TRI-HP PROJECT

Trigeneration systems based on heat pumps with natural refrigerants and multiple renewable sources

Concise Cycle Test (CCT) method definition

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Version 1.0

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Executive Summary

Testing of systems for space heating, space cooling and domestic hot water preparation is a complex task, especially when several energy sources and storage options should be taken into account. The measurement of individual steady-state operating conditions can hardly represent all relevant operating conditions; moreover, the influence of the control strategy in dynamic operation is of decisive importance. For this reason, measurements using the hardware-in-the-loop approach are performed in the TRI-HP project to test the performance of the newly developed systems.

The method used in TRI-HP is the Concise Cycle Test (CCT) and this is applied in the laboratories of SPF as well as IREC, each in a version adapted to the systems to be tested. The common feature of the measurements is the systematic approach with the emulation of the fluctuating sources and sinks. The procedure for simulation and emulation can be described as follows: a real-time online simulation runs in parallel to the measurement. At the end of each simulation/emulation time step, measured values are passed from the test bench control software to the system simulation software. Based on these values, the simulation software is simulating the answer (response) of the emulated device for the next time step and returns the result to the test bench control software. During the next time step, the test bench control software controls the emulation of the simulated device, while the simulation software pauses and waits for the next input of measured values from the test bench control software.

Two different systems will be tested in the CCT: i) the solar ice-slurry system including a propane or CO_2 heat pump with an ice-slurry storage and solar thermal collectors, ii) the dual source system including a reversible propane heat pump with air and/or ground as source. The first system is designed for the climatic conditions from central Europe with heating as the main purpose and only low cooling demands. The dual source system is designed for the climatic conditions from southern Europe with higher cooling demands.

The selection of suitable test cycle periods are derived differently for both systems. The source temperatures, and therefore the system efficiency, in the dual source system mainly depend on the weather conditions, therefore the days for the test cycles are chosen from the weather conditions in combination with the thermal demands of the building (from building simulation). In the solar ice-slurry case, the system efficiency is strongly dependent on the status of the ice storage, therefore a selection based on weather data is not sufficient. Annual simulations of the whole system were used to get a database for the selection of days considering the weather conditions, the heating demand and the status of the ice-slurry storage. In the next step, both the load-side components (buildings and user profiles) and the sources (such as the PV systems) as well as the tested systems itself were scaled according to the performance data of the test benches. Based on these simulations, typical and relevant test days were then selected to allow a qualitative and quantitative assessment of the systems.

These boundary conditions were then combined into a test cycle in different ways for the measurement of the ice-slurry system at SPF and the dual source heat pump system at IREC. For the ice-slurry system, 7 individual days from the entire year were combined into a continuous test cycle with contiguous days from different seasons. In this way, the ice-slurry storage scaled to laboratory scale can also be included in the test. For the dual source system, series of 4 consecutive days were gathered into clusters depending on weather conditions, and one series of 4 days was selected as representative for each cluster. These selected series of 4 consecutive days are tested individually. In this way, the smart control strategy can also be tested on a longer period, to assess its benefits and observe its behavior from one day to the next in terms of storage strategy.

Key Performance Indicators were defined to verify the intended goals from the system developments. The experimental setup for carrying out the CCT tests are presented, including the measuring equipment and their accuracy, as well as the boundary conditions for the tests and the testing procedure.

List of Acronyms

AEM	advanced energy management
AC	alternating current
CCT	concise cycle test
CL	heat exchanger unit
DC	direct current
DHW	domestic hot water
DUT	Duty under test
EC	emulator cabinet
GA	genetic algorithm
KPI	key performance indicator
MR	measuring range
MV	measuring value
PV	photo voltaic
R	ratio
RER	renewable energy ratio
SPF	seasonal performance factor
SH	space heating
TB	test benches

1 Introduction

1.1 Purpose and general procedure of the concise cycle test

The implementation of different energy sources for systems for space heating space heating (SH), space cooling and domestic hot water preparation often leads to a complex architecture of the overall system. The efficiency of the resulting system is highly dependent on dynamic operating conditions due to transient on/off cycles, component interactions, thermal storage, hydraulic designs, overall system control, and other factors. Performance evaluation of such systems is not trivial and cannot be done via steady-state measurements of individual components. For this reason, measurements using the hardware-in-the-loop approach are performed in the TRI-HP project to test the performance of the newly developed systems.

A method called concise cycle test (CCT) has been developed at SPF and IREC for this purpose. This method will be adapted to the systems to be tested and applied in the different variants at SPF as well as at IREC. The CCT shall show the behavior of a complete system for heating and cooling under real-life conditions at different days of the year. In TRI-HP, the functionality of the ice-slurry storage will be tested in the system test as well as the advanced energy management (AEM) control developed within the project. Therefore, the complete system is installed on a test rig. The test rig emulates a building, including the SH and cooling distribution system, the domestic hot water (DHW) draw offs, the solar collector field and the photo voltaic (PV) installation. The system under test must act completely autonomously to cover the demand for heating and cooling of the building and the draw-offs during a test cycle. This test cycle is composed of a number of representative days of a real year. The selected days are put together to a consecutive test-cycle.

1.2 Procedure for online simulation and emulation

Emulation can be based on load files or on real-time online simulations. In order to emulate the true response that is dependent on the behaviour of the tested system, real-time online simulations are used to calculate the behaviour of those components that interact with the environment: the solar collectors, the PV installation, the building with the heating and cooling distribution system and the ground source heat exchanger.

The procedure for simulation and emulation can be described as follows: at the end of each simulation/emulation time step, measured values are passed from the test bench control software to the system simulation software. Based on these values, the simulation software is simulating the answer (response) of the emulated device for the next time step and returns the result to the test bench control software. During the next time step, the test bench control software controls the emulation of the simulated device, while the simulation software pauses and waits for the next input of measured values from the test bench control software. The input data for the simulation is based on measurements that were acquired before the emulated time step. The actual values may deviate from those values during the current time step. In order to minimize the error resulting from this deviation, the time steps of the simulation shall not be larger than 2 min. Those components whose behavior is independent of the rest of the system are implemented using predefined load profiles: a draw-off profile for the DHW consumption and a household electricity profile.

2 Boundary conditions and loads

2.1 Ice-slurry system (SPF)

A principle diagram of the ice-slurry system considered in TRI-HP is shown in Fig 2.1. Solar thermal energy is used directly to partly cover the heating demand. This is stored in an ice slurry storage which serves as a source for the heat pump. Additionally, a PV plant delivers electricity for the heating system and the households, a battery is included to reach the goal of 80 % renewable onsite share.

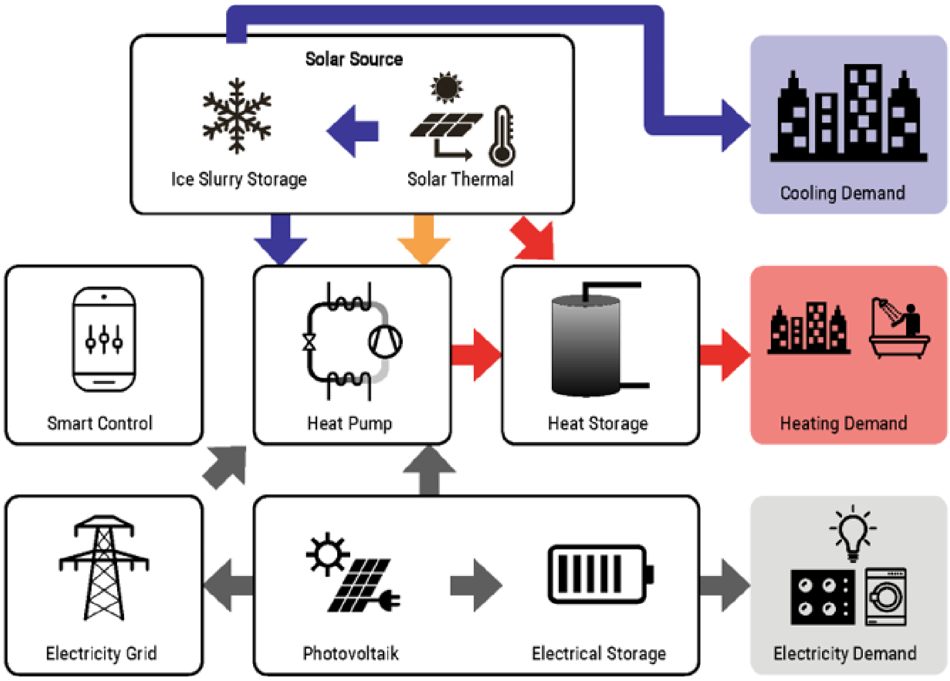

Figure 2.1: Schematic diagram of the solar ice slurry system considered in TRI-HP for colder climatic conditions.

The SIA weather data uses the standard SN EN ISO 15927-4 to generate a collection of so called *Design Reference Years*. This collection is based on measurement data from the years 1984 to 2003. It contains weather data of 40 different locations in Switzerland, each with an extreme warm, an extreme cold and a normal design reference year as described in [1]. For selection of days, weather conditions of the city of Bern are chosen. Bern represents the dense populated Swiss midlands with rather cold winter and foggy periods. In order to be able to analyze the cooling potential in the system tests, SIA-warm weather data are used. Temperatures and solar irradiation for Bern are shown in Fig. 2.2. The average ambient yearly temperature for warm weather data in Bern is 12.3 °C, the yearly total horizontal irradiation 1230 kWh/m^2.

Other boundary conditions are the user profiles for household electricity, DHW consumption and internal gains in the building due to the presence of the people themselves and the equipment used or their activities in the building. Single profiles for each of the six apartments with coordinated contents were considered:

- Couple under 30 years old, both at work.
- Family with two children (14-16), one at work, one at home.
- Family both at work, two children (9-12).
- Retired couple, both at home.
- Shift worker couple.
- Family, two children (6-12), both parents at home.

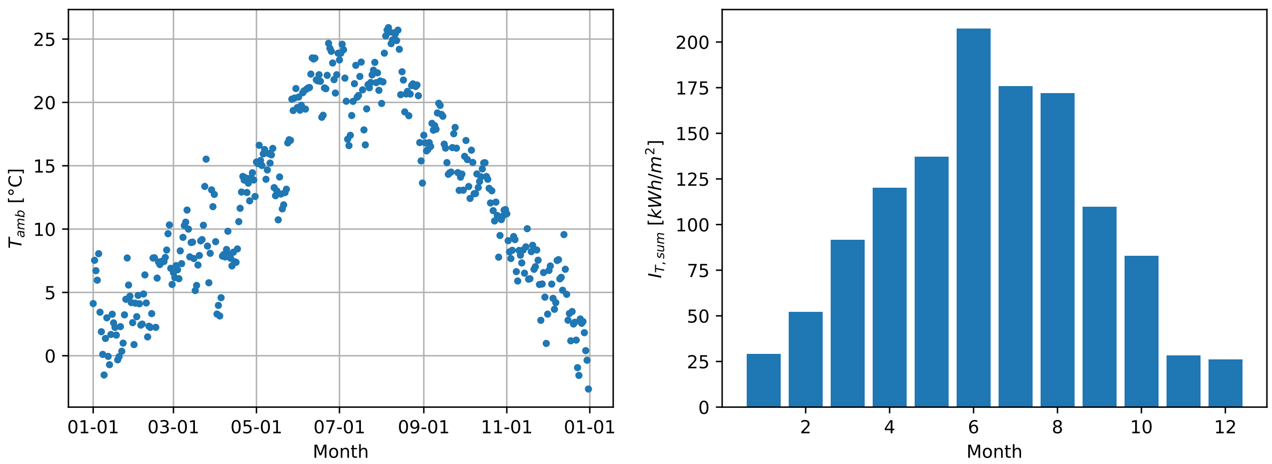

Figure 2.2: Daily averages of ambient temperature and monthly sum of total horizontal irradiation for the city of Bern under the assumption of a warm climate.

The heating system is scaled to reach an SPF of about 4. The PV-field covers about the rest of the available roof space (400 m^2 minus 75 m^2 space at the edges and space for other relevant installations on the roof). The battery is sized to about a daily electricity demand of households and heating system. Yearly demands for DHW, SH and household electricity are given in Table 2.1. The building used for simulation is further described in the TRI-HP deliverable D1.1 [2].

Table 2.1: Yearly demands of heat and electricity of the simulated reference system and dimensions of the system components.

Category	Demand / Size
Hosehold electricity (MWh/a)	16.2
DHW demand (MWh/a)	16.5
SH demand (MWh/a)	35.4
Size of battery (kWh)	100
Size of PV plant (m^2)	225
Size of solar thermal collector field (m^2)	100
Size of ice storage (m^3)	50
Max. ice fraction (%)	80

2.2 Dual source/sink system (IREC)

The schematic representation of the dual source system developed in TRI-HP is shown in Figure 2.3. The dual source heat pump is able to use both a ground source borehole or the ambient air as heat sink (or source), and can provide both heating or cooling depending on the season. The systems are completed by thermal storages, photovoltaic panels and a battery for the electrical part.

In the previous deliverable D1.1 [2], four different scenarios have been proposed for the Southern Europe case study with the dual-source system: the two climates of Tarragona or Bilbao, combined with two versions of the multi-family building, old or renovated. For the studies from WP6 and WP7, it has been decided to focus on a single study case: the renovated building, in the city of Tarragona. This climate zone presents a significant cooling load, contrary to the city of Bilbao. This enables to study the performance of the energy management system both in the heating and the cooling season. Furthermore, the renovated version of the building corresponds to the current standards of the Spanish Building Code, which is in force for all new constructions.

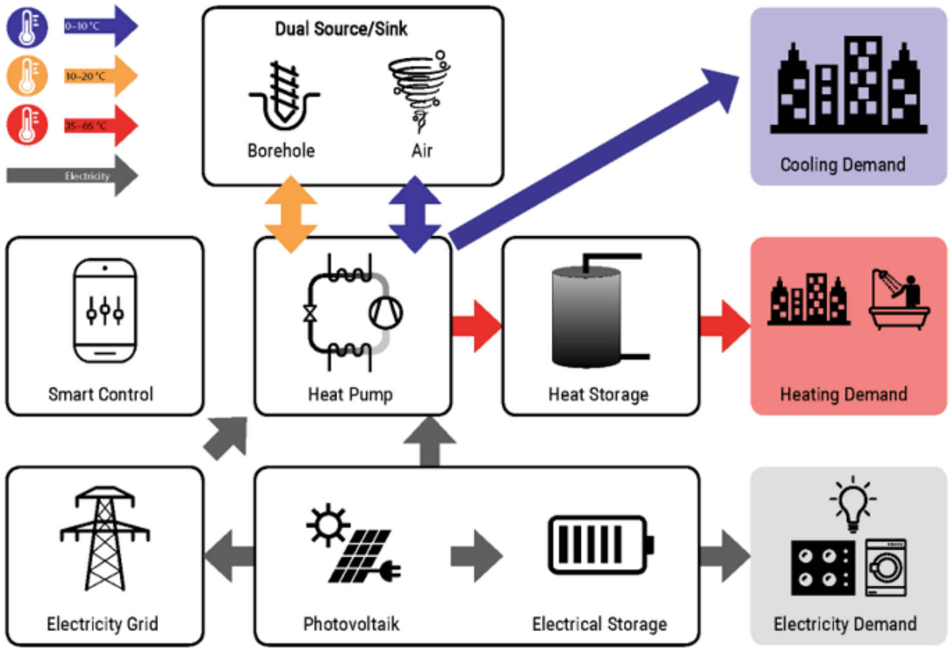

Figure 2.3: Schematic diagram of the dual source/sink system developed for warm regions with high cooling demand

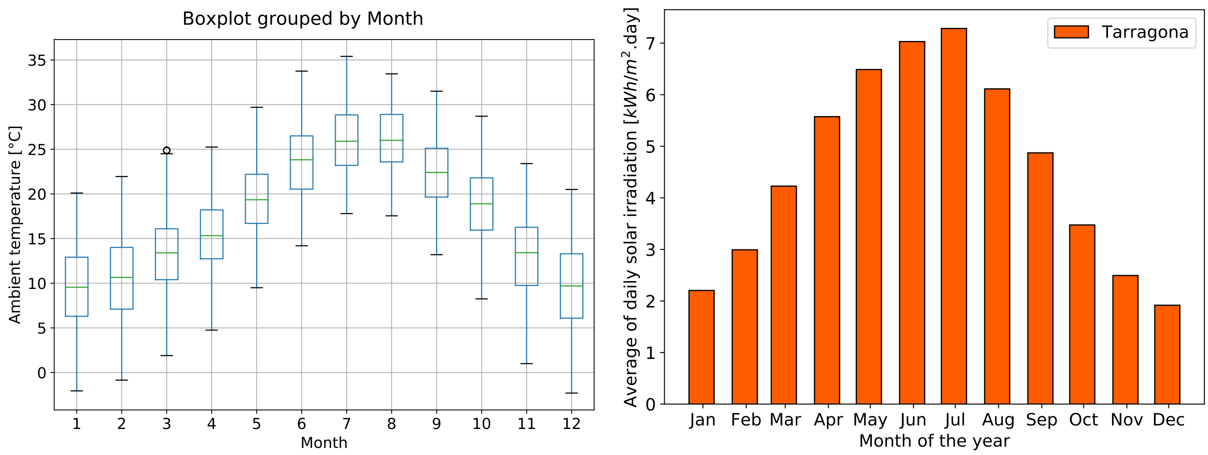

Figure 2.4: Monthly temperature and irradiation for the chosen climate of Tarragona.

The weather for Tarragona was retrieved from the software Meteonorm, which produces a typical year file based on historical records from official weather stations covering the years 1991 to 2007. The monthly temperature and irradiation can be observed in Fig 2.4. The yearly average temperature is 17.4 °C in Tarragona, while the yearly total horizontal irradiation sums up to 1665 kWh/m^2. This weather file was used to proceed to the selection of the typical days.

Apart from the weather, different profiles of occupancy have been implemented in the modelling environment. The internal gains from occupants, lighting and equipment are defined from the CTE (Spanish Building Code) [3] and represented in Fig 2.5. Considering these assumptions, the peak heating load of the building amounts to 43.9 kW, while the peak cooling load amounts to 28.3 kW. The DHW tapping profile is generated with a tool that enables to distribute the DHW load stochastically for every day, keeping a certain pattern and a global energy demand corresponding to the number of families in the building. The electricity consumption from appliances (not considering HVAC) is also generated as a 10 minutes stochastic profile, with a peak load of 44.7 kW (99% percentile at 29.5 kW).

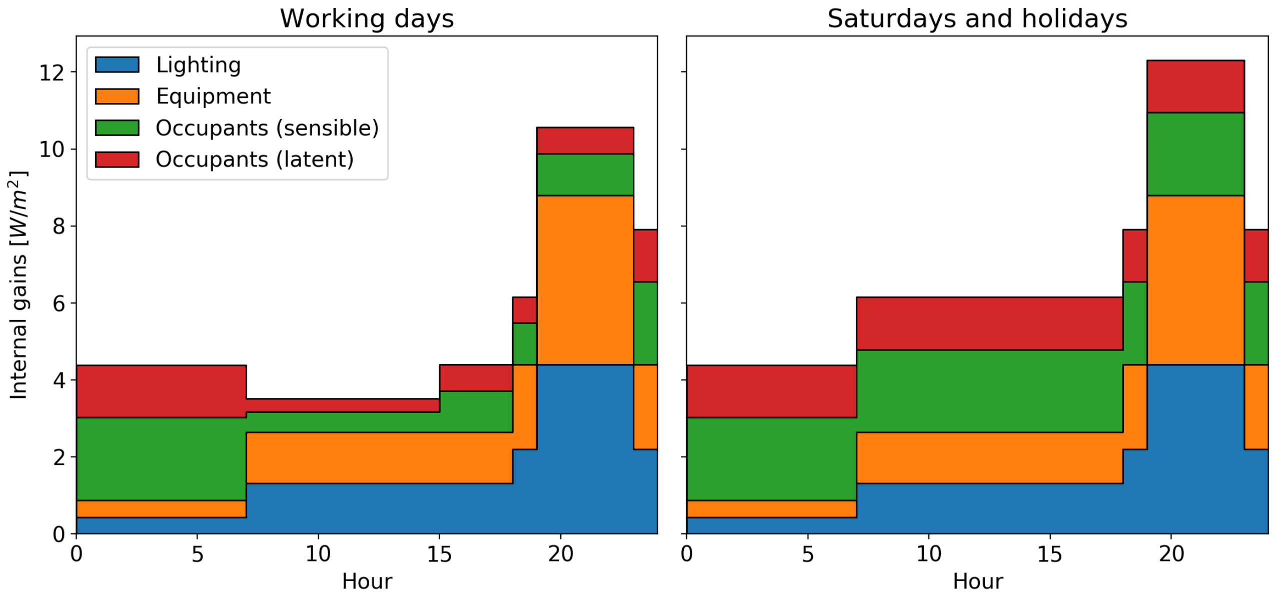

Figure 2.5: Profiles of internal heat gains according to the Spanish Building Code (CTE)

2.3 Scaling of laboratory systems

2.3.1 Ice-slurry systems (SPF)

The test rig for system tests at SPF is limited to a maximum of 10 kW in order to ensure the appropriate recooling. However, the multi family building in Bern has about 20 kW heating capacity, such the building simulation has been scaled down with a factor of 2. The size of the building (building capacity, floor area and as a result the heating demand), all additional demands (DHW, household electricity) as well as internal gains and sizes of the energy system (ice storage, thermal collector field area, PV area, battery) have been sized to half of the initial size of the reference system. The yearly simulations of both the scaled and the original were compared and resulted in the same yearly efficiency. From this scaled building, the days for the system tests are selected. In order to test the system in the test rig the ice storage was scaled down to a size of 2 m^2 in order to represent it's behaviour as seasonal storage in a seven day test. The ice storage will be installed as a prototype within the test rig in the system test.

2.3.2 Dual source/sink system (IREC)

The test rig at IREC also has physical limitations, therefore the size of the systems and the test case had to be adapted for the experimental campaign. The dual source heat pump prototype developed at Tecnalia has a nominal thermal capacity of 10 kW, compared to 44 kW needed for the multi-family building of Tarragona, therefore the scaling factor is around 4.5. All boundary conditions have been scaled down with this factor, notably the building floor area and capacity, the DHW demand profile and appliances electrical consumption. The capacities of the thermal storages have also been reduced accordingly. In the case of the electrical systems, the electrical cabinets present in the lab are also limited to 7.5 kW, therefore the scaling factor is slightly higher in that case, and these systems are a bit undersized relatively to the rest of the systems.

The final sizes of the systems to be tested in the lab are the following:

- Heat pump: 10 kW nominal heating power
- DHW storage tank: 500 liters
- SH/cooling storage tank: 300 liters
- Battery: capacity of 10 kWh / charging power of 5 or 10 kW
- PV: 7.5 kWp peak power
- Appliances consumption: electrical cabinet of maximum 7.5 kW.

3 Physical boundaries : emulation/simulation

Complete systems are installed on the test benches and put into operation the same way as for an installation in the technical room of a real house. This chapter describes which components are part of the Duty under test (DUT) and how the controller of the tested system has to be parameterized. It also defines the boundaries and connections between the tested systems and the test benches.

3.1 Ice-slurry system (SPF)

3.1.1 Hydraulic installation

The physical boundaries of the hydraulic installation of the ice-slurry system are shown in Fig. 3.1. The following items are considered to be part of the tested system:

- the heat pump
- the storage tanks on the sink side of the heat pump
- the devices needed to provide DHW to the DHW distribution line and the circulation line
- the devices needed for feeding the space heat and cooling distribution
- the ice slurry tank on the source side of the heat pump
- the crystallizer
- any parts that are necessary to connect the individual parts (e.g. heat exchangers, switching valves, tee pieces and piping)
- any temperature sensors needed for the control of the system

The solar collector field is not part of the DUT, instead it is emulated by the test bench. The building with the SH distribution is also emulated, just like the DHW supply including the circulation.

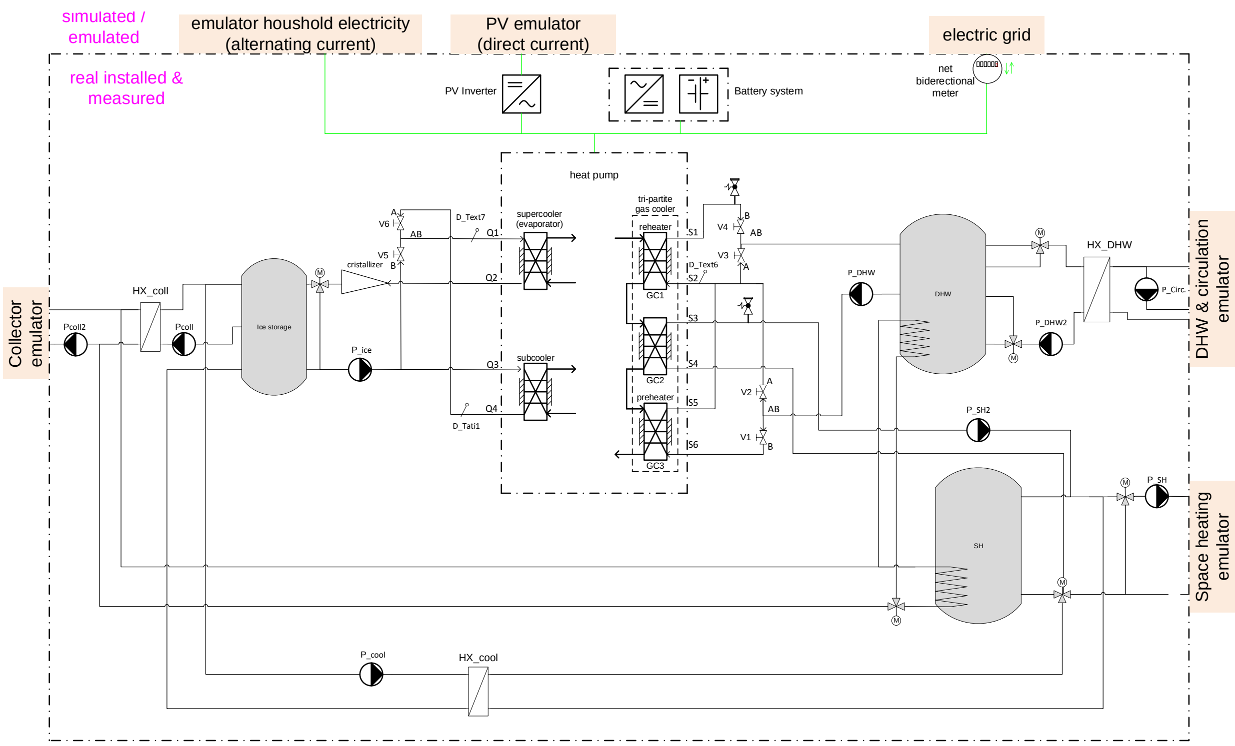

Figure 3.1: Hydraulic scheme showing the boundary between the tested system and the test rig. Energy balances are measured on the intersection of DUT and the test rig.

3.1.2 Electric installation

The physical boundaries of the electric installation of the ice-slurry system are shown in Fig. 3.2. The following items are considered to be part of the tested system:

- the PV-inverter
- the heat pump
- the electric backup heating
- the battery system including battery charge controller and the battery inverter
- the controller
- any devices needed to connect and control the individual components (e.g. smart meter).

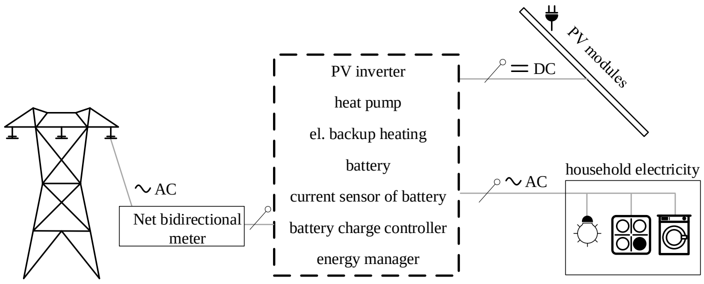

Figure 3.2: Scheme showing the boundary between the electric components of the tested system and the test rig. Energy balances are measured on the intersection of DUT and the test rig. Example for system test with CO_2 heat pump.

The PV modules are not part of the tested system, instead they are emulated by a controllable direct current (DC) source.

3.1.3 Controller

The aim of the whole system test method is to test systems under realistic operating conditions. This implies that the unit under test uses its own controller and control strategy. However, the control parameters have to be adjusted in a way that the heat demand of the emulated building will be met. Since the test sequence represents a short term test sequence, the following points have to be considered:

- Averaging of the ambient temperature for the determination of the heating season and the supply temperature set point for SH has to be switched off or shortened to $\leq$1 h.
- Heating season: the thresholds for start and stop of the heating season for the emulated building are 14 °C and 15 °C, respectively.
- Heating curve: the flow rate in the heat distribution system may not be identical to the previously executed simulations because it is influenced by the characteristics and control of the SH pump which is part of the tested system. Accordingly, the heating curve has to be adjusted individually, taking into account the installed heating circuit pump.

Due to the short test sequence with representative days for all seasons within a cycle of seven days, a learning phase for a smart controller is not possible. Additionally, the slurry tank is scaled to the demand of the test-cycle. For both reasons the advanced management system (smart control) cannot be tested this way. In order to be able to test the new control strategies nevertheless, a second cycle of contiguous days from one season will be used in a second system test. For this measurement, in addition to the new and advanced controller, an adaptation of the hydraulics may also be necessary in case of the measurement of cold winter days. The slurry store must then be emulated via the test bench, whereby the simulation model must represent the size of the store installed in the field. For test periods in the transitional period or in summer, this adjustment is not necessary.

3.2 Dual source/sink system (IREC)

Figure 3.3 represents the real building installation to be tested (real) or emulated (virtual) at the SEILAB. The tested system comprises the following elements:

- Heat pump
- Geothermal, DHW and SC circulating pumps
- Thermal storages and necessary equipment to connect them to the heat pump
- Electric battery with inverter acting as an electrical storage
- Connection to the electrical grid and necessary equipment to create an auxiliary (micro) grid.

Elements such as test benches (TB) and primary heat exchanger units (CL) emulate heat sinks and sources as described. Similarly, emulator cabinets emulate electrical generation (PV modules) and consumption (household appliances). The climate chamber is also emulating weather conditions affecting the air side of the dual source heat exchanger.

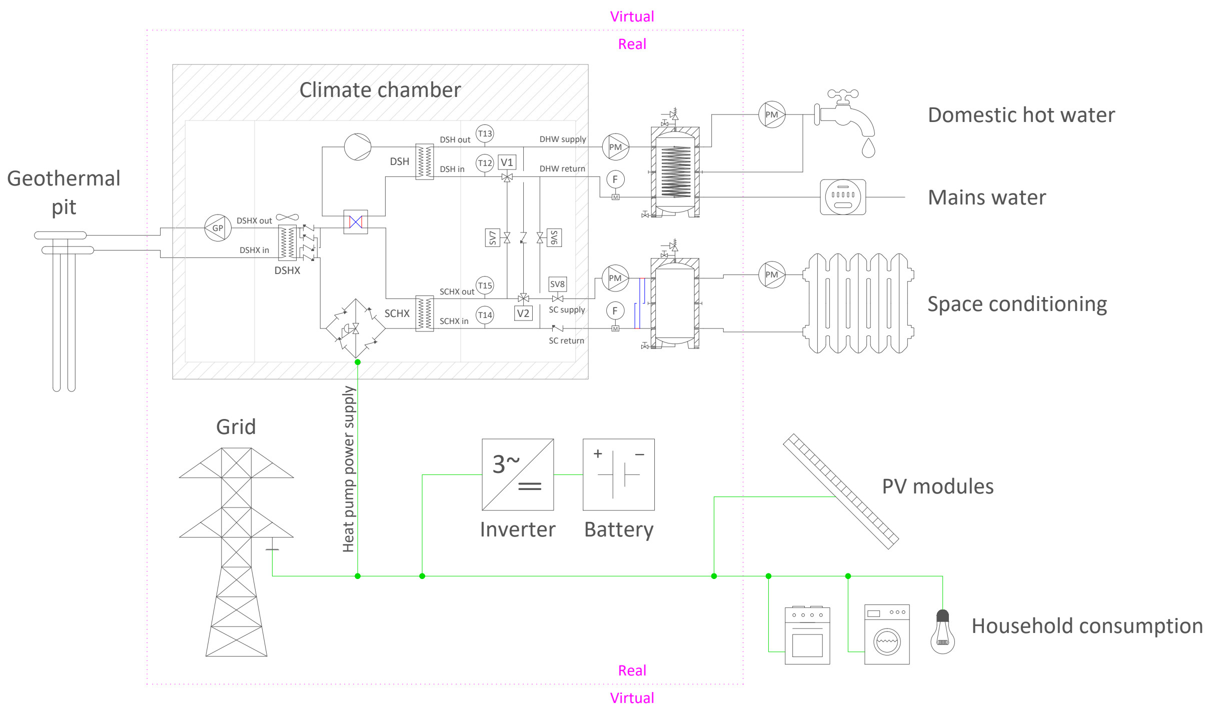

Figure 3.3: Scheme of the boundaries between real and simulated equipment for SEILAB.

4 Description of laboratories for whole system test

4.1 Key Performance Indicators (KPI)

The system test should prove that the energy goals of TRI-HP, reaching 80 % renewable onsite share with net zero approach (20 % exchange with the grid is allowed, but at least the same amount electricity should be produced than consumed. In order to evaluate the systems, the key performance indicators key performance indicator (KPI) described in the following will be used.

External energy purchase ratio R_{ext} and renewable on-site share $R_{RE,local}$

The external energy purchase ratio ratio (R) describes the part of the energy provided by external sources.

$$R_{ext} = \frac{E_{ext}}{E_{used}} \tag{4.1}$$

while E_{ext} is the sum of all external energy sources in the systems of TRI-HP it is just the grid-electricity El_{grid} as no additional external energy sources are used.

E_{used} is the sum of the energy used onsite including heating ($Q_{dhw} + Q_{sh}$) and cooling (Q_{sc}) demands as well as household electricity (El_h):

$$E_{used} = Q_{sh} + Q_{dhw} + Q_{sc} + El_h$$

Pipe, storage and circulation losses are not included in the used thermal energy. Without a DHW circulation loop 10 % of the energy demand in the DHW profile is not counted as useful energy in order to account for the first Liters that are not on the set-temperature that should be delivered. As we assume a DHW circulation loop in the systems, the water is immediately hot in each tapping, such all energy demand for DHW is counted as useful energy.

In the case of the TRI-HP systems, where only renewable energy (like PV-electricity and heat from ground, air or solar thermal collectors) is produced locally, the renewable onsite share describes the part of used energy that is produced on-site without using electricity from the grid or energy sources transported to the site and is therefore 1 minus the external energy purchase ratio:

$$R_{RE,local} = 1 - R_{ext} \tag{4.2}$$

Seasonal Performance Factor (SPF)

The seasonal performance factor (SPF) is an important indicator for the annual efficiency of heat pump systems. It describes the ratio between thermal demands (heating and cooling) and the electricity demand for the heating system including the annual electrical demand for pumps (El_{pumps}), control ($El_{control}$) and auxiliary heater (El_{aux}):

$$SPF_{global} = \frac{Q_{sh} + Q_{dhw} + Q_{sc}}{El_{HP} + El_{pumps} + El_{control} + E_{aux}} \tag{4.3}$$

where Q_{sh} is the yearly SH demand in kWh, Q_{dhw} is the yearly heat demand for DHW in kWh and Q_{sc} is the yearly demand for space cooling, if cooling is not considered $Q_{sc} = 0$.

PV Generation Ratio ($R_{PV,gen}$)

The PV generation ratio describes the ratio between on-site produced PV electricity and total on-site electricity consumption. In the TRI-HP systems, this value is at least 100 %

$$R_{PV,gen} = \frac{El_{PV}}{El_{used}} = \frac{El_{PV}}{El_{sys} + El_h} \tag{4.4}$$

Renewable Energy Ratio (RER)

The share of renewable energy is defined by the Renewable Energy Ratio (RER), which is calculated relative to all energy use in the building, in terms of total primary energy and accounting all the energy renewable sources. These include solar thermal, solar electricity, wind and hydroelectricity, renewable energy captured from ambient heat sources by heat pumps and free cooling, renewable fuels.

$$RER = \frac{PE_{ren,RER}}{PE_{tot}} \tag{4.5}$$

whereby $PE_{ren,RER}$ is the renewable primary energy used by the whole system (electrical and thermal energy) in kWh and PE_{tot} is the total primary energy calculated using total primary conversion factors in kWh (for details see [4] and [3]).

4.2 Laboratory at SPF

4.2.1 General description of SPF installations

The test facility emulates all consumers in a building in a realistic, thus dynamic way. In addition, the test bench provides emulation of the regenerative energy used by the tested system from sources like solar thermal collectors, PV-modules or air to water heat exchangers. For emulation, the test bench has a central master computer running a software programmed in LabView. This software controls the various thermal and electrical components and brings together the measurement data from the different circuits. For the emulation, the components of the virtual building are divided into different subsystems that operate independently from each other. Either a real time simulation with TRNSYS (see Chapter 1.2) or a predefined load profile is used to control the individual circuits. In the following chapters, the principles and the measurement equipment used are described in more detail.

4.2.2 Test room

The room where the DUT will be installed is conditioned to 20 °C ±0 5K. Stratified temperature profiles within the room is prevented through the air conditioning system. The temperature is taken as an average sampling of different heights by an appropriate device.

4.2.3 Propane safety system

The lower explosion limit of propane is 1.7 vol%. Both in the climate chamber of the SPF and in the test room, this limit would be exceeded with the amount of refrigerant in a normal refrigeration circuit. For this reason, the test rig is equipped with a gas warning system. One sensor is placed in the housing of the tested heat pump and another sensor in the environment. If these sensors detect a quantity of propane above the detection limit, the following measures are initiated:

- Both the heat pump and all surrounding equipment are disconnected from the power supply.
- A visual and acoustic warning signal is started.
- The installation site of the heat pump is vented via emergency ventilation.

4.2.4 Experimental setup - Thermal systems

As described in Fig 3.1, three different thermal components are emulated to test the solar-ice system:

- Thermal collectors
- DHW & circulation
- SH and cooling

The individual emulators each consist of a conditioning circuit, in which the appropriate temperature is set independently of the current operating state, and connections for supply and return to the DUT. The heat required for the emulation is provided in the individual emulators by heating rods. A central cooling supply is available for the cold, which is integrated via heat exchangers. To balance the performance, temperature sensors calibrated in pairs and a measurement of the volume flow are used in all emulators. From these values, the power is calculated every second, which is then accumulated to energies.

$$\dot{Q} = \dot{m}\left[h(\vartheta_{in,i} - h(\vartheta_{out,i})\right] \tag{4.6}$$

$$E = \sum \dot{Q}\Delta t \tag{4.7}$$

A description of the measuring equipment used can be found in Table 4.3.

Table 4.1: Measuring equipment

Measured variable	SI-unit	Measurement principle	Standard deviation u	Comment
$\vartheta_{\mathrm{x,in}}$, $\vartheta_{\mathrm{x,out}}$	°C	4-wire Pt100	0.1 K	Immersed temperature sensor at system boundary.
$\Delta\vartheta$	K	4-wire Pt100	0.03 K	Temperature sensor calibrated in pairs. Therefore, the systematic uncertainty of the calibrator can be deducted for the difference.
$\dot{m}$	kg/s	Coriolis	0.1 %	Measurement of mass flow.

4.2.5 Experimental setup - Electrical systems

As shown in Chapter 3.1.2, the PV modules are not part of the system under test. They are simulated and emulated by the test bench. The inverter to convert the DC current into alternating current (AC), on the other hand, is actually installed. The emulation of the PV field is performed by means of a controllable DC source. The DC source is controlled according to the calculated values from a simulation model. This model requires several inputs: the radiation data, the load voltage and the cell temperature. The radiation data is passed from the weather data of the building simulation. The load voltage is the one from the real installed inverter (MPP tracking). The cell temperature is calculated in a second simulation model of the PV modules. This is necessary because the software of the emulator cannot calculate the cell temperature itself. The control of the emulator based on the described simulations is continuously within the following range:

- 0 kW to 15 kW
- 0 VDC to 1500 VDC
- 0 A to 13 A

Due to the combination of a real installed inverter with MPP tracking and simulated and emulated PV modules with their own power control, oscillations can occur. Depending on the installed inverter, a choke with 600 μF is therefore additionally serially integrated on the DC side. The actual emulated DC power is given by the emulator itself (device-integrated current and voltage measurement). The uncertainty is 0.15 %FS (1 VDC and 0.013 A, respectively). The household electricity emulator consists of three identical combinations of rectifiers with associated bidirectional DC power supplies (see Table 4.2), all of which can be controlled individually according to the actual setpoint from an predefined load profile. Any deviation between the target and actual household electricity consumption is corrected in the next time step.

Table 4.2: Emulation of household electricity

Function	Power	Voltage	Current
Rectifier	max. 15 kW	nom. 230 V	65 A_{eff}
Bidirectional DC-power supply	max. 15 kW	max. 500 VDC	90 A

The measurement of all electrical AC quantities is galvanically integrated. APLUS type measuring devices from the manufacturers Camille Bauer / Metrawatt are used. These are each combined with winded current transformers, which are matched to the power of the quantity to be measured. Table 4.3 indicates the measurement uncertainty of the devices.

Table 4.3: Measurement uncertainty of AC power (MR: measuring range, MV: measuring value)

Measuring point	Winded current transformer	Measurement uncertainty
PV_{AC}	20/5	0.16 %MV + 0.04 %MR
		winded current transformer class 1.0
HH_{AC}	20/5	0.16 %MV + 0.04 %MR
		winded current transformer class 0.2
$Grid_{AC}$	60/5	0.16 %MV + 0.04 %MR
		winded current transformer class 0.2

For better understanding, function control and the calculation of several performance factors additional non-contact measurements are performed using Rogowski spools. Those measurements are for example necessary to calculate the total electricity demand (El_{used}), which also contain the battery system losses (E_{BatSys}).

$$El_{used} = El_{HP} + El_{pumps} + El_{control} + El_{aux} + El_h + El_{misc} \tag{4.8}$$

In this case, the energy referred to as El_{misc} is the losses of the battery system from charging and discharging via the battery inverter, the storage losses from the battery cells and the consumption of the battery charge controller.

Since the individual measurements required for the determination of El_{used} are partly measured with non-contact measuring points, the above shown formula is subject to a large uncertainty. For this reason, the total energy consumption is calculated as the total electricity supplied by the PV system, but not fed into the grid plus the electricity drawn from the grid.

$$El_{used} = El_{Grid,Consumption} - El_{Grid,Feedin} + El_{PV,AC} - El_h \tag{4.9}$$

4.3 Laboratory at IREC

4.3.1 General introduction

The SEILAB provides advanced methods to assess the development and integration of renewable energy solutions and innovative thermal and electrical equipment that are designed to improve energy efficiency in buildings and energy systems.

It is provided with cutting-edge technology comprising systems for energy generation, heat and cold storage and state-of-the-art facilities for testing HVAC equipment and the interaction of energy systems with the grid.

The operation is based on a semi-virtual testing approach, which allows for real equipment to be operated as a function of the behaviour of a dynamic virtual model (hardware-in-the-loop concept) that emulates the thermal loads of heat sink and heat source.

The SEILAB is pioneer in addressing the smart integration of electrical and thermal components and is a leading experimental facility for improving the development of Net Zero Energy Buildings and Energy Flexible Buildings.

4.3.2 Description of test facilities

4.3.2.1 Test benches and primary heat exchangers

Each hydraulic loop comprises one test bench and one or more primary heat exchangers. The function of test benches is to measure pressure and temperature and to measure and control flow. One of the temperature measurements is used for loop temperature control in the primary heat exchanger unit. Primary heat exchanger units include as well the heat exchanger itself and a circulating pump driven by a frequency inverter.

Flow and temperature meters are regularly calibrated to allow an accurate calculation of thermal power. Table 4.4 indicates type and precision of the different measurement elements.

Table 4.4: SEILAB measurements precision

Magnitude	Type	Precision
Pressure	Piezo-resistive	±1%
Flow	Electromagnetic	±0.5%
Temperature	3- or 4-wire Pt100	±0.25 K
Electrical power	Multimeter	±1%

Three-way mixing valves with fast magnetic actuator are used to control flow and temperature. One of the inlets is a by-pass of the tested equipment (flow) or the heat exchanger (temperature).

Heat transfer fluid is soft water free of suspended solid particles. Pipes are insulated with synthetic rubber material (30 mm).

4.3.2.2 Climate chamber

Air flow, temperature and relative humidity are measured and controlled within the walk-in climate chamber. Main characteristics are collected in table 4.5.

Flow, temperature and humidity meters are regularly calibrated to allow an accurate emulation of climatic conditions. Table 4.6 indicates type and precision of the different measurement elements.

Table 4.5: SEILAB's climate chamber characteristics

Magnitude	Working range
Flow	20000 m^3/h max.
Temperature	−15 to 45°C
Relative humidity	15 to 98%
Heat sink power	30 kW max.
Heat source power	30 kW max.
Tested equipment power	20 kW max.

Table 4.6: SEILAB's climate chamber measurements precision

Magnitude	Type	Precision
Flow	Thermopile	±5%
Temperature	3- or 4-wire Pt100	±0.5 K
Relative humidity	Capacitive	±3%
Electrical power	Multimeter	±1%

4.3.2.3 Emulator cabinets

An emulator cabinet acts as an intermediary between two electrical grids (main and micro or auxiliary) delivering to the micro grid a 3-phase electric signal modulated in active and reactive power through external control. For positive power, it is a generator, while, for negative power, behaves as a consumer.

4.3.2.4 Propane safety system

Due to the flammability of the selected refrigerant (R-290 = propane), there is a safety system in the SEILAB to prevent the formation of flammable/explosive atmospheres. It includes automatic gas detection and automatic or manual extraction to a safe area along with measures to remove ignition sources and to limit hazardous consequences.

4.3.3 Experimental setup - systems schematics

Figure 4.1 represents the hydraulic and electrical installation to be set at the SEILAB. The tested system performs the same function as in a real building installation.

Elements such as test benches (TB) and primary heat exchanger units (CL) emulate heat sinks and sources as described. Similarly, emulator cabinets (EC) emulate electrical generation (PV modules) and consumption (household appliances). The climate chamber is also emulating weather conditions affecting the air side of the dual source heat exchanger.

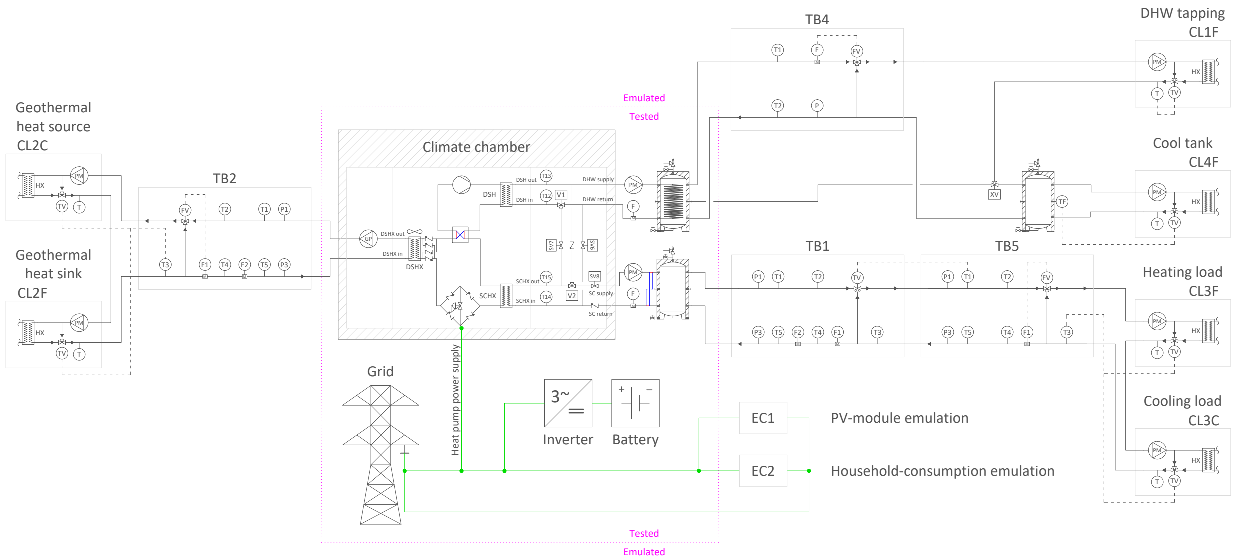

Figure 4.1: Experimental setup of the thermal systems in SEILAB at IREC

5 Selection of periods

5.1 Ice-slurry systems (SPF)

The first goal of testing the solar-ice system in a system test is to approve the functionality of an ice-slurry storage with supercooling water in the evaporator of the heat pump and generating ice-slurry by help of a crystallizer. To achieve this goal, a period of 7 days was selected representing a year in a way that the ice-slurry storage reaches it's maximum ice fraction only in a small period of time. This test will be performed with the propane heat pump. The selection of days is described in Section 5.1.1. Additionally, the simulation model should be validated with the results of this system test in order to evaluate the system performance with a reliable, validated model in a yearly simulation. The second goal is to test the AEM system which will be tested using the CO_2 heat pump and the method for selecting of days described in Section 5.2.1.

5.1.1 Selection of testing parameters for the ice slurry storage

The first step for selecting the days for the system test is to get an overview about the distribution of different weather conditions and their influence in the heating system over the year. Fig. 5.1 shows the distribution of the daily averaged ambient temperatures with the daily sum of solar irradiation into the collector field. The color code indicates different situations in terms of the heating and cooling demands and the ice fraction of the ice storage. The days with low irradiation and low temperatures tend to have a high heating demand but very different status of the ice fraction. The ice fraction on days with high heating demand is deciding on system efficiency. A system with an SPF of 4 reaches the maximum ice fraction only on 3.5 % of the days.

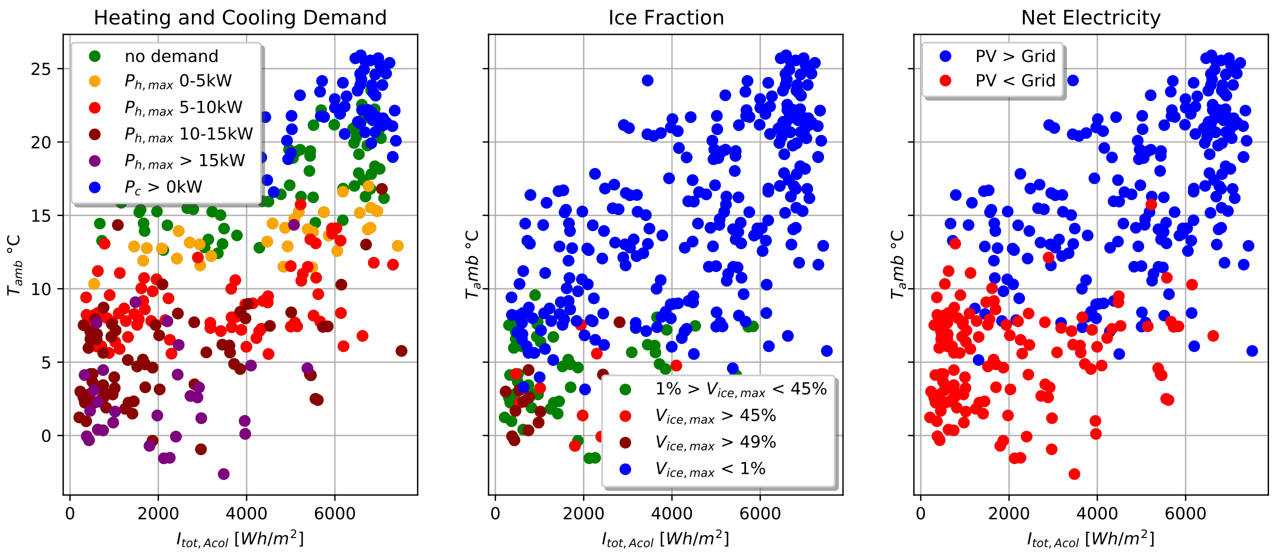

Figure 5.1: Ambient temperature vs total solar irradiation in Wh/m^2 for different conditions of heating and cooling demand, ice fraction and net electricity.

In the yearly simulations, 60 % of the days have heating demand, 20 % have cooling demand and 20 % have no demand for heating nor for cooling. The seven days were choosen in a way that they represent this distribution as far as possible, reaching the fully iced ice storage only for a part of a day in order to be comparable with the yearly simulation.

The ambient temperature and the total horizontal irradiation are shown in Fig. 5.2. The ambient temperature was smoothed at the transitions between the days to get a temperature profiles without any steps. For the system simulation of the seven days, the ice storage was scaled down further to a lab-size of 2 m^3. These profiles of the seven days as well as a seven day profile for household electricity and DHW was then fed into the system simulation and results for the seven day period were calculated.

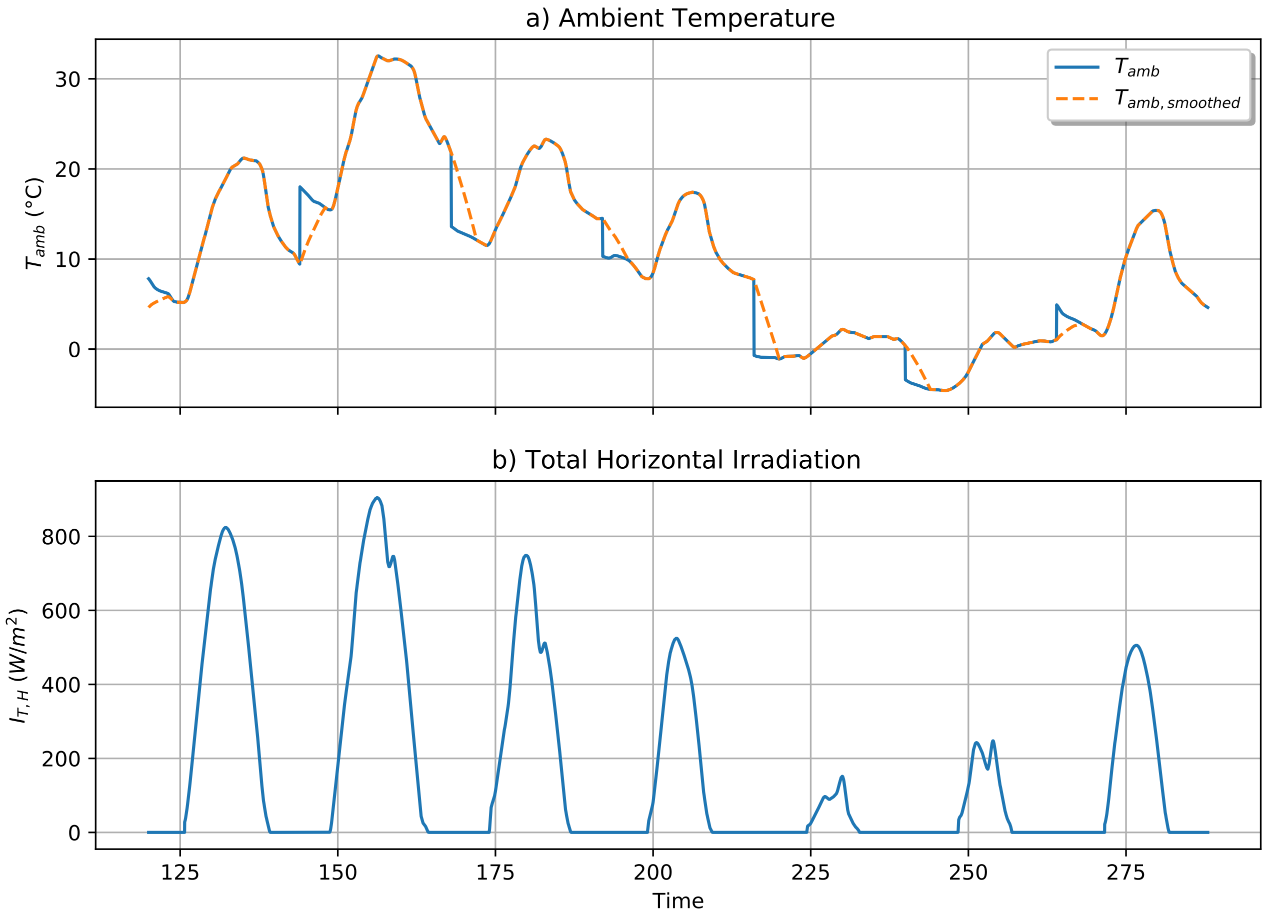

Figure 5.2: Ambient temperature (a) and total horizontal irradiation (b) for the seven selected days. The ambient temperature is smoothed at the transition from one day to the next.

The system test with the propane heat pump using the seven days selected should serve for validation of the simulation model. The results of the system test will be compared with the simulation results of the seven selected days and the simulation model will be optimized. Afterwards, the system efficiency (see example in Fig. 5.3.1) will be calculated with the yearly simulation of the system with the optimized simulation model.

The building respects a high insulation standard and has a high thermal capacity. Such heating up in warm weather periods or cooling down in cold periods takes some days. To get reliable building temperatures for the system test, the temperature of the building is re-initialized every day at midnight with the temperature of the following day from the yearly simulation. In this way, the cooling and heating demand in the system test is not influenced by the short-term change of seasons.

5.1.2 Selection for testing AEM

For the CO_2 heat pump, the aim of the system test is to test the AEM for the ice-slurry system. The selection of days will, in general, follow the methodology described in Section 5.2.1 but with additional consideration of the ice-fraction within the ice storage at the days selected for the different periods. If the ice storage is iced to the maximum ice fraction, the AEM cannot optimize much as the backup heating has to cover the heating demands until enough solar energy melted some ice again. Therefore, the goal of the selection of consecutive winter days is to ensure that the ice storage does not reach the maximum ice fraction for longer than a few hours. Preliminary system-simulations of the selected winter-period will allow us to ensure that this goal will be reached in the system test.

5.2 Dual source/sink system (IREC)

5.2.1 Methodology

As resources are limited, only a few representative days can be tested in laboratories. To choose which days are the most representative for the system's operation over the whole year, IREC developed the method K-meansGA. This method uses the classification method K-means and optimization based on a genetic algorithm (GA). Meteorological and demand data explained in Section 2.2 are used for obtaining the results for Tarragona. Additionnally, some results are also presented for the climate of Bilbao.

Figure 5.3 shows a scheme of the different steps of the process. First, the weather data is classified in a number k of clusters. For this, the k-means algorithm from the python library sklearn is used. The clusters are generated by the data distribution. Each data point is classified using the lowest quadratic distance to the nearest centroid. The centroids are the mathematical centres of the cluster and are not actual data points. In each iteration, the centroids position change until the distance between each data point and their centroid is minimum. The closest point to the centroid is the final result. Secondly, a genetic algorithm is used, based on natural selection applied to optimization problems. In each iteration, random "parent" solutions are selected, crossed and mutated, generating "descendent" solutions for the next iteration. In the end, the most fitted solution is found. The genetic algorithm used has been developed by IREC for this specific use.

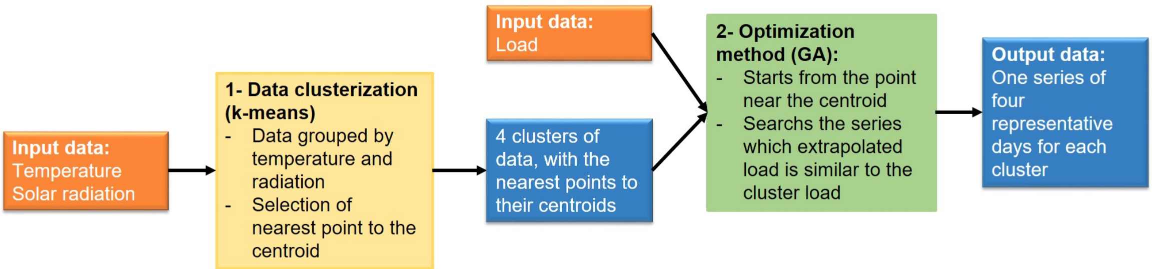

Figure 5.3: Scheme of the kmeansGA algorithm.

For the test of the management algorithm, the days selected must be consecutive rather than different days of the year put together, so as to observe the behavior of the AEM systems over several consecutive days (e.g. storing PV energy on a sunny day for the next day with less production). Because of this, the algorithm selects all the possible combination of consecutive days of the year (e.g. series 1: day 1, 2, 3 and 4, series 2: day 2, 3, 4 and 5). Therefore, each data point is a series of 4 consecutive days. For the current application, the daily average temperature and the daily solar irradiation are used for the k-means. The algorithm does not take into account the chronological order of the days. Therefore, each cluster has points from various dates of the year. Figure 5.4 shows an example of the k-means classification. The intermediate results of the k-means are one series of four days for each cluster, each one representing different conditions of the year. This result is used for the genetic algorithm as seeds for the solutions. Also, cluster classification is used. The function to optimize by the GA is the minimum difference between the extrapolated load of the selected series of days (load of the selected days multiplied by the number of days in the cluster) and the total load of the cluster. The algorithm searches for series of days that minimize that difference and are near the centroids.

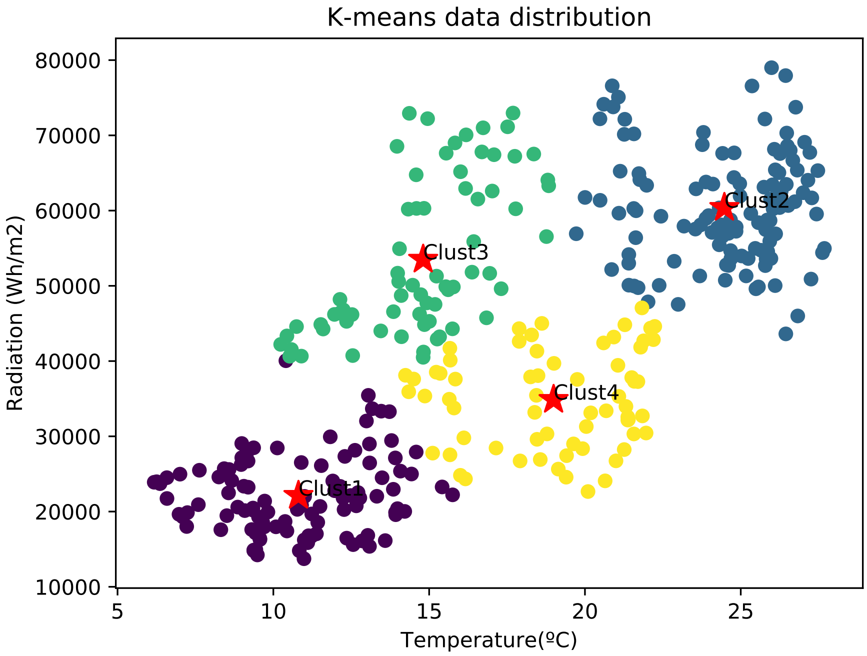

Figure 5.4: K-means clusterization by radiation and temperature. Each cluster is shown with a different colour. The red starts are the centroids of the cluster.

5.2.2 Load selection

The genetic algorithm can optimize for different loads at the same time. For this project, three different load types were considered: space conditioning, DHW and electrical power consumption from the appliances. Space conditioning is the main load associated with the heat pump, divided into SH during the cold season and space cooling during the warm season. This section studies if adding the DHW and appliances consumption to the optimization could improve the results.

For DHW, stochastic data was used to obtain the extraction profiles along the year. SH and DHW can be added together as a total heating demand, but the result may be days where one type of demand is dominating and the other is not correctly represented. To avoid this, SH and DHW are considered as two different variables to optimize.

For the Bilbao climate, the obtained results when using DHW are the same as when only using space conditioning. For Tarragona, the results are the same, except for one cluster where the selected days are different. This new set of days improves the result for DHW but worsens the result for space conditioning.

The results show that the stochastic distribution and the lack of seasonality of the DHW made it hard to select representative days throughout the year. Only one of the eight solutions changed when adding the DHW to the optimization. In that case, the results do not show enough improvement to justify the consideration of the DHW load in the selection process. Therefore, the DHW load will not be considered for optimization.

For the appliances, the electric consumption is based on a typical yearly profile. This annual profile does not present seasonality. When optimizing based on the appliances consumption, half of the results changed while the other half stayed the same as when considering only space conditioning. For the ones that changed, the results for space conditioning worsened. The improvement of the results for the appliances consumption is not enough to justify the worsening of the space conditioning load prediction.

Taking into account the test objectives, the use of only space conditioning as the input load data was considered the most appropriate option. The k-means algorithm considers the climatic data which affects the photovoltaic generation, while the GA algorithm selects the days which best extrapolate the load for the whole year.

5.2.3 Results: selected days for experiments

5.2.3.1 Tarragona climate

Figure 5.5 shows the clusterization of the climate data from Tarragona. Cluster 3 corresponds to the warmest days of the year, while cluster 4 are the coldest ones. Cluster 2 and 1 are in the middle, being cluster 2 the one with less radiation. Figure 5.6 shows the average daily demand of each cluster, for the chosen renovated building. Cluster 1 and 4 have heating demand, while clusters 2 and 3 have cooling demand. The climate of Tarragona is cooling dominated.

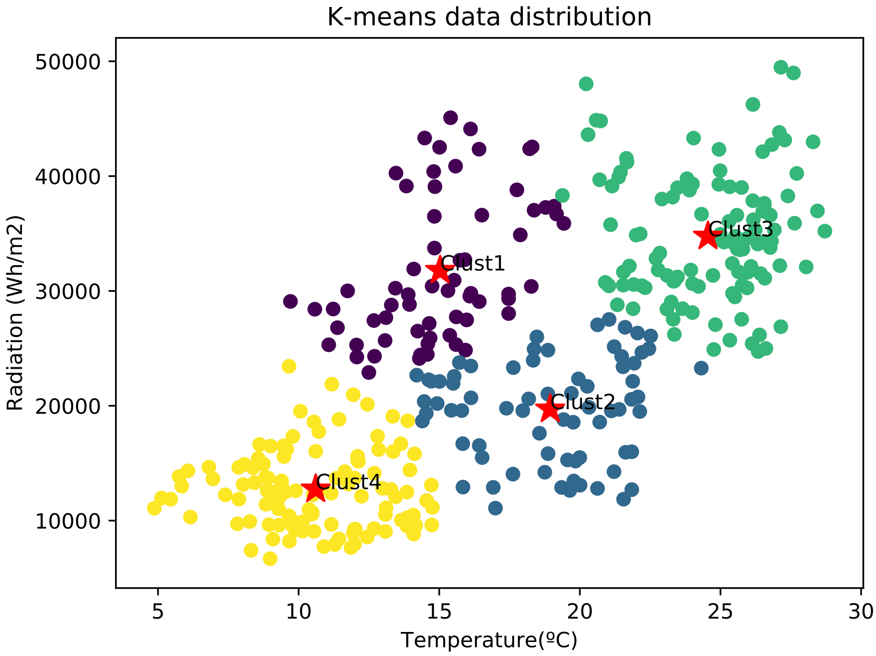

Figure 5.5: K-means clusterization of Tarragona. The solar radiation is the sum of the 4 days series and temperature the average. Each cluster is shown with a different colour. The red stars are the centroids of the clusters.

Table 5.1 shows the selected days for each cluster.

Table 5.1: Selected series of days for the Tarragona climate. The temperature range is the average daily temperature and the radiation range is the total solar radiation for one day.

Cluster	Number of series	Selected days	Temperature range (°C)	Radiation range (Wh/m^2)
1	64	March 15 - 18	9-19	5750-11250
2	72	September 24 - 27	14-24	2750-7000
3	113	August 8 - 11	19-28	6250-12250
4	112	January 28 - 31	4-14	1675-5750

The daily profiles for the selected series are shown in Figure 5.7.

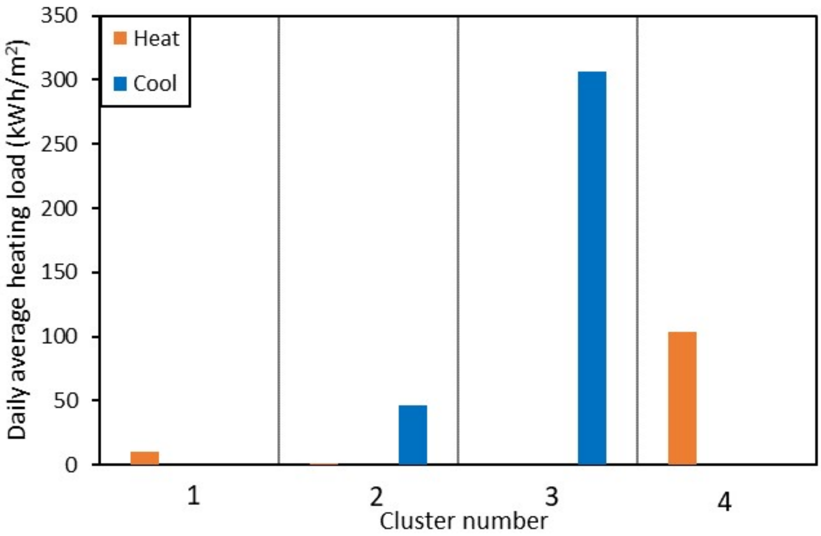

Figure 5.6: Average daily heating and cooling demand for each cluster for Tarragona.

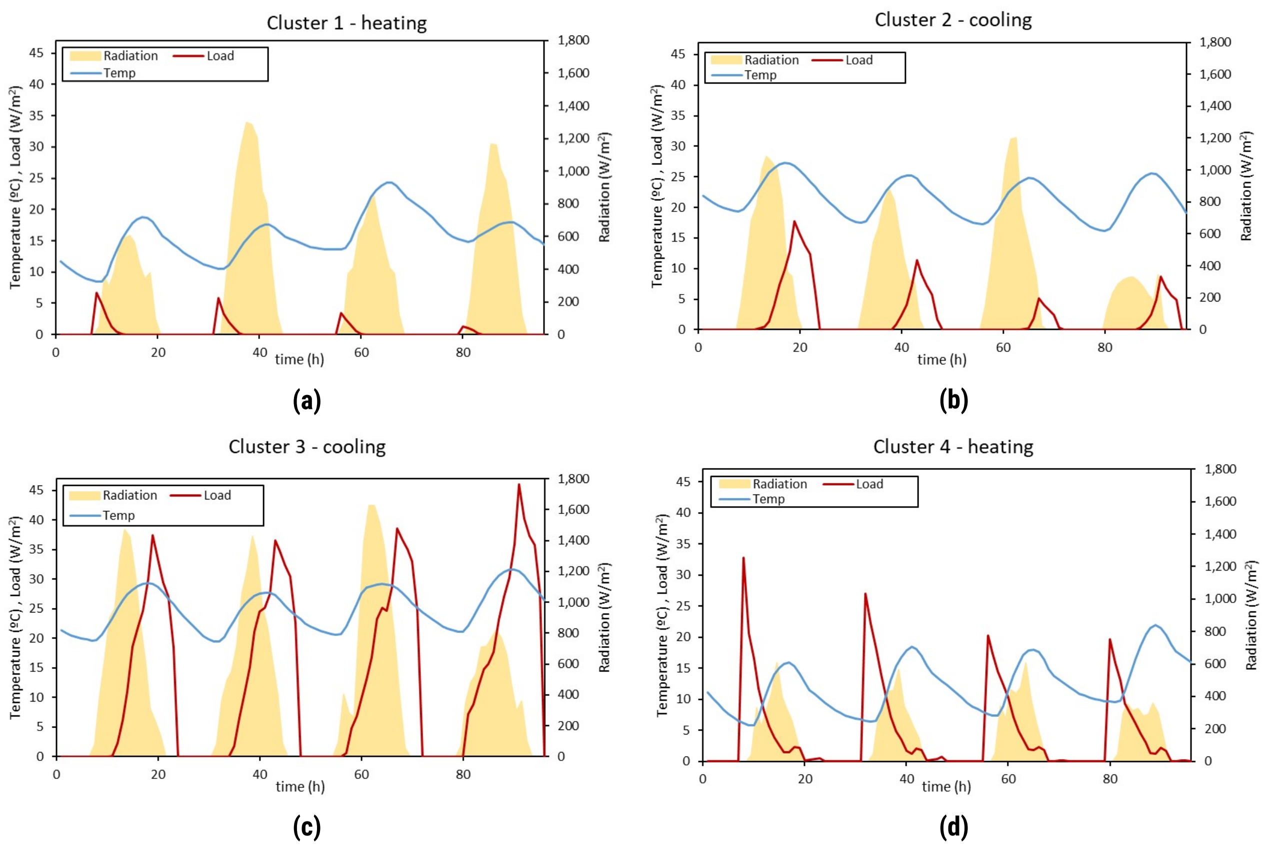

Figure 5.7: Hourly profiles of temperature, solar radiation and load for the selected series of days for Tarragona.

5.2.3.2 Bilbao climate

The laboratory tests with the management algorithm will mainly be made with the Tarragona climate, and additional tests might be performed in the future with the climate of Bilbao, therefore the results for this case are also shown here. Figure 5.8 shows the clusterization of the weather data from Bilbao. Cluster 1 corresponds to the warmest days of the year, while cluster 2 are the coldest ones. Cluster 3 and 4 are in the middle, being cluster 3 the one with less radiation. Figure 5.9 shows the average daily demand of each cluster. Cluster 2 and 4 have only heating demand. The data corresponds to the renovated building with Bilbao climate. Cluster 1 has only cooling demand, and cluster 3 has both heating and cooling demand. The climate of Bilbao is heating dominated because the cooling demand is scarce and present in less than a month of the year.

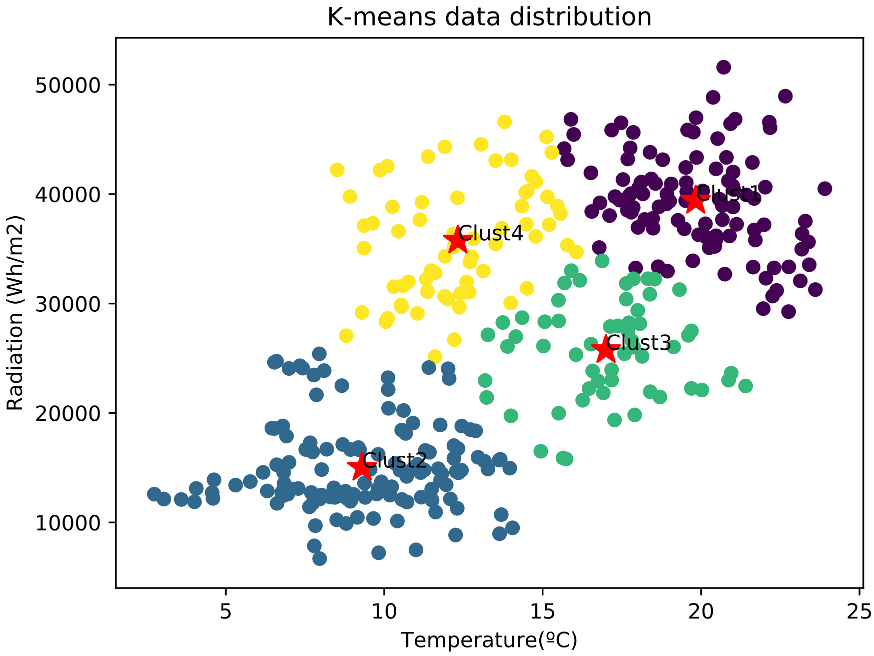

Figure 5.8: K-means clusterization of Bilbao. The solar radiation is the sum of the 4 days series and temperature the average. Each cluster is shown with a different colour. The red stars are the centroids of the cluster.

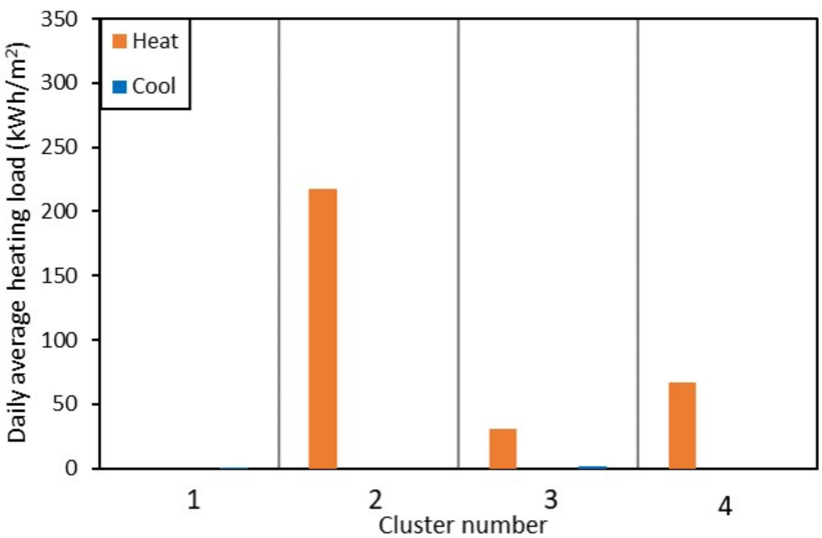

Figure 5.9: Average daily heating and cooling demand for each cluster for Bilbao.

Table 5.2 shows the selected days for each cluster. For cluster number 3, where there is heating and cooling demand, it is shown the days for heating. The heating demand is higher than for cooling, and any day selected for cooling show a high difference when extrapolated because of the low demand of the cluster.

Table 5.2: Selected series of days for the Bilbao climate. The temperature range is the average daily temperature and the radiation range is the total solar radiation for one day.

Cluster	Number of series	Selected days	Temperature range (°C)	Radiation range (Wh/m^2)
1	105	July 30 - August 2	15-23	7500-13000
2	132	February 2 - 5	2-14	1750-6250
3	58	November 10 - 13	13-21	4000-8500
4	66	March 26 - 29	8-16	6250-11750

The daily profiles for the selected series are shown in Figure 5.10.

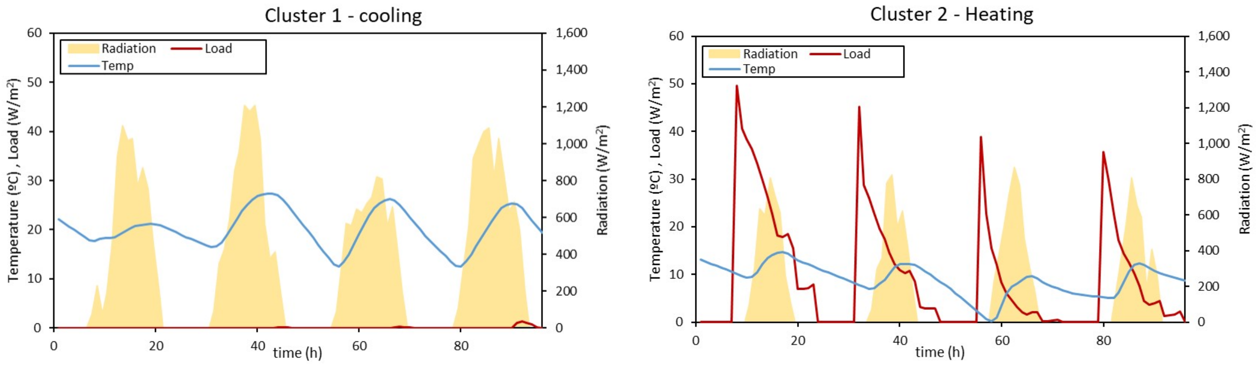

Figure 5.10: Hourly profiles of temperature, solar radiation and load for the selected series of days for Bilbao.

5.3 System performance evaluation

5.3.1 Ice-slurry system (SPF)

The TRI-HP goal of reaching at least 80 % of onsite renewable share is fulfilled for the ice-slurry system in yearly simulations as well as in the simulation of the seven representative days selected (see Table 5.3). Additionally, the electricity produced by the onsite PV plant exceeds the total electricity demand by 50 % in the yearly simulation (70 % in the seven-day simulation that overestimates the PV gains due to the selection of days).

Table 5.3: Comparison of the KPI for yearly simulation and the simulation of the selected 7 days.

KPI	Yearly Simulation	7-Day Simulation
$R_{RE,local}$	81 %	82 %
SPF	4.1	4.3
Electricity from grid	12.6 MWh	275 kWh
Electricity to grid	20.8 MWh	125 kWh

5.3.2 Dual source/sink system (IREC)

The evaluation of the suitability of the selected days is made comparing the total cluster load and the load extrapolated using the selected days. Table 5.4 shows the results for space conditioning for Tarragona. The deviations are below 10% for all the selected series of days and below 2% for all the year.

Table 5.4: Space conditioning results considering the selected days for Tarragona. The extrapolated load is the result of multiplying the space conditioning load of the selected series by the number of series in the cluster and divided by the number of days in the series. The cluster load is the sum of the load of all the series divided by four.

Cluster	Nº of series	Extrapolated load (kWh)	Cluster load (kWh)	Deviation (kWh)	Deviation (%)
1	64	627	673	-46	-6.8
2	72	3670	3354	316	9.4
3	113	35338	34660	678	2.0
4	112	11469	11630	-161	-1.4
Yearly		51104	50317	787	1.6

Table 5.5 shows the results for the DHW for Tarragona. There are underestimation above 20% for the second and third cluster, which have cooling demand. This result is improved in the yearly results which is 12% of underestimation.

Table 5.5: DHW results considering the selected days for Tarragona. The extrapolated load is the result of multiplying the DHW load of the selected series by the number of series in the cluster and divided by the number of days in the series. The cluster load is the sum of the load of all the series divided by four.

Cluster	Nº of series	Extrapolated load (kWh/m^2)	Cluster load (kWh/m^2)	Deviation (kWh/m^2)	Deviation (%)
1	64	7136	7004	132	2
2	72	5175	6869	-1694	-25
3	113	5583	7918	-2335	-29
4	112	13540	13760	-220	-2
Yearly		31433	35551	-4118	-12

Table 5.6 shows the results for the extrapolation of the appliances electric consumption for Tarragona. The deviation is lower than 5% in all the clusters.

Table 5.6: Table with the appliances electric consumption results of the selected days for Tarragona. The extrapolated load is the result of multiplying the appliances electric consumption of the selected series by the number of series in the cluster and divided by the number of days in the series. The cluster load is the sum of the load of all the series divided by four.

Cluster	Nº of series	Extrapolated load (kWh)	Cluster load (kWh)	Deviation (kWh)	Deviation (%)
1	64	77145	79132	-1987	-3
2	72	89921	89811	111	0
3	113	147191	140687	6504	5
4	112	136434	138265	-1831	-1
Yearly		450691	447895	2796	1

6 Test procedure and evaluation of results

6.1 Test procedure

6.1.1 Ice-slurry system (SPF)

After the installation and commissioning of the whole system, the controller must be parameterized. For this purpose, some preliminary tests are required to check the speed of the pumps, the heating curve of the controller and the domestic hot water mixing valves. Before the actual start of the test, all tanks included must be conditioned. This means that the DHW tank should be in the upper range between 50°C and 60°C and the heating buffer at about 30°C. The ice slurry storage should have an ice content of about 50%, and the battery should be discharged to just above the maximum depth of discharge. Once the test has started, no changes or interventions in the system or its controllers are allowed until it is completed. The tested system must operate autonomously to meet the building's heating, cooling and household electricity needs. After 7 days or 168 hours, the end of the test cycle is reached. However, the test is not stopped then but continues seamlessly, starting again at day 1. The end of the test is not reached until the so-called Concise Cycle criterion is reached. This ensures that no energy is stored within the system, or that the state of the system is identical at the beginning and end of the test. The Concise Cycle criterion for the termination, or the successful completion of the test, consists of several points:

Energy consumption

At the end of the eighth test day, the consumption of electrical energy in the period 0h to 168h (cf. phase "A" in Figure 6.1) can be compared with the consumption of electrical energy in the period 24h to 192h (phase "B"). If these values are identical (±1 %), it can be assumed that the energy content of the storage used was identical at the beginning and end of the test. If this is not the case, the conditioning of the storage tanks was insufficient and the test is continued to compare phase "B" with phase "C".

Storage tank temperature

The storage tank temperature is measured by means of contact sensors on the storage tank wall. This temperature measurement can be used to determine an average storage tank temperature. This temperature must be identical at the beginning and end of the test cycle (±0.5 K). If the temperature does not match, this means that the conditioning of the storage tank was not correct and the energy content of the storage tank has changed during the test period. In this case, the test must continue for at least 24 hours and at the end of the next day the comparison between initial and final temperature must be made again.

Battery state of charge

The state of charge of the battery must be identical at the beginning and at the end of the test cycle. This can be done either by the display of the battery itself, or by balancing the supplied and discharged electrical power.

6.1.2 Dual source/sink system (IREC)

Just as in the case of the ice-slurry system, the complete dual source system is installed and commissioned on the test bench. The storage units installed on the consumer side, both thermal and electrical, lead to inertia in the overall system. To start the test in a more realistic state, an additional day of pre-conditioning will be carried out in the experiments: the day before the chosen series of 4 days will also be tested in real time in the experiments, so as to bring the tanks into a usual stratification state that corresponds to a normal operation. We will, however, discard this first day of pre-conditioning, and only consider the 4 actual days of the test for the analysis. Since the capacity of the installed storage units does not exceed the respective daily demand, no further conditioning measures are necessary.

It could happen that because of the control strategy or the test conditions, the states of the storage are different at the start and at the end of the 4 days test period. Therefore the differences in charged/discharged energy will be calculated for all the storage elements (thermal mass of the building, storage water tanks, electrical battery) and taken into account in the energy balances.

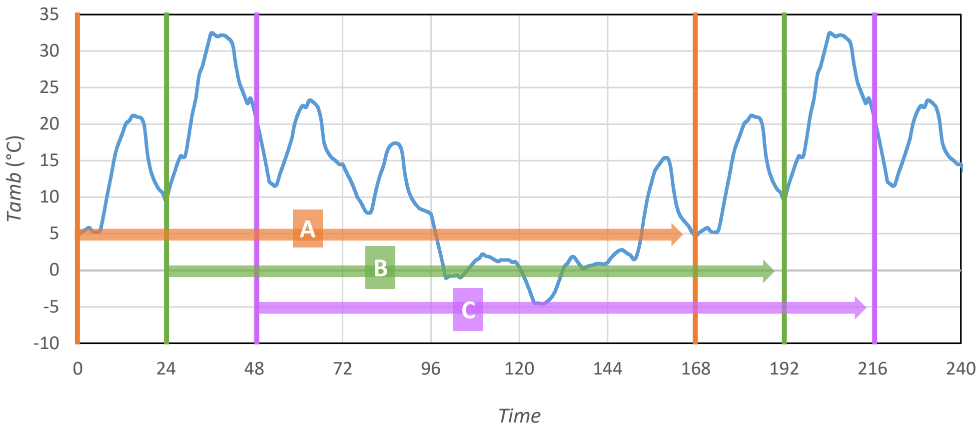

Figure 6.1: 7-day test sequence as a cycle, which is seamlessly aligned, respectively repeated. The test can be completed successfully if the evaluation of two consecutive phases is identical (A = B or B = C etc.).

6.2 Evaluation of results

6.2.1 Ice-slurry system (SPF)

The test cycle used for ice-slurry systems was created with the aim of combining all relevant operating conditions in one test cycle while providing a directly extrapolated result. The comparison of the 7-day simulations and the annual simulations in Chapter 5.1.1 shows that this has been achieved. However, this is only true if, on the one hand, the test confirms the expected efficiency from the simulations carried out in advance and, on the other hand, the dimensioning of all components is suitable for the load of the test. In case of a deviation, the source temperature of the heat pump changes and thus also its efficiency. For this reason, the measured data is used to validate the already existing simulation model of the tested system. If the simulation results from the 7-day simulation match the measured data, the next step can be an annual simulation with a slurry store matched to the annual demand.

6.2.2 Dual source/sink system (IREC)

As described, four different 4-day sequences including one additional conditioning day each are used. From the sequences, quantities such as the useful heat or cold as well as the electricity demand can be extrapolated. The sum of the four extrapolated data then results in the annual value, from which the defined KPI can be calculated.

7 Conclusions

The Concise Cycle Test (CCT) method and the modifications necessary to test the TRI-HP systems in the SPF and IREC laboratories are described. The CCT method will allow testing the efficiency of the TRI-HP systems considering space heating and cooling demands and domestic hot water needs. The procedure for selecting the testing days, the number of testing days and the used profiles for electricity, heating, cooling and DHW demands and the weather data used for each day are presented. The experimental setup for carrying out the CCT tests is described, including the measuring equipment and its accuracy, as well as the boundary conditions for the tests and the testing procedure. Key Performance Indicators were also defined to verify the intended goals from the system developments.

The methods for selecting the representative days are presented for both systems developed in TRI-HP: the propane-dual heat pump system for warm regions with high cooling demand and the ice-slurry system with the propane/CO_2 heat pump for cooler regions with heating demand, mainly. The proposed methodologies demonstrate an efficient selection of the test periods representative for the operation of the system over a whole typical year, and they allow an accurate assessment of the dynamic behavior of the system and its efficiency .

For testing the AEM for the dual-source heat pump system, the weather data are divided into four different seasonal clusters. Representative days for each clusters are selected and used for the system tests in order to evaluate the behaviour of the advanced management control method and their cost-economic advantages compared to a rule-based control.

For selecting the representative days for the ice-slurry system, the weather data alone are not sufficient as the system's source temperature and therefore the system efficiency is strongly dependent on the weather data. Therefore, system simulations were used to select the representative days. The representative days were selected by comparing the KPIs obtained for one year simulations with the ones corresponding to the seven consecutive days selected.

In addition to the methodologies for selecting the representative periods of the year for the tests, the laboratories and the setup for the experiments are also presented. The tested systems mainly consist of the heat pumps with the storage elements (both electrical and thermal), while the different loads are emulated virtually with the hardware-in-the-loop principle. The setup of these electrical and thermal systems constitute the basis for the preparation of the two laboratories for the upcoming system tests. The proof of concept for the ice-slurry storage and the advantages of an AEM system will be also evaluated in these tests.

The concise cycle tests will be used for testing and optimizing the advanced energy management system for both, the dual-source and the ice-slurry system with the propane and CO_2 heat pumps developed within the TRI-HP project. Additionally, an ice-slurry storage prototype integrated in the ice-slurry system will be tested.

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TRI-HP PROJECT

Trigeneration systems based on heat pumps with natural refrigerants and multiple renewable sources

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