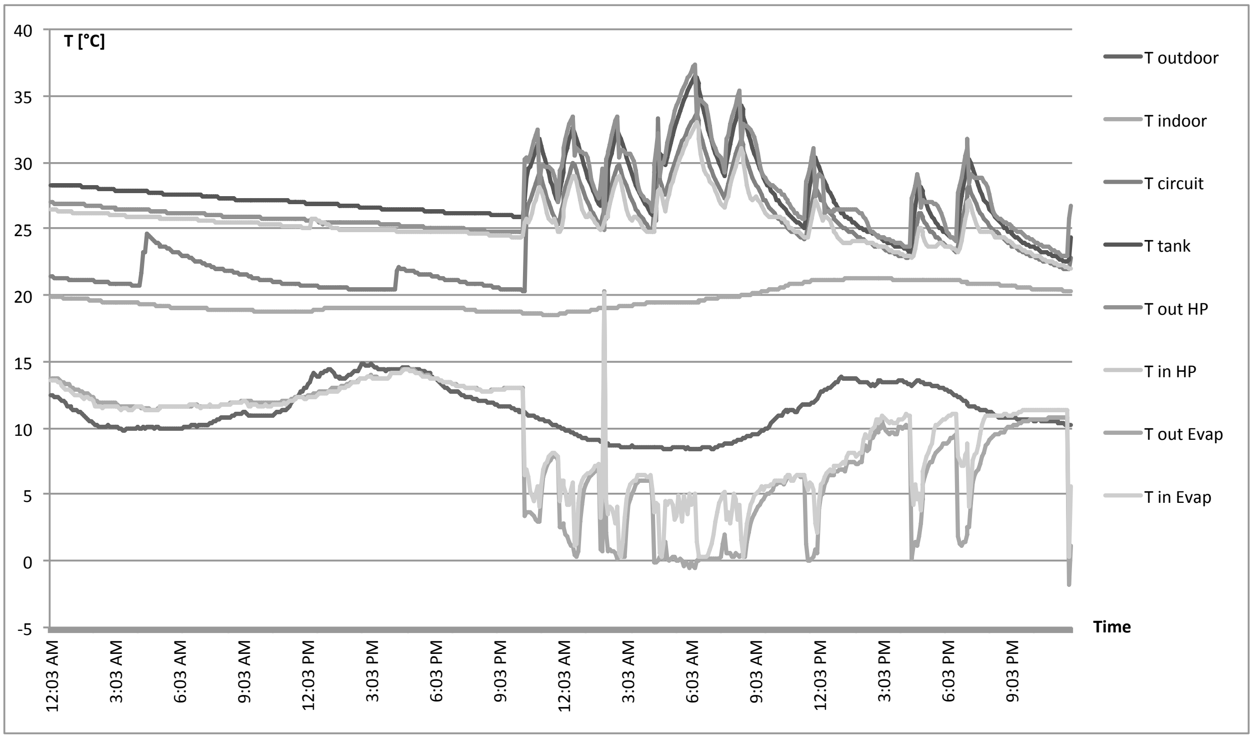

Figure 65. Data time plot from March 20 to 22

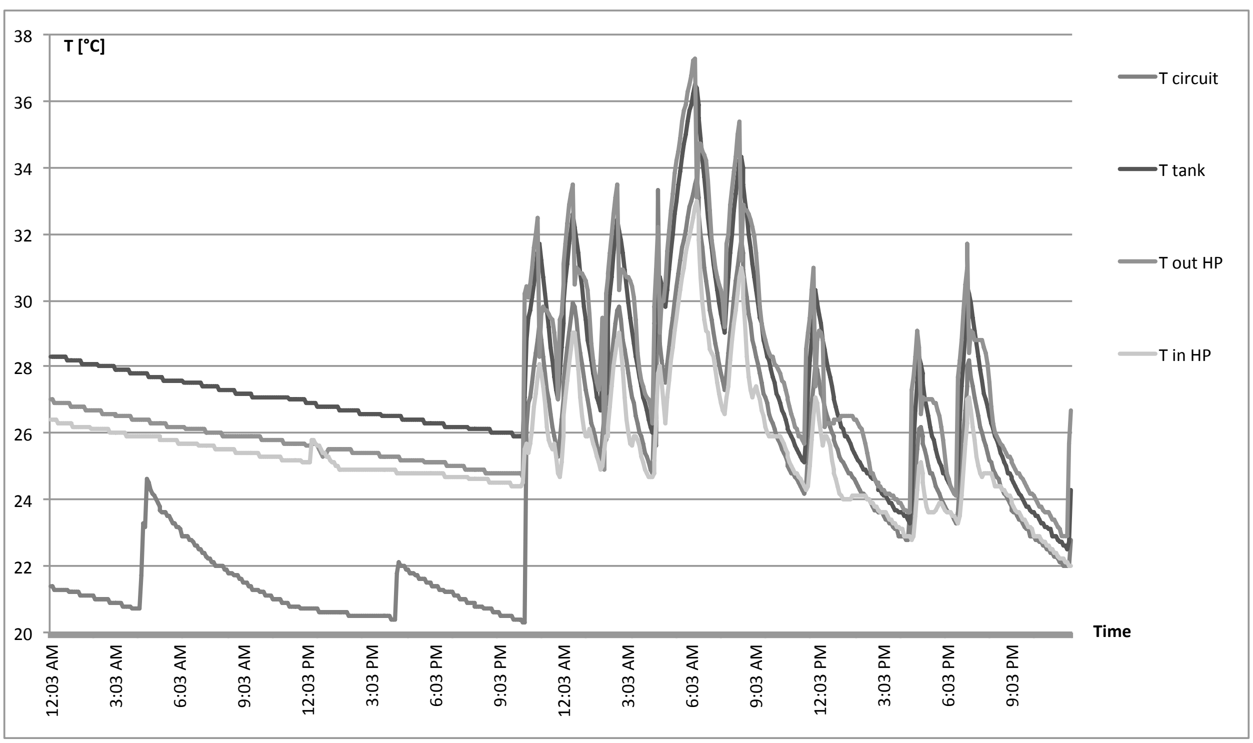

Figure 66. Data time plot from March 20 to 22 (High temperatures)

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