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SYSTEM MONITORING REPORT

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D4.1 System Monitoring Report

1. Introduction

The monitoring and visualization is a very important component of any system since what is not measured and monitored cannot be managed and improved[1]. This report (D4.1) describes the monitoring architecture for the CHESS SETUP from the lowest level of physical magnitudes, sensors, actuators and signals, to the highest level point of view of an operator that interacts with the system using an HMI (Human Machine Interface).

The CHESS SETUP Project aims for efficient energy generation, accumulation and conditioning. Therefore, the main variable that will be monitored for this system is energy, and one of the main targets of the monitoring system is the measurement of the energy transfers (distribution) within the components of the system, i.e. production, storage, conditioning and the final customer.

In addition, the monitoring system has to take into account auxiliary measurements and management signals needed for controlling the individual devices of the system as well as for the alarm generation.

This chapter will provide an overview of the CHESS SETUP control and monitoring approach and the main definitions that will be used in the following chapters.

Note that the final monitoring system to be implemented will be defined further and adapted to each pilot project as the project evolves.

1.1. System control and monitoring

The CHESS SETUP Control and Monitoring System (CMS) will be organized in two layers: the low and the high level control and monitoring subsystems.

Low Level Control & Monitoring Subsystem (LLCMS): This layer will contain an industrial-like controller with a low ratio of failures in order to obtain a very robust final system. An industrial-like HMI (Human Machine Interface) screen will be connected to the controller to monitor the main variables and manipulate the basic operational parameters such as temperature set points or working modes (e.g. summer/winter).

This controller does not typically have secondary memory, therefore, no databases will be considered at this level. Only absolute counters such as energy, power or temperature will be registered and monitored at this level.

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[1] *Lord William Thomson Kelvin*: If you can not measure it, you can not improve it.

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High Level Control & Monitoring Subsystem (HLCMS): This layer will contain a less robust PC-like computer controller with large secondary memory (i.e., hard drives) to store large databases logs of variables and parameters. This PC computer also has the possibility to interact to other computers from the Internet to, for instance, obtain the electricity grid hourly energy price forecasts.

This controller has a local screen for local operators as well a Web page interface for remote operators which can be accessed locally (via the local network) or remotely (via Internet) using any device such as a PC, Smartphone or tablet.

1.2. Users

There are different roles that must be defined from the point of view of what manipulations can be performed on the system using its input interfaces and to what outputs a role can access. In the CHESS SETUP, a viewer role and an operator role will be defined. The different roles are protected by passwords and a physical user can have more than one role. There will be different roles taking into account its level and where the user is located:

- **Local Viewer Role**: The only permission for this role is viewing information in the Low Level Monitoring and Control HMI screen. This role can also view the alarms in this screen.
- **Local Operator Role**: This role has permission to change parameters in the Low Level Monitoring and Control HMI screen as well as clear the alarms.
- **Viewer Role:** This role has full visualization permission of any variable, parameter and alarm from any interface.
- **Operator Role:** This role has full rights to modify anything from the HMI screens or from the Web Interface. This operator also receives the alarms at that level via e-mail and can also clear these alarms. This role will be the responsible of ordering the actions to solve the alarms.
- **Administrator:** This role has permissions to modify anything in the system: the software, the databases, PC, LLCMS controller and HMI screens. This role is reserved only for the programmers and administrators of the system.

Table 1.1 shows a summary of the tasks that every role can perform.

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Role Name	Local Viewer	Local Operator	Viewer	Operator	Administrator
View					
View information in HMI Interface	√	√	√	√	
View information in local PC Screen		√	√	√	
View information remotely		√	√	√	
Modify					
Modify Set Points in HMI Interface		√		√	
Modify variables in HMI Interface		√		√	
Modify variables using local PC Screen		√		√	
Modify variables remotely				√	
Modify set points in HMI Interface		√		√	
Modify set points using local PC Screen		√		√	
Modify set points remotely				√	
Modify parameters in HMI Interface		√		√	
Modify parameters using local PC Screen		√		√	
Modify parameters remotely				√	
Alarms					
View alarms in HMI Interface	√	√	√	√	
View alarms in Local PC Screen		√	√	√	
View alarms remotely			√	√	
Receive alarms via e-mail				√	
Administration					
Modify software and HMI interfaces					√
Modify databases					√
Administer the PC					√

Table 1.1 Control and Monitoring System (CMS) role summary.

1.3. Energy flow monitoring

In this early stage of the project there are still uncertainties in the final localization and definition of the subsystems in the different pilots. However, from the point of view of the monitoring and the control, the CHESS project concept can be divided into the following subsystems shown in **Figure 1.1**.

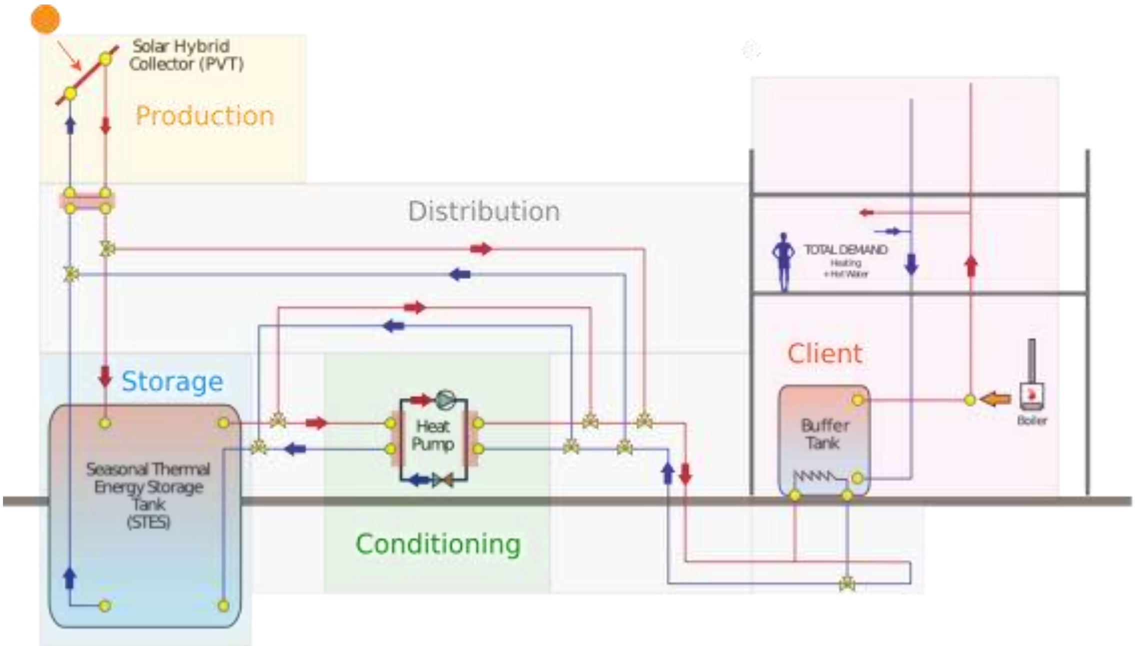

Figure 1.1 Monitoring subsystems in the CHESS Project: production, distribution, storage, conditioning and the client.

Each subsystem is defined from the point of view of the operation performed on the energy process (production, storage, transport, consumption). Therefore, the measurement of the energy flows within sub-systems is very important in terms of monitoring:

- **Production:** In this subsystem the energy is produced by the hybrid solar panels (PVTs). Therefore, in this subsystem both electrical and thermal energy is produced.
- **Distribution:** The energy is moved from a subsystem to another. This subsystem produces thermal energy losses and consumes electrical energy.
- **Storage:** The energy is stored in the form of hot water. This subsystem also produces thermal energy losses.
- **Conditioning:** This subsystem provides thermal energy to the buffer tank using a heat pump that has the STES (Seasonal Thermal Energy Storage) as the source. The CHESS SETUP approach aims to obtain a high COP (Coefficient of Performance) to minimise the electrical input for the heat pump.

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- **Client:** This subsystem delivers energy to the final customers. In this subsystem, the energy is typically buffered in a hot water tank. An auxiliary heating system is considered to overcome the case of a failure in the main supply or as a last step of conditioning when necessary. This system may consume electrical energy as well as auxiliary energy (i.e. Natural Gas or Diesel) and has thermal energy losses in the buffer tank.

In order to later execute an informative evaluation of the performance of the whole setup, the HLCMS will register the produced energy (both electrical and thermal) as well as the energy losses in the distribution and storage.

Thermal Energy: It will be produced mainly in the hybrid solar panels, stored in the STES and consumed in the client side. Different energy flows will happen depending on certain conditions. For instance, if there is enough temperature in the STES tank, it could be delivered directly to the final consumption without being conditioned by the heat pump.

The three different energy flows within subsystems are shown in **Figure 1.2**.

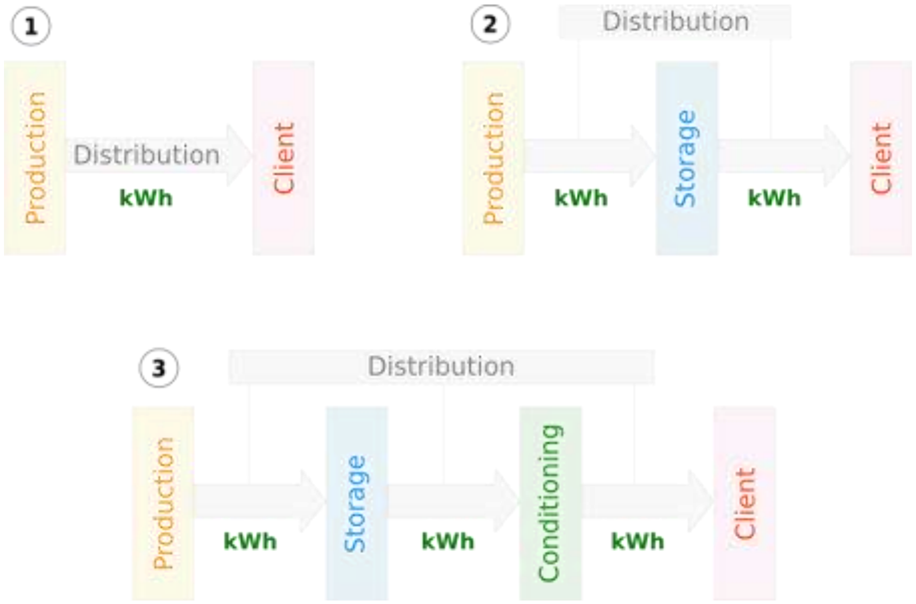

Figure 1.2 This figure shows the tree different energy flows in the CHESS SETUP. 1) When the produced thermal energy in the PVTs is directly delivered to the consumption; 2) When the energy produced and stored in the STES is delivered to the final customer; and 3) when the produced energy is stored in the STES and needs to be conditioned by the heat pump to be finally delivered to the customer.

Electrical Energy: It will be produced in the hybrid solar panels and consumed by the electrical components of the system, mainly the heat pump and the water pumps and elsewhere in the building. The electrical energy excess will be feed-in the utility grid.

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1.4. Sensors

The sensors are the set of devices that allow the CMS acquire physical information of the system.

From the point of view of the main task they will be used for, the sensors are classified in three different groups:

Control Sensors: This group of sensors are used to perform the low level control of the system. Basically they are temperature sensors that will be used to control the water pumps in order to move energy from one point to another. This group of sensors are the more critical for the normal operation of the system. Therefore, the easiest communication interfaces to the LLCMS controller will used in order to avoid system failures. As far as possible, they will be connected to the low level controller directly and sometimes they will have redundant sensors (i.e., it exists a monitoring sensor that provides the same reading) in order to overcome a possible failure.

Although these sensors are mainly for controlling the system, the HLCMS will register them in a database log in order to perform later evaluations.

Monitoring Sensors: This group of sensors are used to monitor high level or relevant information, for instance to evaluate performance of the system. For this project, the fundamental sensors in this group are those for monitoring the energy flows. The information gathered by these sensors will also be registered in a database log by the HLCMS.

Alarm Sensors: These set of sensors are used to send alarms to operator users in order to inform them to perform a handling in the system. For instance, if the water pump should be active but a flow meter is not informing about any flow in the tubes, an alarm is released to an operator to correct any possible problem. These sensors may also be redundant to other monitoring sensors. The different alarms will be shown in the LLCMS and HLCMS interfaces as well as sent via e-mail to the corresponding operator roles.

1.5. External variables

The external variables are those that have to be obtained from outside of the system. In the case of the CHESS SETUP the utility grid hourly energy price and the weather forecast are considered external variables. The external variables will be obtained from the Internet connection. The weather forecast however can be obtained more locally if it is provided by a local weather station.

The external variables depend on the availability of an external connection to the Internet that may fail unexpectedly. Therefore, the design of the control does not consider these variables essential for the main control of system in normal operation, however, they are used to fine tune internal parameters such as set point temperatures.

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Therefore, if they are available the performance of the system will be increased and if they are not, the system will also perform correctly.

1.6. Data processing and storage

From the point of view of the data processing and storage, the CMS must tackle the following points:

- **Control data acquisition:** The main purpose of the monitoring is to gather the physical magnitudes such as temperatures needed by the controller to regulate the system.
- **On-line visualization and control:** A common feature implemented in the monitoring system is provide a human-machine interface (HMI) to the different users of the system and show, in a friendly way, the gathered information, the control parameters and set points. The user will be able to inspect instantaneous values such as temperatures, powers, device status, in order to detect possible problems in the system.
- **Data storage:** The information more sensitive to be needed for the later evaluation of the system (failures, performance, etc.) will be stored in a database log by the HLCMS. Therefore, variables related to both sensors, controls and parameters will be stored in the database under different criteria (on change, periodically, etc.).
- **Historical data visualization:** For the long term evaluation of the performance of system, the stored data must be friendly presented to the user, for instance, as plots and graphics. The databases will be stored locally in the HLCMS controller database and all the required security and redundancy will be taken into account. No sensible information of any user will be stored in that database.
- **Determine and send alarms:** Typically extra sensors are used for monitoring problems in the system. Moreover, internal status computed by the LLCMS or the HLCMS may detect problems and trigger alarms. In the case of detecting a possible problem, an alarm will be triggered and the system will inform the defined roles to solve the incidence. The HMI screens are used to inform locally as well as the e-mail will inform remotely to the users.

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2. CHESS SETUP general case

This chapter describes the operation of the CHESS SETUP general case. **Figure 2.1** shows the hydraulic circuit of that general case and the main devices and actuators involved in the control and monitoring.

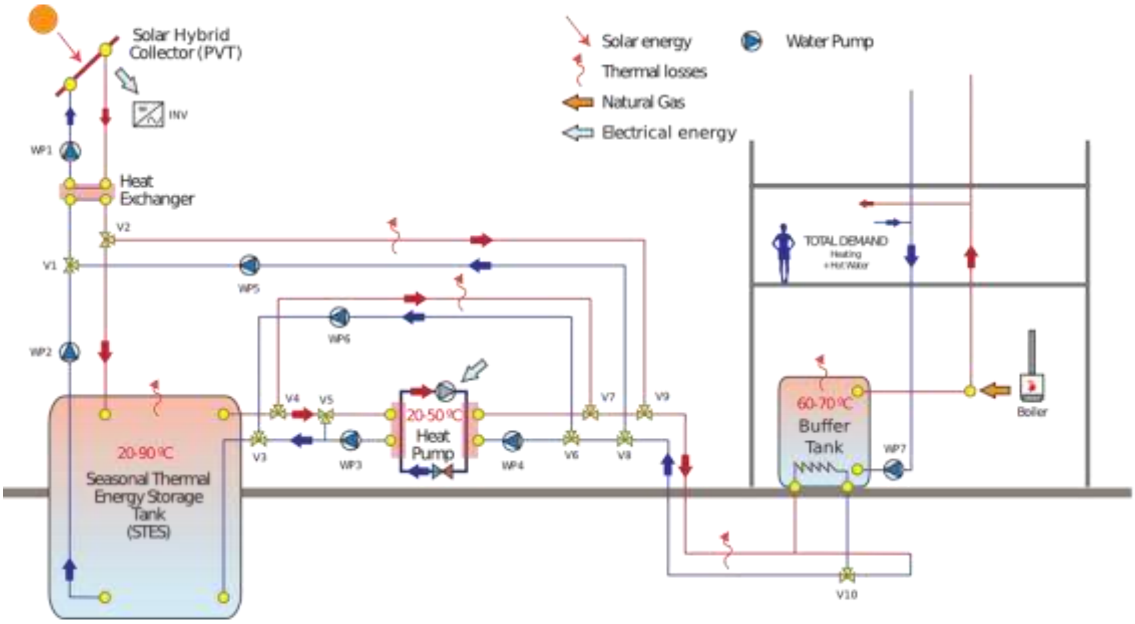

Figure 2.1 Hydraulic circuit for the CHESS SETUP general case.

<u>**Device Summary**</u>

The main devices in the systems are:

Photovoltaic Hybrid Collector (PVT): It is a set of hybrid photovoltaic and thermal panels that will produce thermal energy in form of heated water and produce electrical energy.

- **INV:** It is a solar inverter needed to convert the direct current produced by the solar panels to alternating current used in the grid.
- **STES:** Seasonal Thermal Energy Storage tank used to accumulate thermal energy generated by the solar panels.
- **Heat Pump:** The heat pump will be used to provide thermal energy to the buffer tank at high efficiencies.
- **Buffer Tank:** Energy user buffer tank that will feed the customer circuit.
- **Boiler:** It the case that the water temperature of the buffer tank is not high enough, the boiler provides the needed energy for raising this temperature. This device typically uses a non-renewable energy source such as Diesel or Natural Gas.

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- **Heat Exchanger:** Passive device to exchange heat from a primary circuit to a secondary circuit that are typically used to avoid mixing liquids. In the case shown in **Figure 2.1** is to avoid mixing glycol in the primary circuit with the water in the secondary. The inclusion of this element may not always be necessary.

Actuator Summary

The main actuators of the system are:

- **WPi:** Water pumps used to move energy in the form of hot water within subsystems.
- **Vi:** The control system will have a set of 3-way motorized valves to decide, depending on certain input conditions, where the energy in form of a hot water flow is delivered to. Some of the valves are binary, therefore the water is driven from a source pipe to two possible destinations and, in some cases these valves are regulated and divide an input flow to two different outputs in a certain proportion.

2.1. System operation overview

The control and monitoring divides the task into two main parts: the production plus distribution and the customer. The control is more focused into the production and distribution and the customer side depends on the client needs. (See as example the District Heating and Cooling control system implemented in Olot [1] [2]).

For instance, in **Figure 2.1** what is done beyond the WP7 is not controlled by the CMS and the client is the responsible. Therefore, the CMS will only control up to the buffer tank. It will also be possible to obtain energy demands, supply and return temperatures and flow rates.

System operation description

The final customer will pull water from the buffer tank that should be at a predefined temperature, e.g. 60-65ºC. If the water is not hot enough, the boiler will increase its temperature obtaining energy by burning, for instance, Natural Gas or Diesel fuel. The CMS must be tuned in such a way that this auxiliary boiler usage is minimized.

The main goal of the control system is to maintain the client buffer tank output temperature at the set point. There are three paths for storing energy into the buffer tank:

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a) <u>Directly from the solar panels:</u> The thermal energy collected by the solar panels it is delivered directly to the buffer tank using water pumps (WP1 and WP5) and Valves (V1, V2, V6, V7, V8, V9 and V10) when possible. This path could be beneficial since it is the one that involves less energy loss and the only consumption is the electric energy used by the water pumps. Depending on the case, this option may be possible during summer, when there is more solar radiation.

b) <u>STES direct usage:</u> The thermal energy stored in the STES is delivered to the buffer tank directly using the water pumps (WP3 and WP4) and Valves (V3, V4, V6, V7 and V10) in the case that there is excess energy stored at high temperatures.

c) <u>Heat pump usage:</u> The heat pump will be used to provide thermal energy to the buffer tank at high efficiencies. To ensure a correct use, the heat pump has a maximum temperature of operation in the evaporator, therefore a mixing circuit that involving water pump WP3 and valve V5 will be used when the source temperature (STES) is too high.

d) <u>From ST/PVT to STES storage:</u> When there is still thermal energy generated in the solar thermal/hybrid panels and no demand in the customer buffer tank, this energy will be delivered to the STES using water pumps WP1, WP2 and valves V1 and V2. This path will typically happen in summer when there is more solar radiation and less thermal demand.

System optimization

Using the external information of the weather forecast and the utility grid hourly energy price forecast, the system will act in advance by accumulating more energy in the buffer tank.

Therefore, given the case of a weather forecast of a cold or cloudy day, the system will automatically raise the buffer tank set point (e.g. 10ºC) allowing the system accumulate more energy in that buffer tank. This tuning operation will only be executed under the following conditions:

- **a)** The thermal energy is delivered directly from the PVTs to the buffer tank if possible.
- **b)** The thermal energy is delivered from the STES using the heat pump when possible if the energy price is low.

This optimization can be activated or deactivated using the monitoring and control system interface. Therefore the performance of the optimization will be evaluated comparing results of when it is used and when it is not.

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2.2. System variables

This section will describe all the variables needed to control, monitor and generate alarms for the CHESS SETUP system. Each defined variable has the following properties:

a) **Type:** What type of value it carries (temperature, energy, alarm).

b) **Domain**: The domain of value do they carry: real, discrete, digital, Id...

c) **Storage criterion:** 1) Is not stored; 2) Stored on change; 3) Stored periodically (hourly, daily, etc.); 4) Both.

d) **Direction:** Input or output.

e) **Units:** A variable is typically associated to a physical magnitude with its corresponding units such as ºC, kW, kWh, etc.

f) **Resolution:** In the case of real variables the amount of decimal values required.

2.2.1. Control variables

Tables 2.1 and **2.2** show all the input and output variables needed for controlling the CHESS SETUP system. The control variables are used basically by the control system. However, they will also be registered in the database by the HLCMS since it is important for a later system evaluation. For instance, if an operator wants to evaluate why a set point temperature is not reached (e.g. in the buffet tank) using a plot of set point temperature and the real temperature. The valves and water pumps control variables could also be added to the plot in order to see if the problem is in some physical element or it is a LLCMS regulation problem.

Name	Type	Domain	Storage	Direction	Units	Resolution	Description
T1	Temperature	Real	Change	Input	ºC	1/10	Solar panel collector (PVT) temperature
T2	Temperature	Real	Change	Input	ºC	1/10	STES bottom temperature
T3	Temperature	Real	Change	Input	ºC	1/10	STES middle temperature
T4	Temperature	Real	Change	Input	ºC	1/10	STES top temperature
T5	Temperature	Real	Change	Input	ºC	1/10	Maximum input heat pump temperature
T6	Temperature	Real	Change	Input	ºC	1/10	Buffer tank input temperature
T7	Temperature	Real	Change	Input	ºC	1/10	Buffer tank bottom temperature
T8	Temperature	Real	Change	Input	ºC	1/10	Buffer tank top temperature
V1	Valve status	Digital	Change	2xInput	Open, Close		Valve status
V2	Valve status	Digital	Change	2xInput	Open, Close		Valve status
V3	Valve status	Digital	Change	2xInput	Open, Close		Valve status
V4	Valve status	Digital	Change	2xInput	Open, Close		Valve status
V6	Valve status	Digital	Change	2xInput	Open, Close		Valve status

V7	Valve status	Digital	Change	2xInput	Open, Close		Valve status
V8	Valve status	Digital	Change	2xInput	Open, Close		Valve status
V9	Valve status	Digital	Change	2xInput	Open, Close		Valve status
V10	Valve status	Digital	Change	2xInput	Open, Close		Valve status
V5	Valve position	Real	Change	Input	%	1/10	Valve open percentage
WTH.F	Id	Discrete	Change	Input			Weather forecast Id
H	Price	Real	Hourly	Input	€/MWh	1/10000	Utility grid hourly price forecast

Table 2.1 CHESS SETUP input control variables and their main properties (type, domain, storage, direction, units and resolution). Valve variables are associated to two different digital inputs one that indicates Open and the other than indicates Close and takes into account the state of not open and not closed (when the valve is not totally opened but it is also not totally closed). The status is important to trigger alarms since valves can stick.

Name	Type	Domain	Storage	Direction	Units	Resolution	Description
WP1	Water pump	Digital	Change	Output	On/Off	-	Primary PVTs water circulation
WP2	Water pump	Digital	Change	Output	On/Off	-	Secondary PVTs to STES water circulation
WP3	Water pump	Digital	Change	Output	On/Off	-	Heat pump input water circulation
WP4	Water pump	Digital	Change	Output	On/Off	-	Heat pump to buffer tank water circulation
WP5	Water pump	Digital	Change	Output	On/Off	-	Secondary PVTs to buffer tank water circulation
WP6	Water pump	Digital	Change	Output	On/Off	-	STES to buffer tank water circulation
WP7	Water pump	Digital	Change	Output	On/Off	-	Buffer tank to customer water circulation
HP.s	Heat pump	Digital	Change	Output	On/Off	-	Heat pump activation

Table 2.2 CHESS SETUP output control variables and their main properties (type, domain, storage, direction, units and resolution).

2.2.2. *Monitoring variables*

Monitoring variable are complementary data that is not used in the control but they are very important for the system evaluation. Variables such as the thermal or electric power are instantaneous absolute value readings (in kW). The energy variable (electric or thermal) is an accumulated variable that will be read periodically. The energy readings can be incremental or absolute.

Incremental Energy: If the energy variable is incremental the value of this variable is the total amount of energy between the two readings, for instance, $E_{t1} = 5$, $E_{t2} = 6$, $E_{t3} = 10$, means that between E_{t1} and E_{t2} the produced/consumed energy is 6 kWh and between E_{t2} and E_{t3} is 10 kWh.

Absolute Energy: If the energy variable is the absolute value, for instance, $E_{t1} = 5$, $E_{t2} = 11$, $E_{t3} = 21$, then the energy produced/consumed between two intervals must be

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calculated by a subtraction, therefore between E_{t1} and E_{t2}, the produced/consumed energy is $E_{t2} - E_{t1} = 11 - 5 = 6$ kWh.

The preferred reading and storage methodology for the accumulated variables is the absolute since then, for any interval, the total amount of energy can be calculated by a single subtraction.

Tables 2.3, **2.4**, **2.5**, **2.6** and **2.7** show the monitoring variables defined for the CHESS SETUP. The attributes are the same than the control variables. The attribute direction is not specified since is always Input.

Name	Type	Domain	Storage	Units	Resolution	Description
Available						
WTH.ThP	Thermal power	Real	Change	kW	1	Total available solar thermal power estimation
Production						
PVT.ThP	Thermal power	Real	Change	kW	1	Solar thermal power generated by the PVTs
HP.ThP	Thermal power	Real	Change	kW	1	Thermal power generated by the heat pump
B.ThP	Thermal power	Real	Change	kW	1	Thermal power generated by the boiler
Stored						
STES.IThP	Thermal power	Real	Change	kW	1	STES thermal input power
STES.OThP	Thermal power	Real	Change	kW	1	STES thermal output power
BT.IThP	Thermal power	Real	Change	kW	1	Buffer tank input thermal power
BT.OThP	Thermal power	Real	Change	kW	1	Buffer tank output thermal power
C.ThP	Thermal power	Real	Change	kW	1	Total thermal power delivered to the client
Losses						
D.ThPL	Thermal power	Real	Change	kW	1	Thermal power loss in the distribution network

Table 2.3 Instantaneous thermal power variables.

Name	Type	Domain	Storage	Units	Resolution	Description
Production						
PVT.ThE	Thermal energy	Real	Hourly	kWh	1	Solar thermal energy generated by the PVTs
HP.ThE	Thermal energy	Real	Hourly	kWh	1	Thermal energy generated by the heat pump
B.ThE	Thermal energy	Real	Hourly	kWh	1	Thermal energy generated by the boiler
Stored						
STES.IThE	Thermal energy	Real	Hourly	kWh	1	STES thermal input energy
STES.OThE	Thermal energy	Real	Hourly	kWh	1	STES thermal output energy
BT.IThE	Thermal energy	Real	Hourly	kWh	1	Buffer tank input thermal energy
BT.OThE	Thermal energy	Real	Hourly	kWh	1	Buffer tank output thermal energy
C.ThE	Thermal energy	Real	Hourly	kWh	1	Total thermal energy delivered to the client
Losses						

D.ThEL	Thermal energy	Real	Hourly	kWh	1	Thermal energy loss in the distribution network
STES.ThEL	Thermal energy	Real	Hourly	kWh	1	STES total energy loss
BT.ThEL	Thermal energy	Real	Hourly	kWh	1	Buffer tank energy loss

Table 2.4 Thermal energy variables.

Name	**Type**	**Domain**	**Storage**	**Units**	**Resolution**	**Description**
Available						
WTH.ElP	Electrical power	Real	Change	kW	1	Total available solar electrical power estimation
Production						
PVT.ElP	Electrical power	Real	Change	kW	1	Photovoltaic electrical power generated by the PVTs
Consumption						
HP.ElP	Electrical power	Real	Change	kW	1	Heat pump consumed electrical power
WP.ElP	Electrical power	Real	Change	kW	1	Water pumps consumed electrical power
T.ElP	Electrical power	Real	Change	kW	1	Total consumed electrical power
Grid Demand / Feed - In						
G.ElP	Electrical power	Real	Change	kW	1	PVT.ElP - T.ElP

Table 2.5 Instantaneous electrical power variables.

Name	**Type**	**Domain**	**Storage**	**Units**	**Resolution**	**Description**
Production						
PVT.ElE	Electrical energy	Real	Hourly	kWh	1	Photovoltaic electrical energy generated by the PVTs
Consumption						
HP.ElE	Electrical energy	Real	Hourly	kWh	1	Heat pump consumed electrical energy
WP.ElE	Electrical energy	Real	Hourly	kWh	1	Water pump consumed electrical energy
T.ElE	Electrical energy	Real	Hourly	kWh	1	Total consumed electrical energy
Grid Demand / Feed - In						
G.ElE	Electrical energy	Real	Hourly	kWh	1	PVT.ElE - T.ElE

Table 2.6 Electrical energy variables.

Name	**Type**	**Domain**	**Storage**	**Units**	**Resolution**	**Description**
WTH.Ot	Temperature	Real	Change	ºC	1/10	Outside temperature
HP.COP	Coefficient of performance	Real	Hourly		1/10	Heat pump performance coefficient
STES.V	Water volume	Real	Change	l	1	STES water volume
HP.HPT	Temperature	Real	Change	bar	1/10	High pressure circuit temperature

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HP.HPP	Pressure	Real	Change	ºC	1/10	High pressure circuit pressure
HP.LPT	Temperature	Real	Change	ºC	1/10	Low pressure circuit temperature
HP.LPP	Pressure	Real	Change	ºC	1/10	Low pressure circuit pressure

Table 2.7 Other monitoring variables of interest.

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2.2.3. Alarm variables

The alarm variables are related to error events that may happen during the normal control operation that will trigger alarms in the form of messages to the monitoring interface screens, via e-mail, SMS or similar. **Table 2.8** summarises the error variables that generate alarms and their attributes. These alarm variables sometimes correspond directly to sensor readings but others are calculated internally by the LLCMS or the HLCMS. Since alarm values are digital, the units and resolution attributes are not needed and the attribute of how Critical they are will be added.

Name	Type	Domain	Storage	Critical	Description
Low Level Control and Monitoring					
V1.Al	Valve error	Digital	Change	Yes	Valve positioning error
V2.Al	Valve error	Digital	Change	Yes	Valve positioning error
V3.Al	Valve error	Digital	Change	Yes	Valve positioning error
V4.Al	Valve error	Digital	Change	Yes	Valve positioning error
V6.Al	Valve error	Digital	Change	Yes	Valve positioning error
V7.Al	Valve error	Digital	Change	Yes	Valve positioning error
V8.Al	Valve error	Digital	Change	Yes	Valve positioning error
V9.Al	Valve error	Digital	Change	Yes	Valve positioning error
V10.Al	Valve error	Digital	Change	Yes	Valve positioning error
T1.Al	Temperature error	Digital	Change	Yes	Temperature read error
T2.Al	Temperature error	Digital	Change	Yes	Temperature read error
T3.Al	Temperature error	Digital	Change	Yes	Temperature read error
T4.Al	Temperature error	Digital	Change	Yes	Temperature read error
T5.Al	Temperature error	Digital	Change	Yes	Temperature read error
T6.Al	Temperature error	Digital	Change	Yes	Temperature read error
T7.Al	Temperature error	Digital	Change	Yes	Temperature read error
T8.Al	Temperature error	Digital	Change	Yes	Temperature read error
WP1.Al	Pump error	Digital	Change	Yes	Water pump is not working (high temperature in PVTs)
WP2.Al	Pump error	Digital	Change	No	Water pump is not working
WP3.Al	Pump error	Digital	Change	No	Water pump is not working
WP4.Al	Pump error	Digital	Change	No	Water pump is not working
WP5.Al	Pump error	Digital	Change	No	Water pump is not working
WP6.Al	Pump error	Digital	Change	No	Water pump is not working
WP7.Al	Pump error	Digital	Change	Yes	Water pump is not working (client delivery problem)
PVT.Al	High temperature	Condition	Change	Yes	Solar panel temperature too high
FL1.Al	Flow	Condition	Change	Yes	No flow in PVT primary circuit
FL2.Al	Flow	Condition	Change	Yes	No flow in PVT secondary circuit
HP.Al	Error	Digital	Change	Yes	Heat pump error/alarm

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B.Al	Error	Digital	Change	Yes	Boiler error/alarm
High Level Control and Monitoring					
H.Al	Error	Condition	Change	No	Utility grid energy prices are can not be loaded
WTH.Al	Error	Condition	Change	No	Error obtaining weather forecast

Table 2.8 CHESS SETUP error variables that trigger alarms. Alarms that are Digital come directly from sensors and those defined as Condition are calculated by the CMS. The Critical alarms indicate that the system cannot operate.

2.2.4. Modes and set points

As practically any air-conditioning system, the CMS will operate in two modes (summer and winter) and will provide a set of parameters, basically set points that will be tuned by the users and operators of the system.

Working Modes

Two different working modes will be defined: winter and summer which will be commuted automatically by using the current date. The operator will be allowed to change it manually. Depending on the current working mode the CMS will adapt its behaviour. For instance:

a) Subset of weather forecast Ids used for considering “bad weather” could be different in winter or in summer.

b) The default set points for the two periods are different.

Set Points

The CMS will allow the operator user of the system to define set points to tune the system operation. These different set point definitions will depend on the type of regulation executed on the final actuators (see chapter 2.6). Two main types of regulations will be executed depending on whether the final device is controlled digitally or analogically.

The set points are considered as variables in terms of storage. Therefore, they will also be stored by the HLCMS in the databases logs, typically when they are changed.

<u>Set Point for a Proportional Integral Derivative (PID) regulation:</u> This type of regulation only needs a single value as a set point, for instance, a temperature. This mode will be used to regulate, for instance, the input water temperature delivered to the heat pump from the STES in order to maintain an optimal predefined working temperature in the evaporator of the heat pump. This regulation will be done over the valve V5. Another PID regulation might be needed over the water pump WP1 in the case a constant temperature extracted from the PVT is required.

Set points for a 2-Point regulation: When this type of regulation is used, the set point is a set of two or three values. For user usability, this set point is defined in two different ways:

a) Set point for a Temperature: It is defined as a tuple of values (To, T1) where To >= T1.

b) Set point for a differential Temperature: It is defined as a value plus an offset. For usability, the offset is typically fixed (in the system) and the value is defined by the user operator. For instance, given a set point T for a temperature, an offset O is predefined so that, the final set point will be the interval (T-O, T+O). The user may define T but O is usually fixed in the system. As an example, for the set point of temperature of the buffer tank. The user can set the set point T = 65ºC and the internal offset is 5ºC, therefore, O = [-5, 5]ºC. Then, the set point for the buffer tank is T + O = 65ºC + [-5, +5]ºC = [65-5, 65+5]ºC = [60, 70]ºC. In some cases the offset may be asymmetric, for instance O=[-5, 3]ºC.

Figure 2.2 illustrates how it is done the comparison of a variable value V to a 2-point set point (T_0, T_1). When the comparison is enabled by E and value V reaches T_1 then the result of the 2-point comparison R is 1. If the value V falls below T_0 then R is 0.

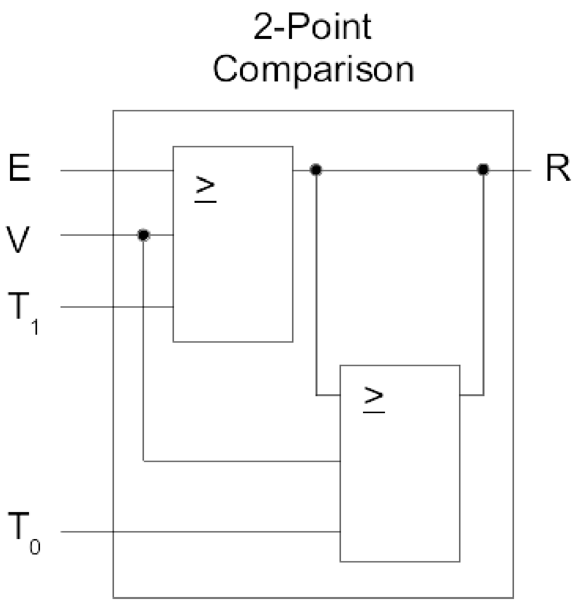

Figure 2.2 When the 2-point comparison is enabled by setting E = 1, then, if the variable V reaches T_1, the output of the comparison R is 1 while V is maintained above of T_0.

Table 2.9 summarizes the set points defined for the CHESS SETUP as well as their main properties:

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a) **Type:** What type of value it carries (temperature, energy, alarm,).

b) **Domain**: The domain of value they carry: real, discrete, digital, Id, ...

c) **Regulation:** 2-Point or PID.

d) **Fixed:** It is fixed/predefined or is varied by the CMS.

e) **Storage Criterion:** 1)Is not stored; 2) Stored on change; 3) Stored periodically (Hourly, Daily, ...); 4) Both.

f) **Units:** A set point is typically associated to a physical magnitude with units such as ºC, kW, kWh, ...

g) **Resolution:** In the case of real variables the amount of decimal values required.

Name	Type	Domain	Regulation	Fixed	Storage	Units	Resolution	Description
Client								
B.ST	Temperature	Real	-	Yes	Change	ºC	1/10	Boiler temperature set point (60-70º)
Production								
PVT.Ts	Temperature	Real	2-Point	Yes	Change	ºC	1/10	PVTs Temperature to control WP1
PVT.Tm	Temperature	Real	-	Yes	Change	ºC	1/10	PVTs Maximum temperature (Alarm)
Buffer tank								
BT.Ts	Temperature	Real	2-Point	No	Change	ºC	1/10	Buffer tank temperature set point
BT.dTi	Temperature	Real	2-Point	No	Change	ºC	1/10	Buffer tank feed-in diff. temp. (BT bottom - input)
PVT.dTBT	Temperature	Real	2-Point	Yes	Change	ºC	1/10	Differential temp. between PVTs and buffer tank
Heat pump								
HP.Ti	Temperature	Real	PID	No	Change	ºC	1/10	Input temp. to the heat pump to regulate the mixer
HP.To	Temperature	Real	-	No	Change	ºC	1/10	Output temperature set point for the heat pump
STES								
STES.dTPVT	Temperature	Real	2-Point	No	Change	ºC	1/10	Differential temp. between PVTs and STES
External values								
EP	€	Real	-	No	Change	ºC	1/10000	Below this price, electrical energy is cheap
WF	Id	Set	-	No	Change			Set of weather forecast Ids for bad weather

Table 2.9 CHESS SETUP set points. Those where Fixed is No are the ones that will be varied depending on the working mode (summer/winter).

2.2.5. External information

There are two input data that will be obtained from external sources: the weather forecast and the utility grid hourly energy price.

Wheather Forecast: This variable can be obtained from a professional weather station such as Davis Vantage Pro 2[2]. In that case, the reading of this variable is less critical since it will be located more locally. In the case that a professional weather station is not used, the forecast can also be obtained from the Internet sources[3]. **Table 2.10** shows the Davis Vantage Pro 2 forecasts defined by Ids or Icons:

Id	Forecast
1	Mostly Clear
2	Partially Cloudy
3	Mostly Cloudy
4	Partially Cloudy (rain within 12 hours)
5	Partially Cloudy (snow within 12 hours)
6	Partially Cloudy (rain or swno within 12 hours)
7	Mostly Cloudy (rain within 12 hours)
8	Mostly Cloudy (snow within 12 hous)
9	Mostly Cloudy (rain or snow within 12 hours)

Table 2.10 Forecast Ids for a Davis Vantage Pro 2.

The subset (5, 8 and 9) could be used in summer and the subset (4, 5, 6, 7, 8 and 9) could be used in winter as the "bad weather" forecast.

Utility Grid Hourly Energy Price: This variable must be obtained from Internet[4] typically in the form of plain text files or Excel tables. The HLCMS will obtain, parse and store this information in the local database to be used by the LLCMS.

Table 2.11 shows an example of the utility grid hourly energy price for the Spanish PVPC tariff during the December of 2016.

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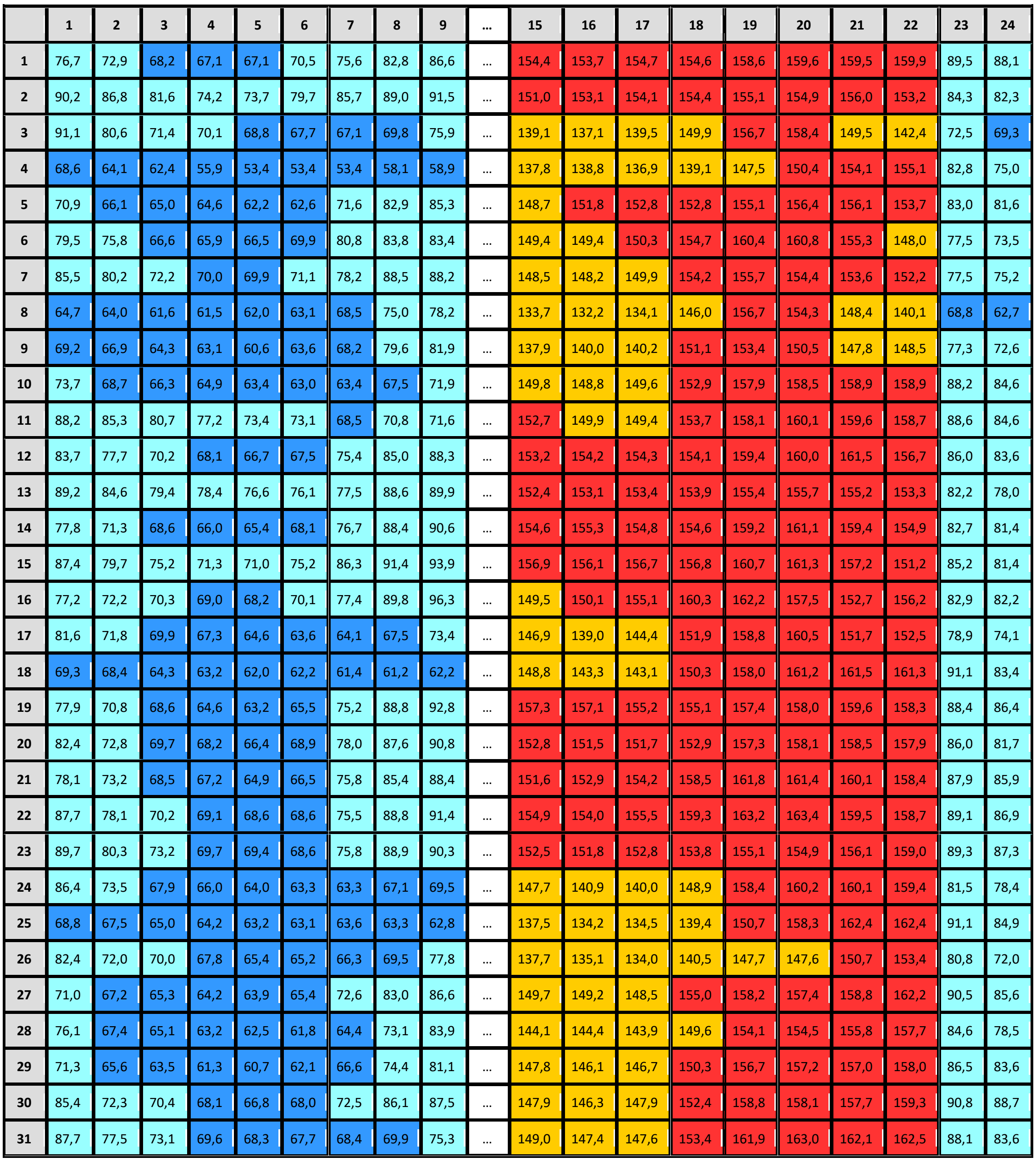
[2] http://www.davisnet.com/solution/vantage-pro2/

[3] http://www.weather-forecast.com/

[4] In Spain: http://www.ree.es and http://www.omie.es



	1	2	3	4	5	6	7	8	9	...	15	16	17	18	19	20	21	22	23	24
1	76,7	72,9	68,2	67,1	67,1	70,5	75,6	82,8	86,6	...	154,4	153,7	154,7	154,6	158,6	159,6	159,5	159,9	89,5	88,1
2	90,2	86,8	81,6	74,2	73,7	79,7	85,7	89,0	91,5	...	151,0	153,1	154,1	154,4	155,1	154,9	156,0	153,2	84,3	82,3
3	91,1	80,6	71,4	70,1	68,8	67,7	67,1	69,8	75,9	...	139,1	137,1	139,5	149,9	156,7	158,4	149,5	142,4	72,5	69,3
4	68,6	64,1	62,4	55,9	53,4	53,4	53,4	58,1	58,9	...	137,8	138,8	136,9	139,1	147,5	150,4	154,1	155,1	82,8	75,0
5	70,9	66,1	65,0	64,6	62,2	62,6	71,6	82,9	85,3	...	148,7	151,8	152,8	152,8	155,1	156,4	156,1	153,7	83,0	81,6
6	79,5	75,8	66,6	65,9	66,5	69,9	80,8	83,8	83,4	...	149,4	149,4	150,3	154,7	160,4	160,8	155,3	148,0	77,5	73,5
7	85,5	80,2	72,2	70,0	69,9	71,1	78,2	88,5	88,2	...	148,5	148,2	149,9	154,2	155,7	154,4	153,6	152,2	77,5	75,2
8	64,7	64,0	61,6	61,5	62,0	63,1	68,5	75,0	78,2	...	133,7	132,2	134,1	146,0	156,7	154,3	148,4	140,1	68,8	62,7
9	69,2	66,9	64,3	63,1	60,6	63,6	68,2	79,6	81,9	...	137,9	140,0	140,2	151,1	153,4	150,5	147,8	148,5	77,3	72,6
10	73,7	68,7	66,3	64,9	63,4	63,0	63,4	67,5	71,9	...	149,8	148,8	149,6	152,9	157,9	158,5	158,9	158,9	88,2	84,6
11	88,2	85,3	80,7	77,2	73,4	73,1	68,5	70,8	71,6	...	152,7	149,9	149,4	153,7	158,1	160,1	159,6	158,7	88,6	84,6
12	83,7	77,7	70,2	68,1	66,7	67,5	75,4	85,0	88,3	...	153,2	154,2	154,3	154,1	159,4	160,0	161,5	156,7	86,0	83,6
13	89,2	84,6	79,4	78,4	76,6	76,1	77,5	88,6	89,9	...	152,4	153,1	153,4	153,9	155,4	155,7	155,2	153,3	82,2	78,0
14	77,8	71,3	68,6	66,0	65,4	68,1	76,7	88,4	90,6	...	154,6	155,3	154,8	154,6	159,2	161,1	159,4	154,9	82,7	81,4
15	87,4	79,7	75,2	71,3	71,0	75,2	86,3	91,4	93,9	...	156,9	156,1	156,7	156,8	160,7	161,3	157,2	151,2	85,2	81,4
16	77,2	72,2	70,3	69,0	68,2	70,1	77,4	89,8	96,3	...	149,5	150,1	155,1	160,3	162,2	157,5	152,7	156,2	82,9	82,2
17	81,6	71,8	69,9	67,3	64,6	63,6	64,1	67,5	73,4	...	146,9	139,0	144,4	151,9	158,8	160,5	151,7	152,5	78,9	74,1
18	69,3	68,4	64,3	63,2	62,0	62,2	61,4	61,2	62,2	...	148,8	143,3	143,1	150,3	158,0	161,2	161,5	161,3	91,1	83,4
19	77,9	70,8	68,6	64,6	63,2	65,5	75,2	88,8	92,8	...	157,3	157,1	155,2	155,1	157,4	158,0	159,6	158,3	88,4	86,4
20	82,4	72,8	69,7	68,2	66,4	68,9	78,0	87,6	90,8	...	152,8	151,5	151,7	152,9	157,3	158,1	158,5	157,9	86,0	81,7
21	78,1	73,2	68,5	67,2	64,9	66,5	75,8	85,4	88,4	...	151,6	152,9	154,2	158,5	161,8	161,4	160,1	158,4	87,9	85,9
22	87,7	78,1	70,2	69,1	68,6	68,6	75,5	88,8	91,4	...	154,9	154,0	155,5	159,3	163,2	163,4	159,5	158,7	89,1	86,9
23	89,7	80,3	73,2	69,7	69,4	68,6	75,8	88,9	90,3	...	152,5	151,8	152,8	153,8	155,1	154,9	156,1	159,0	89,3	87,3
24	86,4	73,5	67,9	66,0	64,0	63,3	63,3	67,1	69,5	...	147,7	140,9	140,0	148,9	158,4	160,2	160,1	159,4	81,5	78,4
25	68,8	67,5	65,0	64,2	63,2	63,1	63,6	63,3	62,8	...	137,5	134,2	134,5	139,4	150,7	158,3	162,4	162,4	91,1	84,9
26	82,4	72,0	70,0	67,8	65,4	65,2	66,3	69,5	77,8	...	137,7	135,1	134,0	140,5	147,7	147,6	150,7	153,4	80,8	72,0
27	71,0	67,2	65,3	64,2	63,9	65,4	72,6	83,0	86,6	...	149,7	149,2	148,5	155,0	158,2	157,4	158,8	162,2	90,5	85,6
28	76,1	67,4	65,1	63,2	62,5	61,8	64,4	73,1	83,9	...	144,1	144,4	143,9	149,6	154,1	154,5	155,8	157,7	84,6	78,5
29	71,3	65,6	63,5	61,3	60,7	62,1	66,6	74,4	81,1	...	147,8	146,1	146,7	150,3	156,7	157,2	157,0	158,0	86,5	83,6
30	85,4	72,3	70,4	68,1	66,8	68,0	72,5	86,1	87,5	...	147,9	146,3	147,9	152,4	158,8	158,1	157,7	159,3	90,8	88,7
31	87,7	77,5	73,1	69,6	68,3	67,7	68,4	69,9	75,3	...	149,0	147,4	147,6	153,4	161,9	163,0	162,1	162,5	88,1	83,6

Table 2.11 Sample table containing the utility grid hourly energy price in €/MWh for the Spanish PVPC tariff. The hour of the day is represented in columns, while the 31 days of December 2016 are shown in rows. Cyan cells are those with price lower than 70€/MW, blue cells are prices between 70 and 120 €/MW, in orange prices between 120 and 150€/MW and, in red, prices higher than 150€/MW.

The reliability of obtaining external data is lower than using local information from sensors, the usage of a professional weather station is preferred and might be more accurate than using Internet sources. In the case of the utility grid hourly energy price or the weather forecast being obtained from Internet, a default behaviour will be predefined in the case of a read failure.

Default behaviour in case of read failures

Weather Forecast: Use current weather if available or do not use any forecast.

Utility grid hourly energy price: Use a fixed table estimated by averaging the energy price for every hour during the previous days. Use the fixed price discrimination table typically used in fixed price tariffs.

2.3. Physical magnitudes and measurements

In order to obtain the variables defined in the previous section for controlling and monitoring the system, physical magnitudes must be measured as well as some external data has to be gathered. Moreover, there are variables that will be extracted directly from the measured physical magnitudes and others must be calculated combining different readings. This section describes the physical magnitudes that need to be obtained to compute the variables defined in **section 2.2**. for executing the control system defined in **section 2.7**.

These main physical magnitudes are: temperatures, water flows, pressures, powers and energies.

2.4. Sensors

The set of different sensors installed in the CHESS SETUP must provide the variables defined in **section 2.2** by measuring physical magnitudes. The main sensors installed are shown in **Figure 2.3**.

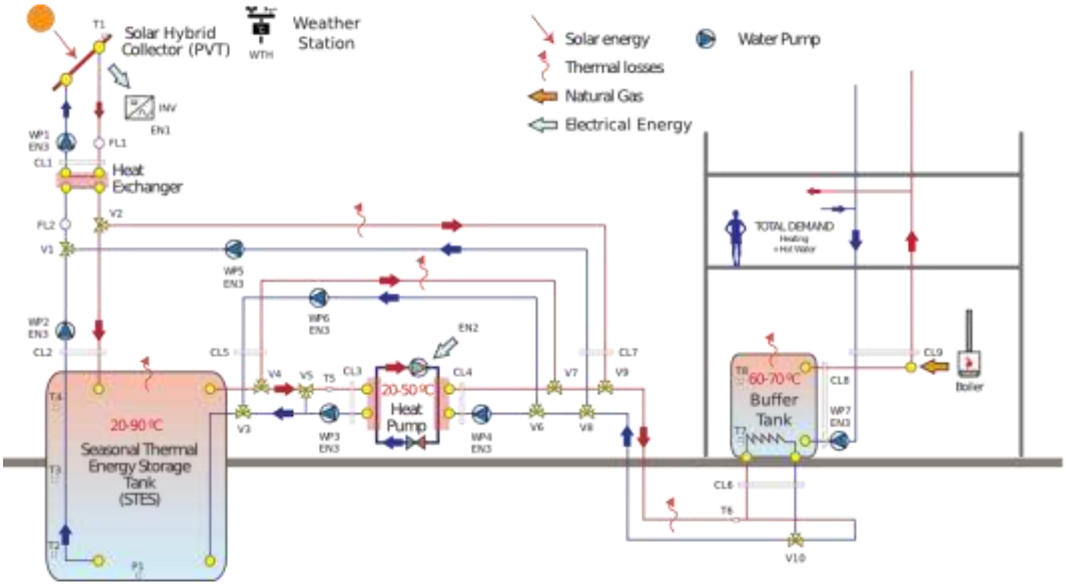


Figure 2.3 Sensor placement and types for the CHESS SETUP. The name CLi stands for calorimeter, Ti temperature probe, ENi for an electrical power-meter, Pi pressure sensors, FLi are flow-meters and WTH a weather station.

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Table 2.12 summarises the sensors, their measurements shown in **Figure 2.3** and the type of communication to the CMS.

Name	Description	Physical Magnitudes	Other	I/O or Protocol
EN$_i$	Electrical power-meter	Electric Power, energy, voltage, intensity, ...		ModBus TCP
CL$_i$	Calorimeter	Thermal power and energy, flow, flow and return temperature	Alarm	M-Bus
T$_i$	Temperature	Temperature		Direct I/O
P$_i$	Pressure	Pressure		Direct I/O
FL$_i$	Flow-meter	Flow		Direct I/O
WTH	Weather Station	Solar radiation, Outside temperature, Weather forecast		Serial I/O

Table 2.12 Summary of sensors installed in the CHESS SETUP and the physical magnitudes read.

2.4.1. Control sensors

This set of sensors must be the most reliable and will be connected as simple as possible to the LLCMS and will provide the control variables defined in **section 2.2.1.**

Temperature sensors

One of the fundamental variables to use is the temperature since most of the low level control will be based on this variable. Variable temperatures T$_1$ to T$_8$ will be obtained by the corresponding temperature sensors T$_1$, to T$_8$. The sensors will be 3-wire PT1000 RTD (Resistance Temperature Detectors) such as the manufactured by Osaka[5], IFM or similar. The RTD PT1000 sensors are very linear and reliable. The 3rd wire is used to compensate the resistance of the cable, although the distance is limited to few meters (~20m with 0.5mm^2 section cable) anyway. Most of the controllers have modules available for executing the RTD sensor 3-wire readings. The resolution depends basically on the controller I/O module but typically is ºC/10 or better.

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[5] http://osakasolutions.com/productos-equipos-electronicos/sondas-transductores/sonda-temperatura-pt100/

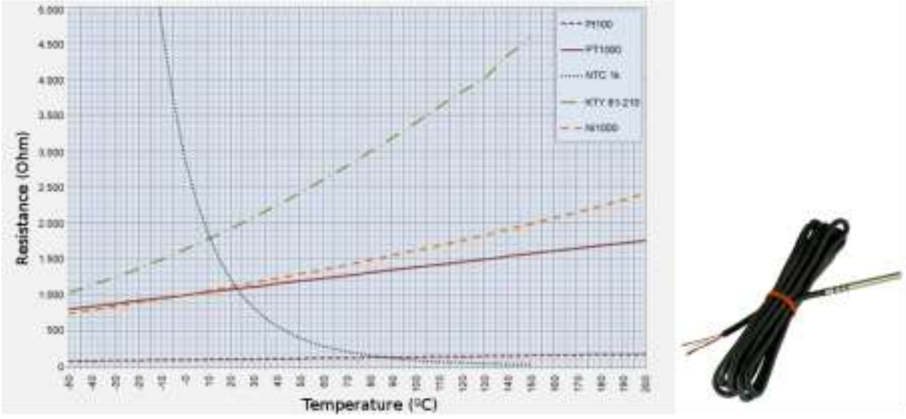

Figure 2.4 The left plot shows the linearity of different temperature sensors (PT, NTC and KTY). PT100 and PT1000 are the most linear. The only difference between the two is that the 0ºC is at 100Ω and1000Ω, respectively. PT1000 is more suited for larger distances since the resistance of the error of the cable resistance affects less than in the case of a PT1000. The left picture shows a commercial 3-wire PT1000 sensor.

The RTD sensors are not submersible. Commercial water tanks (the buffer tank) have pre-installed pods to install the temperature probes. However, in the case of the STES, it has to be taken into account the installation of submersible temperature probes using pods or torpedoes.

<u>**Valve status sensors:**</u>

This set of control sensors are pre-installed in the respective valve actuators. There is two types of sensors depending on the type of regulation done over the actuator:

<u>**Digital valves:**</u>

The 3-way motorized valves (V1, V2, V3, V4, V6, V7, V8, V9 and V10) will be commercial valves such as Belimo PRCA-S2-T which already have two built-in 220V input signals for positioning and two output potential free digital signals that indicate opened and closed.

<u>**Analogical Valves:**</u>

The 3-way motorized valve V5 will be a commercial valve such as a Belimo EV24A-SZ-TPC which already has a built-in analogical 0-10V input signal to indicate the percentage of positioning of the valve and an analogical output 0-10V signal which indicates the degree of positioning of the valve.

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Figure 2.5 The left image corresponds to a Belimo PRCA-S2-T 3-way motorized valve with the digital input and output control signals. The right picture corresponds to a Belimo EV24A-SZ-TPC with the analogical input and output control signals.

Considerations in the temperature readings

The temperatures read by sensors placed in water flows (e.g. T1, T5, T6 and CL_i) only provide the right reading when there is water flow in the tube, therefore, in that cases, the acquisition algorithm for the temperature reading has to take into account to start the respective water pumps during a preconfigured certain amount of time before considering the temperature reading.

2.4.2. Monitoring sensors

The monitoring sensors are basically for providing additional information to the users and operators of the systems as well as for the later system evaluation. Sometimes are also used as redundant sensors for the control in the case of a failure of a control sensor.

This set of sensors is not as critical as the control sensors set, therefore are connected using gateways and communicated using high level protocols because, typically, they are multi-meters (i.e. power-meters and calorimeters)

a) Thermal energy measurement

The thermal power and energy is measured using calorimeters. These type of sensors are multi-meters that measure water flow and temperature in order to calculate the energy power that circulates through the tube section. They also integrate the calculated power to compute the energy.

The thermal power and energy will be measured by calorimeters such as Kamstrup Multical 602 or similar. The Kamstrup Multical 602 are very precise sensors that use PT100 or PT500 sensors to measure temperature and an ultrasonic sensor for

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measuring the water flow. They satisfy the MID (Measuring Instruments Directive) European directive.

Kamstrup Multical 602

Flow : 0,6 .. 15 m^3/h [kWh]
0,6 .. 1500 m^3/h [MWh]
0,6 .. 3000 m^3/h [GWh]

Temperature sensor 602-A : PT100 2-wire (2x0.25mm^2 2.5m; 2x0.5mm^2 5m), 602-C: PT500 2-wire (2x0.25mm^2 5m, 2x0.5mm^2 10m) or 602-B, 602-D: PT500 4-wire (2x0.5mm^2 20m; 2x0.5mm^2 100m)

Temperature range : $\theta = 2^{\circ}C .. 180^{\circ}C$

Temperature differential : $\Delta\Theta = 3^{\circ}K .. 170^{\circ}K$

Accuracy : $Ec \pm (0.5 + \Delta\Theta min / \Delta\Theta)\% \rightarrow \pm(0.5 + 3/170) .. \pm(0.5 + 3/3)$
$= \pm(0.5176 .. 1.5)\%$

Interfaces : M-Bus, Ethernet/IP, Wireless M-Bus

Figure 2.6 Kamstrup multical 602 calorimeter.

b) Electrical energy measurement

The electrical power and energy is typically provided by an electrical power-meter. These devices measure voltage and intensity at a high frequency (e.g. ~1000Hz) to compute power and to integrate energy. Other measurements such as the cos(ϕ) or the harmonics are also provided. While voltage is measured directly from the line, the intensity is acquired by the power-meter using current transformers which provide a scaled version of the intensity. For instance, the N/5 Current Transformers (CT) provide the intensity scaled to 0-5A. This means that a CT 100/5 provides the scaled intensity to

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0-5A in the secondary of the CT with respect to the 0-100A in the primary. The user has to configure the type of current transformers used.

There are different intensity measurements standards such as N/5A N/1A, N/250mA, N/333mV. Depending on the precision and the wiring distance one standard or another is preferred. For instance, the N/333mV has less limitations the wiring distances than a N/5A.

An electrical power-meter such as Circutor CVM-Mini or similar will provide all electrical parameters (power, energy, voltage, intensity, …)

This power-meter is Class 0,5 for Intensity and Voltage and has a ModBus/TCP interface to the CMS. Class 0,5 means that measurement errors are bounded to the 0,5%.

Figure 2.7 Left image is a Circutor CVM-Mini N/5A power-meter. The right image corresponds to a set of 3 current transformers 100/5A.

c) Outside temperature

The outside temperature will be provided by the weather station. A professional weather station such as Davis Vantage Pro2 has a temperature sensor with the following technical parameters:

Resolution	: 0.1ºC
Range	: -40 ..65ºC
Accuracy	: ± 0.3ºC

d) Solar radiation

The solar radiation is also provided by the weather station and will serve to estimate the available thermal and electrical power from the sun.

Resolution	: 1 W/m²
Range	: 0 .. 1800 W/m²
Accuracy	: ±5%
Temp. Coeff	: -0.12% per ºC (Ref Temp. 25ºC)

This project has received funding from the European Union's Horizon 2020 Research and Innovation Programme under Grant Agreement No 680556.

e) Pressure sensor

A pressure sensor will be used to estimate the water volume inside the STES tank (considering the STES is at atmospheric pressure). If the STES tank is emptied this sensor the system will estimate the remaining water volume inside the tank. The pressure sensors such as the Disibeint TPSP-22 or similar are pre-calibrated for a maximum water column height and produce an output signal 0-10V proportional to the current column of water. The control system will scale the reading to obtain the current column height in meters and the multiply by the STES surface to obtain the current volume of water.

Variable calculation

The following **Tables 2.13** to **2.17** describe how to calculate every variable defined in **section 2.2.2** using the sensors described in this **section 2.4.2**.

Variable Name	Sensors
Available	
WTH.ThP	WTH.SolarRadiation * ρ
Production	
PVT.ThP	CL1.ThermalPower
HP.ThP	(CL4 - CL3).ThermalPower
B.ThP	(CL9 - CL8).ThermalPower
Storage	
STES.IThP	CL2.ThermalPower
STES.OThP	(CL3 + CL5).ThermalPower
BT.IThP	CL6.ThermalPower
BT.OThP	CL8.ThermalPower
C.ThP	CL9.ThermalPower
Losses	
D.ThPL	((CL1 - (CL2 + CL7)) + ((CL4 + CL5 + CL7) - CL6)).ThermalPower

Table 2.13 Thermal power variable calculation using instantaneous thermal power reads from calorimeter sensors and solar radiation sensors. The constant ρ will be estimated by the PVTs thermal performance.

Variable Name	Sensors
Production	
PVT.ThE	CL1.ThermalEnergy
HP.ThE	(CL4 - CL3).ThermalEnergy
B.ThE	(CL9 - CL8).ThermalEnergy
Storage	

STES.IThE	CL2.ThermalEnergy
STES.OThE	(CL3 + CL5).ThermalEnergy
BT.IThE	CL6.ThermalEnergy
BT.OThE	CL8.ThermalEnergy
C.ThE	CL9.ThermalEnergy
Losses	
D.ThEL	((CL1 - (CL2 + CL7)) + ((CL4 + CL5 + CL7) - CL6)).ThermalEnergy
STES.ThEL	(CL5 - CL2).ThermalEnergy
BT.ThEL	(CL8 - CL6).ThemalEnergy

Table 2.14 Thermal energy variable calculation using energy reads from calorimeter sensors.

Variable Name	Sensors
Available	
WTH.ElP	WTH.SolarRadiation * ε
Production	
PVT.ElP	EN1.ElectricalPower
Consumption	
HP.ElP	EN2.ElectricalPower
WP.ElP	EN3.ElectricalPower
T.ElP	(EN2 + EN3).ElectricalPower
Grid Demand / Feed - In	
G.ElP	PVT.ElP - T.ElP

Table 2.15 Electrical power variable calculations using instantaneous electrical power reads from power-meter sensors and solar radiation sensors. The constant ε will be estimated by the PVTs electrical performance.

Variable Name	Sensors
Production	
PVT.ElE	EN1.ElectricalEnergy
Consumption	
HP.ElE	EN2.ElectricalEnergy
WP.ElE	EN3.ElectricalEnergy
T.ElE	(EN2 + EN3).ElectricalEnergy
Grid Demand / Feed - In	
G.ElE	PVT.ElE - T.ElE

Table 2.16 Electrical energy variable calculation using energy reads from power-meter sensors.

Variable Name	Sensors
WTH.Ot	WTH.OutsideTemperature
HP.COP	(CL4 - CL3).ThermalEnergy / EN2.ElectricalEnergy
STES.V	P1 [m] * STES.Surface [m²] * 1000

Table 2.17 Other complementary variable calculations.

Analogical variable reads

The analogical variable reads will be done using 0-10V LLCMS inputs. However, for larger distances a conversion to 4-20mA using converters such as the Weidmuller MAS DC/DC select might be needed.

2.4.3. Alarm sensors

This section describes the sensors that generate the variable alarms defined in **section 2.2.3** that, eventually, trigger the alarms. Most of the alarms are directly generated by sensors but others will be internal checks computed by the CMS. The most important alarms are those related to water pumps, valves and temperatures.

Direct-sensor generated alarms

Water pumps

The water pump alarms variables WP1.Al, WP2.Al, WP3.Al, WP4.Al, WP5.Al, WP6.Al, WP7.Al will be physically generated by a digital chamber attached to the MCB (Mini Circuit Breaker) and to the RCD (Residual Current Device) installed for each water pump. If there is a short circuit in the water pump or the water pump sticks, the MCD or the RCD will trigger the digital chambers that are serialized to a single input in the LLCMS.

Flow meters

The flow meters FL1, FL2 will provide a digital input each to the LLCMS informing whether there is flow in the pipes or not. If water pumps WP1 is on and there is no water flow in FL1 an alarm will be released. If water pump WP2 or WP5 is working and there is no flow in FL2 an alarm must be triggered. These alarms correspond to the variables FL1.Al and FL2.Al and inform that there is no way of extracting heat from the solar panels.

Calorimeters

The commercial calorimeters such as the Kamstrup Multical 602 provide alarms during malfunctions of the device, for instance, air detected in the water circuit. These calorimeters provide the alarms using high level protocols such as M-Bus.

Boilers (auxiliary heating device) and heat pump alarms

Boilers and heat pumps usually have digital outputs than inform that the device has some problem and it is not working. These alarms correspond to variables HP.Al and B.Al and will be wired to digital inputs of the LLCMS.

Software generated alarms

Valve alarms

Motorized 3-way valves such as Belimo PRCA-S2-T or similar, do not have alarm signals themselves; however, using the controller software, alarms of device malfunction will be generated. If the system is moving a valve to one of the two directions (open/close) and after a prudential amount of time the valve signal of open/close is not triggered this means there is a problem in the valve, e.g., the valve is stuck. These alarms correspond to the variables V1.Al, V2.Al, V3.Al, V4.Al, V6.Al, V7.Al, V8.Al, V9.Al and V10.Al.

Temperature alarms

The T1, to T8 RTD temperature sensors will be connected directly to the controller. In the case of a short-circuit or an open circuit in the RTD sensor the reading of the controller will produce a value out of the normal range. In the case this event occurs, a temperature sensor error will be released. These alarms correspond to variables T1.Al, to T8.Al.

If the temperature T1 is too high (out of a predefined software set point) an alarm of temperature too high (PVT.Al) will be triggered.

High level alarms

A failure in the communication to the weather station or in the acquiring of the utility grid hourly energy price will trigger an alarm, however, in that case it is not as critical as the alarms defined above since there will be a default CMS behaviour under that circumstance. These alarms correspond to variables H.Al and WTH.Al, respectively.

2.5. Actuators

The actuators of the CHESS SETUP system will be the water pumps, the valves, the heat pump and the auxiliary heating system (Boiler).

The water pumps are digitally controlled except WP1 that could be regulated by a PID.

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Digital water pumps

The digital signals from the CMS for starting and stopping the water pumps will be connected to a relay that will switch on/off the water pump. In the case of a powerful water pumps the relay will activate a contactor.

PID-regulated water pumps

Water pump WP1 could be regulated digitally using a 2-point controller or using a PID that will try to keep a PVTs output temperature to a set point. In the case it is regulated using a PID an output analogical signal 0-10V will be used.

Heat pump

Typically heat pumps are controlled by a LLCMS digital output to start/stop them. Sometimes commercial heat pumps such as NIBE F1255 also provide a ModBus TCP interfaces. However, to start/stop the direct I/O is preferred.

Auxiliary heating (Boiler):

Boilers have typically the same interfaces than heat pumps.

3-Way motorized flip-flop valves

These valves are managed by using two digital outputs that will activate two relays which will deliver the 220V to the two input valve directions.

3-Way motorized proportional valves:

The valve V5 will be regulated by an analogical output 0-10V.

Table 2.18 shows the actuator summary and the input/output signals connected to them.

Actuator Name	Input Signals	Input Type	Output Signals	Output Type
WPi	Alarm	Digital	Start/Stop	Digital
V1, V2, V3, V4, V6, V7, V8, V9, V10	Opened	Digital	Open	Digital
	Closed	Digital	Close	Digital
V5	Position	Analogical (0-10V)	Position	Analogical (0-10V)
HP	Alarm	Digital	Start/Stop	Digital
	Status	ModBus TCP	Output Temperature	ModBus TCP
Boiler	Alarm	Digital	Start/Stop	Digital

Table 2.18 Actuator summary and their input/output signals and the type of communication to the CMS.

2.6. Control signals

Two types of output control signals will be used by the CMS to regulate the CHESS SETUP actuators:

2-Point regulation

This type of regulation is performed using a digital output. A set point plus an offset that could be asymmetric defines an interval ST=[T+Ou, T-Od] (see section 2.2.4.). The regulation tries to keep the controlled variable inside the interval. If the controlled variable is below the interval an output signal is activated or deactivated and if the controlled variable is above the interval that output signal is reversed.

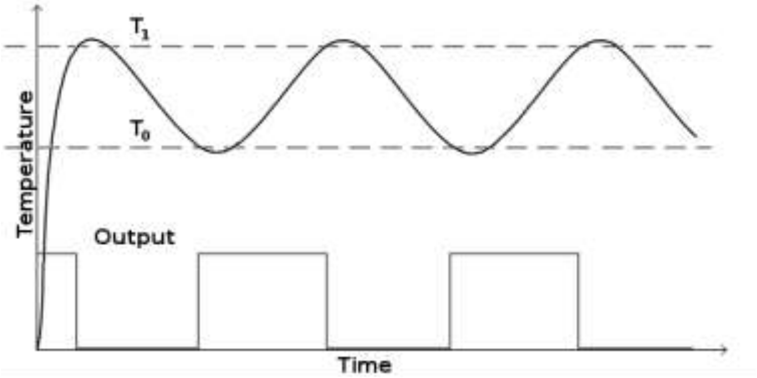

Figure 2.8 2-Point regulation of the Temperature in the interval ST=[T0, T1] using the digital Output signal.

PID regulation

The PID (Proportional Integral Derivative) regulation is executed using an analogical output connected to an actuator (e.g. valve or water pump). The set point is a real value. The controller will try to adjust a measurement of the real variable (e.g. temperature) to the defined set point by adjusting the three constant parameter of the PID.

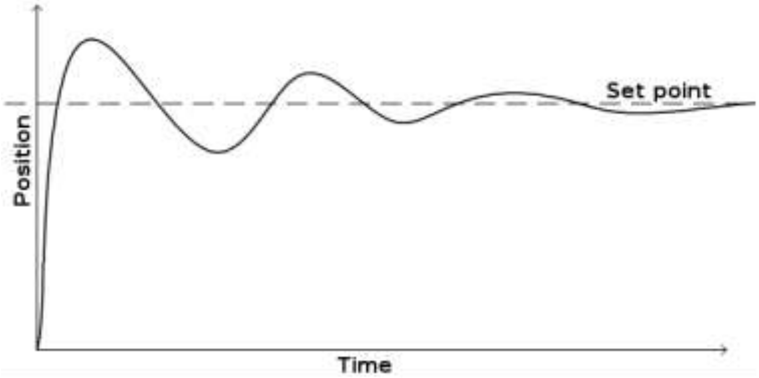

Figure 2.9 The PID tries to adjust the Position variable to a predefined Set Point by changing an output real value that produces changes the Position variable.

The PID regulators are more complicated to parametrise than the 2-Point regulators and are more suited for dynamic systems that evolve rapidly and that need to be very precise with respect to the set point. However, for slow systems that allow a certain degree of inaccuracy such as the temperature in a water tank, the 2-Point controller is enough and simpler to implement and parametrise.

Analogical Control Outputs

The analogical control outputs will be done using 0-10V LLCMS outputs. However, for larger distances a conversion to 4-20mA using converters might be needed.

Table 2.19 summarizes the output control signals needed by the CMS to regulate the system.

Name	Type	Domain	Regulation	Storage	Units	Description
WP1	Start/Stop	Digital	2-Point / PID	Change		Start/Stop water pump 1
WP2	Start/Stop	Digital	2-Point	Change		Start/Stop water pump 2
WP3	Start/Stop	Digital	2-Point	Change		Start/Stop water pump 3
WP4	Start/Stop	Digital	2-Point	Change		Start/Stop water pump 4
WP5	Start/Stop	Digital	2-Point	Change		Start/Stop water pump 5
WP6	Start/Stop	Digital	2-Point	Change		Start/Stop water pump 6
WP7	Start/Stop	Digital	2-Point	Change		Start/Stop water pump 7
V1.o	Open	Digital	2-Point	Change		Open valve V1
V1.c	Close	Digital	2-Point	Change		Close valve V1
V2.o	Open	Digital	2-Point	Change		Open valve V2
V2.c	Close	Digital	2-Point	Change		Close valve V2
V3.o	Open	Digital	2-Point	Change		Open valve V3
V3.c	Close	Digital	2-Point	Change		Close valve V3
V4.o	Open	Digital	2-Point	Change		Open valve V4
V4.c	Close	Digital	2-Point	Change		Close valve V4
V6.o	Open	Digital	2-Point	Change		Open valve V6
V6.c	Close	Digital	2-Point	Change		Close valve V6
V7.o	Open	Digital	2-Point	Change		Open valve V7
V7.c	Close	Digital	2-Point	Change		Close valve V7
V8.o	Open	Digital	2-Point	Change		Open valve V9
V8.c	Close	Digital	2-Point	Change		Close valve V9
V9.o	Open	Digital	2-Point	Change		Open valve V9
V9.c	Close	Digital	2-Point	Change		Close valve V9
V10.o	Open	Digital	2-Point	Change		Open valve V10

V10.c	Close	Digital	2-Point	Change		Close valve V10
V5	Open	Analog	PID	Change		Open/Close valve V5
HP	Start/Stop	Digital		Change		Start/Stop heat pump
B	Start/Stop	Digital		Change		Start/Stop auxiliary heating device (Boiler)

Table 2.19 Output control signals summary.

2.7. Control system

The control system has three main algorithms: the main control, the solar production and the STES load, each one developed in the following sections. The three algorithms run in parallel in the LLCMS.

2.7.1. Main control algorithm

This algorithm starts when the customer demands thermal energy to the buffer tank by starting the water pump WP7. A extra control signal such as a contact input from the WP7, an extra flow-meter in that circuit or a signal from the boiler will inform the LLCMS that the customer is demanding energy.

The main control algorithm gives priority to work directly from solar energy from the PVTs. If it is not possible it tries to use energy directly from the STES and, finally, if this is not possible either, the heat pump will be used. **Figure 2.10** describes the flow of the main control algorithm.

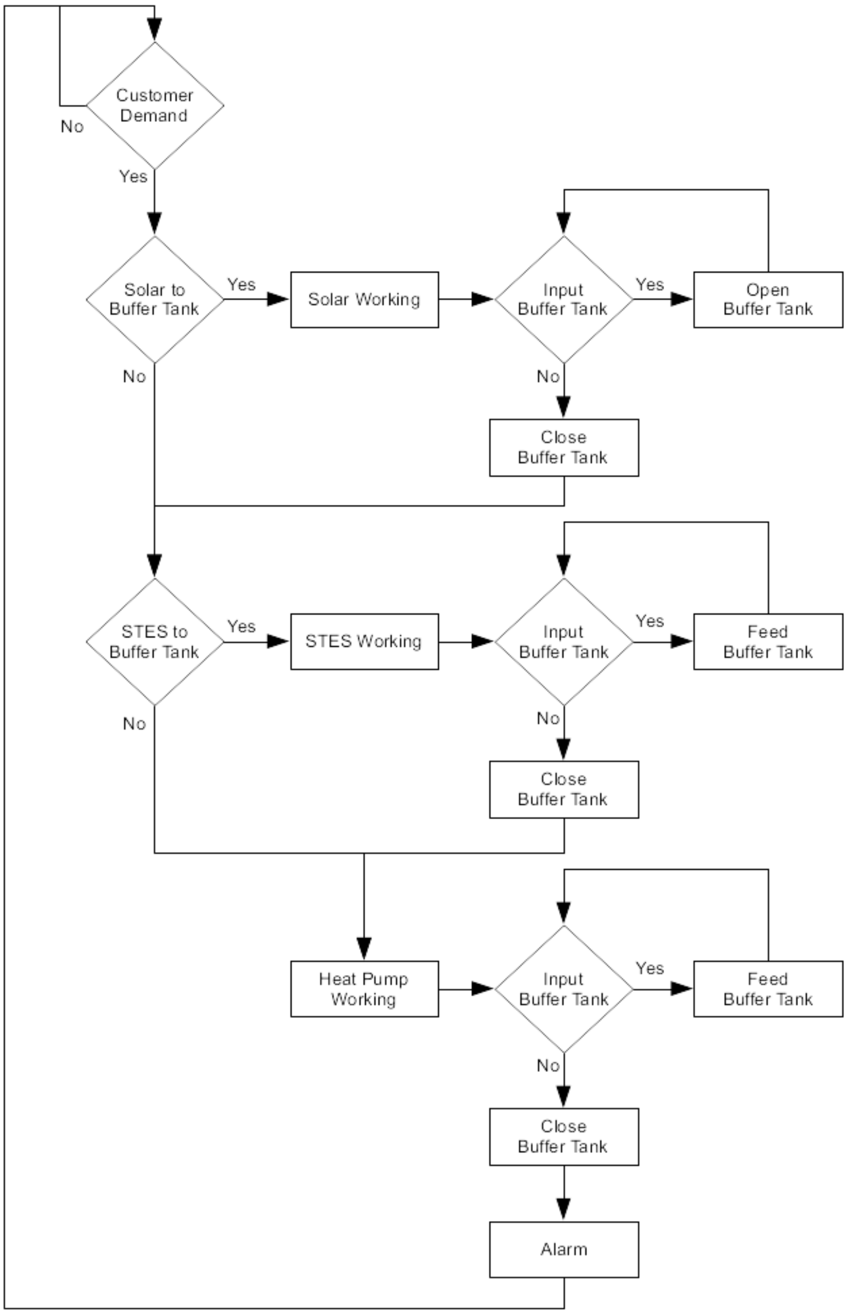

Figure 2.10 The diagram shows the main control algorithm run by the LLCMS. Squares depict control boxes that execute lower level tasks and diamonds describe alternatives depending on conditions which are basically one or more 2-Point comparisons.

The control boxes **Customer Demand?**, **Solar to Buffer Tank?**, **STES to Buffer Tank?**, **Input Buffer Tank?** are software conditions in form of 2-Point comparisons described below:

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Customer demand? It is a 2-Point comparison (T8, BT.Ts). The boiler typically has an internal set point B.ST (e.g. 60ºC) for the water output temperature. Depending on the boiler, this set point can be configured from the HLCMS using ModBus TCP or prefixed manually in the device itself. The internal boiler control will always try to keep the outgoing water temperature to the predefined set point by burning gas or diesel. **Figure 2.11** shows the involved circuits when there is customer demand of energy.

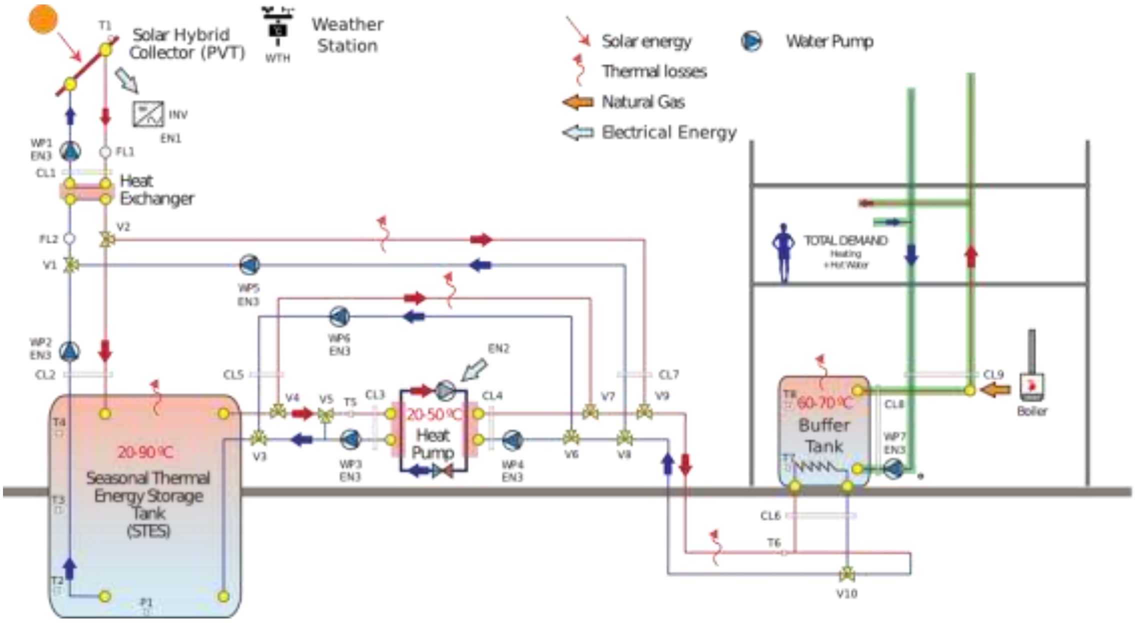

Figure 2.11 The picture shows using green lines the elements involved when there is a **Customer Demand** of energy: water pump WP7 and calorimeters CL8 and CL9.

Solar to Buffer Tank? It is the 2-Point comparison (T1-T7, PVT.dTBT).

STES to Buffer Tank? It is the 2-Point comparison (T1-T4, PVT.dTPVT).

Input Buffer Tank? It is the 2-Point comparison (T7 - T6, BT.dTi). When this comparison is 'Yes', the next step is always to open the valve V10 to deliver energy to the buffer tank. When it is 'No', the algorithm waits for a certain amount of time before jumping to the next step to close valve V10. This time is configurable. For simplicity, this box is repeated as the same box in the three cases, when the energy comes from PVTs, from the STES or from the heat pump, however, in the implementation, the three versions might be slightly different, for instance, the minimum recirculation time set point.

The control boxes **Solar Working**, **STES Working**, **Heat Pump Working**, **Close Buffer Tank**, **Open Buffer Tank**, **Alarm** are lower level algorithms that perform sets of sequential operations such as opening valves and starting pumps that may also release alarms depending on certain conditions, for instance, when valves are moved, if they do not trigger the positioning signals, there is a problem in the valve.

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Solar Working

This control box has to move the valves V1, V2, V8 and V9 to the right path. When the signals of valve status indicate that they are in the right position the water pump WP5 will be started. The execution of this sequence of steps may also trigger alarms such as that a valve is not positioned after a certain amount of time. **Figure 2.12** shows the active circuit when this control box is active and **Figure 2.13** shows an overview of the internal low level control algorithm for this control box.

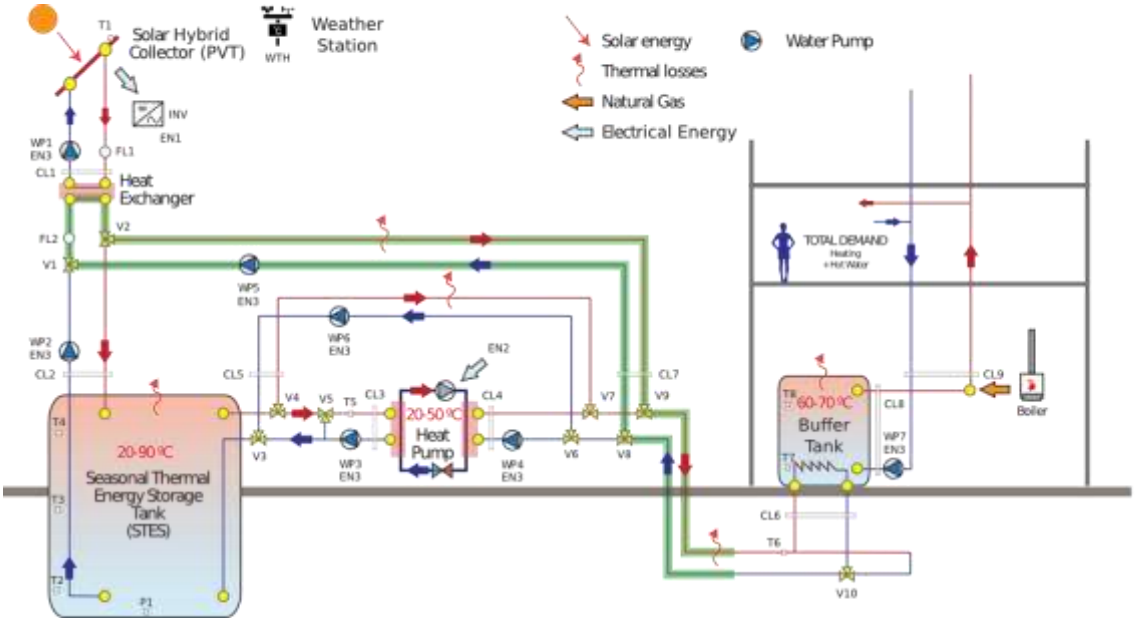

Figure 2.12 Green lines highlight the circuit involved in the **Solar Working** control box: valves V1, V2, V8, V9, water pump WP5, flow meter FL2 and calorimeter CL7.

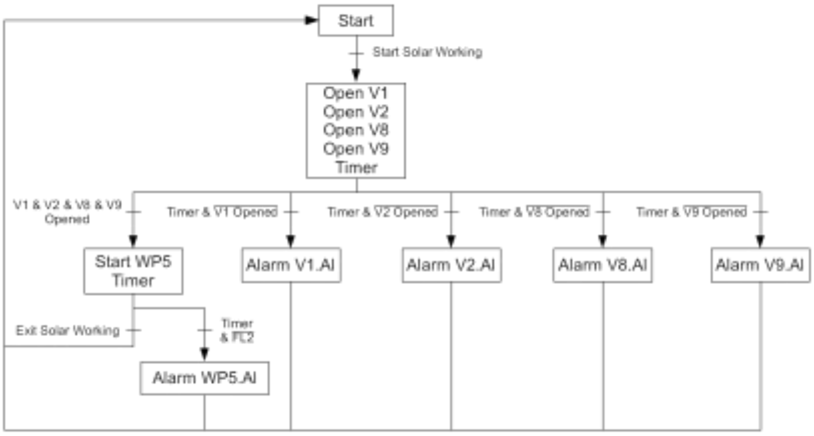

Figure 2.13 Internal low level control algorithm for the Solar Production control box. First the algorithm opens all the valves while starts a timer with a pre-configured waiting time. If a valve is not opened after the waiting time, an alarm will be released and the algorithm resumed. If all the valves are opened before the time expires, then the water pump WP5 is started. If there is no water flow in the circuit after another certain amount of time an alarm will be released.

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STES Working

This control box has to move the valves V3, V4, V5, V7, V8 and V9 to the right path. After the status signals of the valves signal that they are positioned, the water pump WP6 will be started. **Figure 2.14** shows the active circuit during this control box.

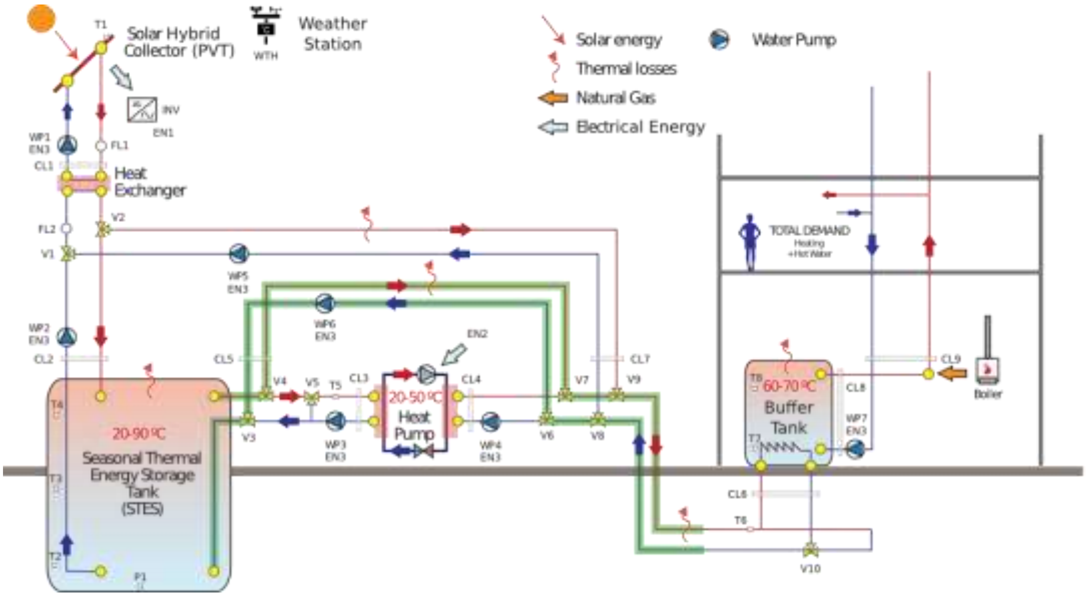

Figure 2.14 Green lines highlight the circuit involved in the **STES Working** control box: valves V3, V4, V6, V7, V8 and V9, water pump WP6 and calorimeter CL5

Heat Pump Working

During this control box, the valves V3, V4, V6, V8 and V9 have to be positioned. When the status signals of this valves inform that they are positioned, the water pumps WP3 and WP4 will be started, the heat pump enabled and the low level PID controller for valve V5 will be activated: V5 = PID Control (T5, HP.Ti). **Figure 2.15** shows the active circuit during this control box.

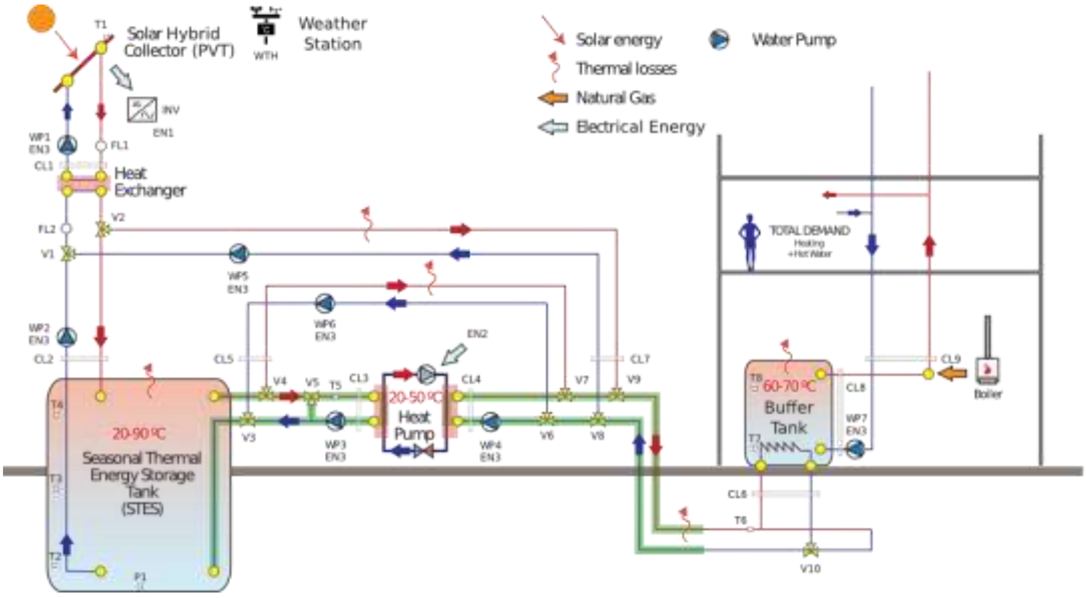

Figure 2.15 Green lines highlight the circuit involved in the **Heat Pump Working** control box: valves V3, V4, V5, V6, V7, V8 and V9, water pumps WP3 and WP4 and calorimeters CL3 and CL4.

Close Buffer Tank

To deliver energy to the buffer tank from any of the sources, the temperature (T6) of the water must be high enough. This control box closes the valve V10 waiting for this event. This recirculation is needed to avoid that boiler heats the buffer tank primary water circuits or the STES. **Figure 2.16** shows the involved elements in this control box.

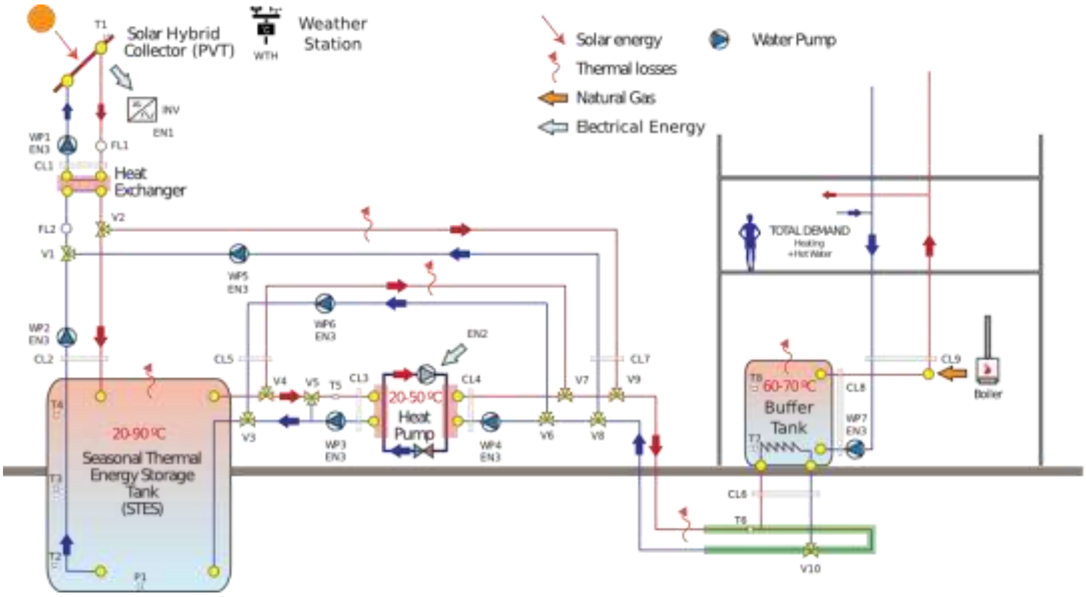

Figure 2.16 During this control box the buffer tank will not receive energy from the energy sources since V10 is closed.

Open Buffer Tank

When this control box is executed, the temperature is high enough to deliver thermal energy to the buffer tank. **Figure 2.17** shows the involved elements in this task.

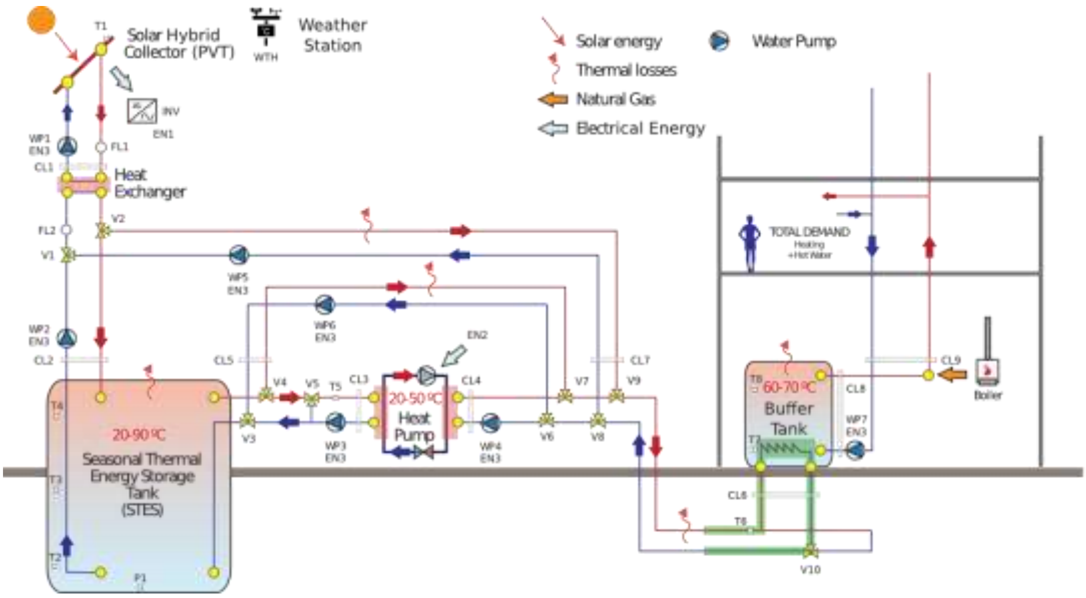

Figure 2.17 During this control box the energy is delivered to the buffer tank by opening the valve V10. The calorimeter CL6 will count the energy delivered to the buffer tank.

2.7.2. Production algorithm

The production algorithm works in parallel to the main control algorithm. This algorithm will try to deliver energy from the primary PVTs to the rest. **Figure 2.18** describes the flow of the production algorithm.

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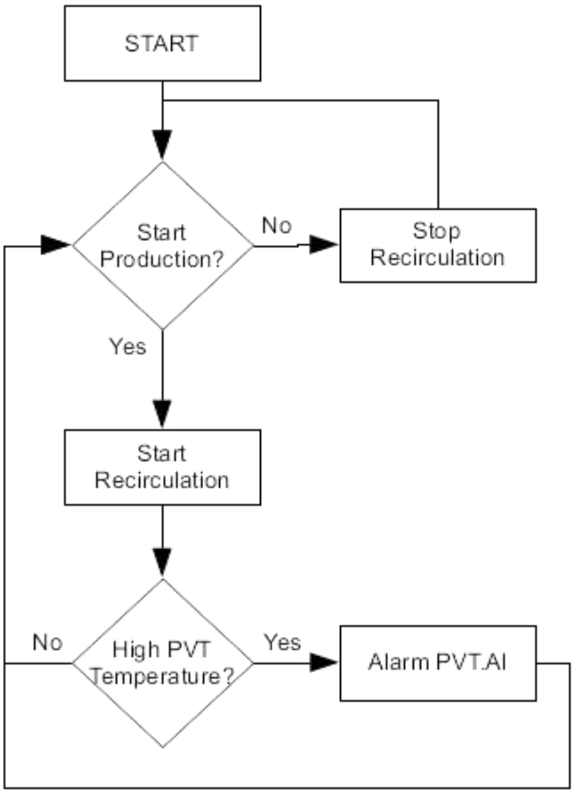

Figure 2.18 The picture shows the production algorithm flow control. The recirculation of WP1 is started depending on the condition '**Start Production?'**

Start Production? It is the condition:

2-Point Comparison (T1-T7, PVT.dTBT) or

2-Point Comparison (T1-T4, PVT.dTPVT) or

2-Point Comparison (T1, PVT.Ts)

Start Recirculation

This control box starts the recirculation using WP1. During the low level control the alarm when there is no flow (provided by FL1 sensor) will be released if needed. **Figure 2.19** shows the active path when this control box is executed.

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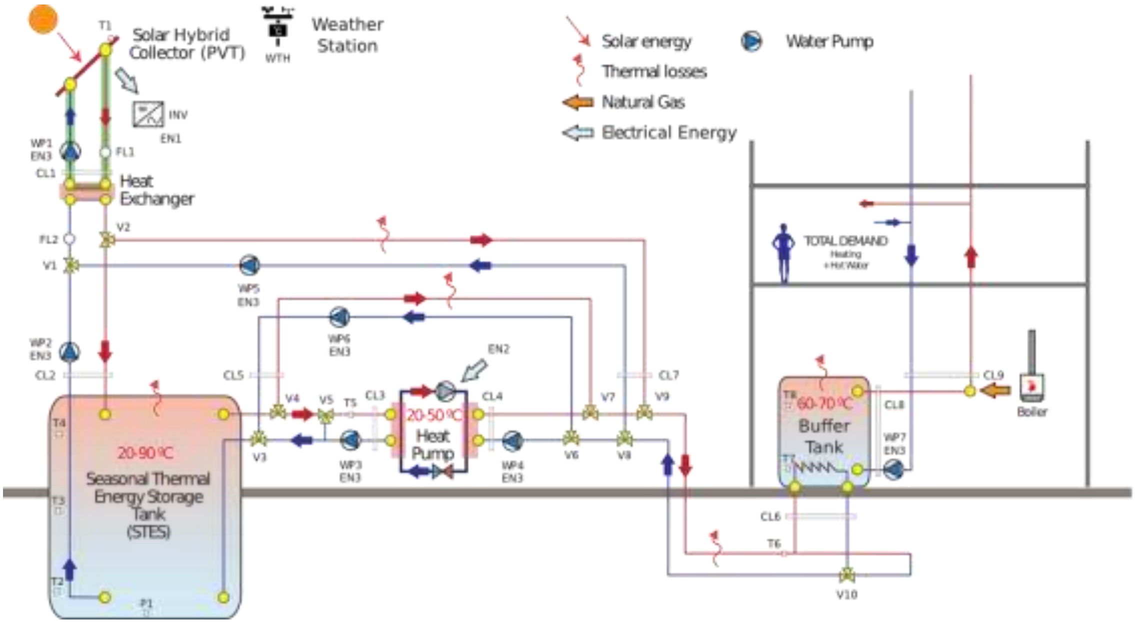

Figure 2.19 Green lines highlight the circuit involved in the **Start Recirculation** control box: water pump WP1, flow meter FL1 and calorimeter CL1.

Stop Recirculation

If there is no demand from the STES or the buffer tank, or there is not enough temperature in the panels the pump WP1 will be stopped accordingly.

High PVT Temperature?

This control box is the comparison T1 > PVT.Tm to release an alarm to inform that the temperature in the panels is too high meaning that there might be a failure in the system.

2.7.3. Load STES algorithm

This algorithm is the responsible of delivering the energy from the solar panels to the STES. **Figure 2.20** describes the flow of the load STES algorithm.

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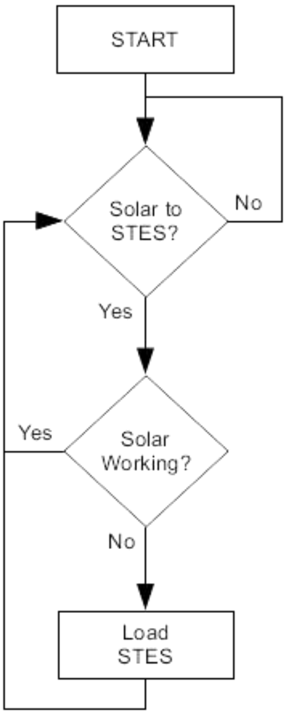

Figure 2.20 The picture shows the load STES algorithm. The **Load STES** control box is the low level control that will deliver energy to the STES and will be activated depending on the conditions '**Solar to STES?'** and '**Solar Working?'**

Solar to STES? It is the 2-Point Comparison (T1 - T4, STES.dTPVT).

Solar Working? It is true if the control box '**Solar Working**' is being executed. If the '**Solar Working'** control box is executing this means than energy is preferably delivered to the buffer tank than to the STES.

Load STES

When this control box ix executed, first the valves V1 and V2 have to be positioned. When the status signals of the valves inform that they are on the right position, the water pump WP2 is started. If there is any error positioning the valves the corresponding alarms will be released. **Figure 2.20** shows the elements involved in the '**Load STES'** control box.

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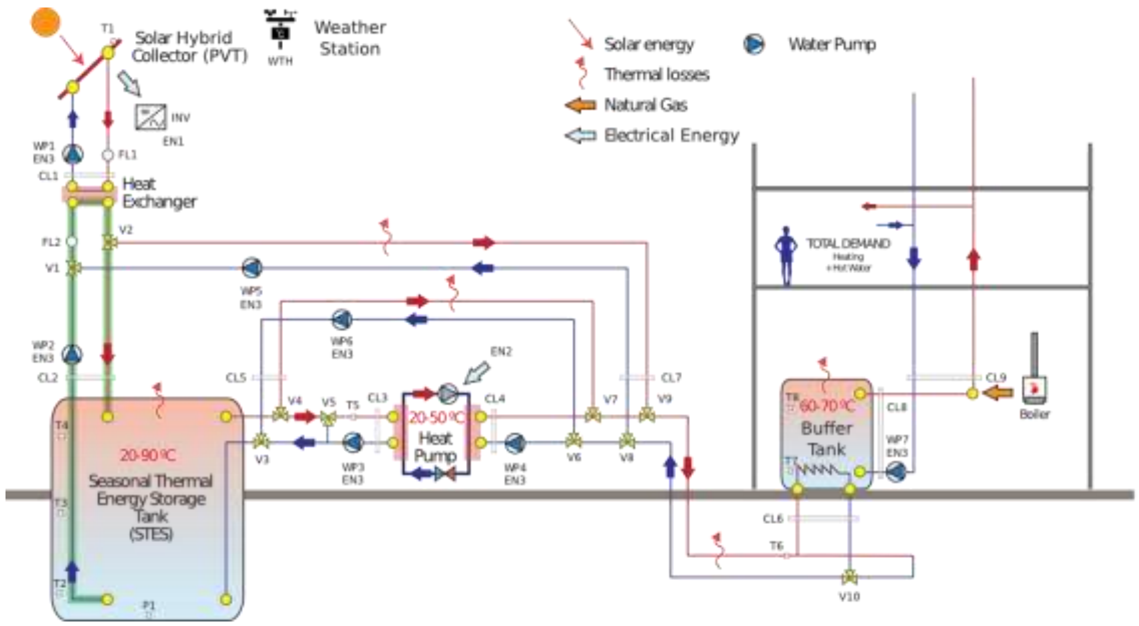

Figure 2.20 Green lines highlight the circuit involved in the **Load STES** control box: valves V1 and V2, water pump WP2, flow-meter FL2 and calorimeter CL2.

3. Data storage and control architecture

For the control and monitoring of the CHESS SETUP a two level approach will be implemented. The CMS (Control and Monitoring System) will be divided into two different layers as introduced in **section 1.1**: the LLCMS (Low Level Control and Monitoring System) and HLCMS the (High Level Control and Monitoring System). The LLCMS is the responsible of the direct control of the actuators and the readings of the necessary sensors for the basic system functioning. This control system will implemented by using an industrial controller and low level simple communications to avoid possible failures.

The HLCMS is the responsible of obtaining higher level information such as the external variables, the data-log and sending e-mails to the external operators (using Internet).

The interfaces to the system, in both layers, will be operator user interfaces since the final customer will not need to access to the system.

The physical interfaces attached to the system will be an HMI screen and the local PC screen that executes the HLCMS and operator thin clients such as tablets or mobile phones will be used as well.

Low Level Control and Monitoring Layer (LLCMS)

This layer will be composed by a central industrial controller such as Siemens S7-1500 or similar where the low level control software will be executed non-stop. For the local visualization, parameter tuning and alarm visualization and clearing an HMI interface such as a Proface GP-4601T screen or similar will be used.

High Level Control and Monitoring Layer (HLCMS)

This layer will be composed by a PC server hardware as a controller with a supervision software (SCADA: System Control and Data Acquisition) such as Wonderware Indusoft[6] Web Studio1 or similar. This software will be de responsible for the visualization in local operator PC screen, the remote visualization using the HTTP Web protocol, the data acquisition, visualization and the data-log.

3.1. Control I/O architecture

The control architecture will be a SCADA-like architecture where the SCADA system centralizes all the information gathered directly from sensors or from the PLC controller. The SCADA software also provides to the user the different interfaces: the local ones using local terminals such as computers, tables or mobile phones connected to the local Ethernet network or the remote ones connected via Internet.

The SCADA system will be also connected to a database where all the information will be registered in a tabular form. This database will use the standard protocol SQL that will allow external software such an SPC (Statistical Process Control) or any other data-mining program to exploit the stored data.

Moreover, the database will also be used as a way for communicating external pieces of software to with the system. For instance, it might be needed an external piece of software and hardware that will read the utility grid hourly energy prices from the Internet and will insert them into the database automatically. **Figure 3.1** shows the 'Input/Output' architecture of the system.

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[6] http://www.indusoft.com/

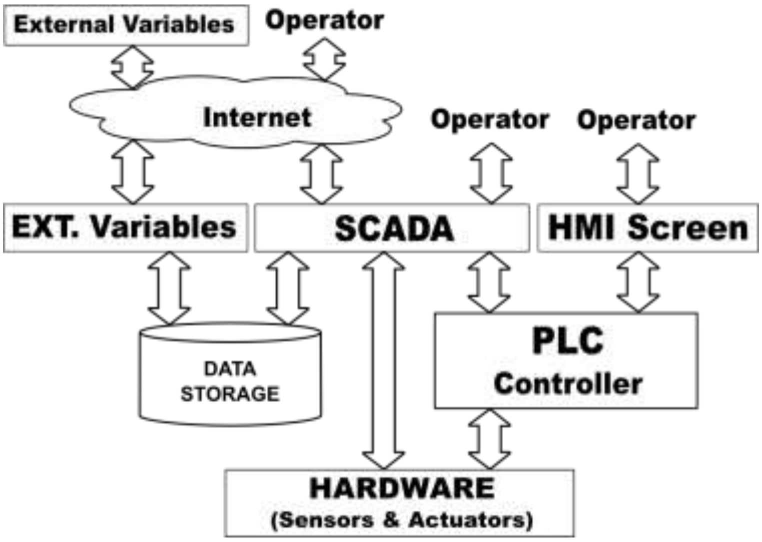

Figure 3.1 The picture shows the Input/Output architecture of the CMS. Typically sensors and actuators are accessed by the PLC and the SCADA tool communicates to the PLC. However, sometimes the SCADA may read directly sensors such as power-meters that are not used by the PLC. The HMI screen provides a local interface to the operators. The SCADA provides local (PC screen) and remote interfaces (via WEB) to local and remote operators. The external variables might be accessed by the SCADA itself or via third party software. The database storage is used by the SCADA tool to store the data-log information.

Personal Information

The information stored in the database by the SCADA system is not sensitive since no end user personal information will be stored in it. Anyway, if required, the file-system and, therefore, the database, can be easily encrypted. If any identification of particular homes must be stored, labels such as $home_n$ ($home_1$, $home_2$...) will be used instead of personal information or physical mail addresses. The database will agree to the local regulations and the data protection acts.

3.2. Communications and protocols

All the devices in the system will be communicated to each other using different communication protocols. The simplest and lowest level protocols will be used for the control signals that need to be more robust and less failure prone. Therefore, digital I/O modules and analogical modules attached directly to the controller will be used in that case. However, in some cases, because of physical distances remote I/O modules will be used over a high robust protocol such as ProfiNET or similar on top of an Ethernet communication.

The heat pump and boiler will be connected to the system both using I/O for the alarm and the start/stop signals but might also be connected to the system for gathering monitoring information using standard protocols, typically ModBus TCP or RTU.

The power-meters are typically read directly from the SCADA using ModBus TCP or RTU protocols.

The calorimeters will be connected to the system by using M-Bus protocol and a gateway to the ProfiNET in order to be read by both the PLC controller and the SCADA system.

Finally, local HMI interfaces such as the Proface screen will be communicated by using the controller protocol such as MPI.

Figure 3.2 summarises the set of protocols used for communicating all the components each other.

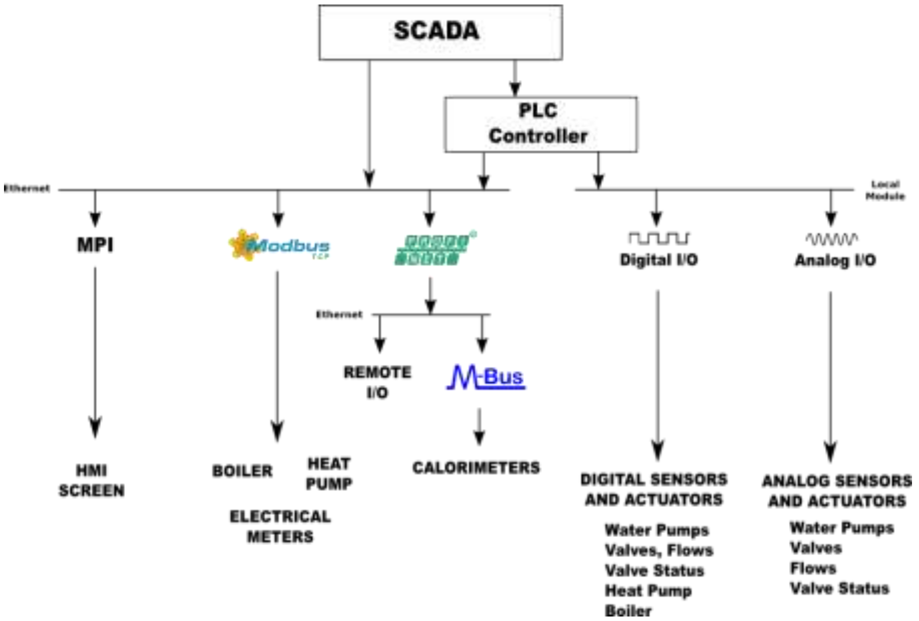

Figure 3.2 Summary of protocols that will be used in the CMS for the CHESS SETUP. The LLCMS implemented in the PLC will connect using the more simple and direct communications and protocols: direct I/Os.

3.3. System controller (PLC)

The controller of the LLCMS will be a commercial industrial PLC such as the Siemens S7-1500 PLC. Typically, commercial PLCs are scalable systems where CPU and I/O modules are bought separately depending on the needs.

Among others, a commercial PLC has the following features:

- **Programmable:** The PLC is a general purpose controller that need to be programmed by an specialist engineer to solve a particular problem using its own programming language.

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- **Scalability:** Modern PLCs are easily scalable in terms of I/O modules and communications. The main module is a CPU and there is wide range of modules for different purposes available.
- **Digital I/O Modules:** Different modules attachable to the controller with different I/O combinations: 8, 16 or 32 inputs or 8, 16, 32 outputs.
- **Analogical I/O Modules:** Attachable modules with different amounts of analogical I/O combinations (4, 8, 16, 32).
- **Temperature Modules:** Modules ready for reading directly temperatures using RTD probes such as 2, 3 or 4-wire PT100 or PT1000.
- **Standard Protocols:** Communications to other devices using standard protocols such as ModBus RTU or TCP and ProfiNET.

Table 3.1 shows the modules needed for an S7-1500 according the control and monitoring system defined in previous chapters.

Module	# Modules	Description
RTD	2	Modules with 4 x 3-wire RTD for temperature reads
16 Digital inputs	2	Valves, water pumps, heat pump and boiler
16 Digital outputs	2	Valves and water pumps
2 Analogical output	1	Control the proportional valves and the variable speed water pumps

Table 3.1 PLC I/O module set summary needed for the CHESS SETUP control and monitoring.

For the analogical I/O modules and RTD modules, depending on the distances, a conversion stage to 4-20mA might be needed using Weidmueller MAS DC/DC select module or similar.

The digital I/O modules will be transistor based and will be connected to external relays since if there is relay damage it will be changed without the need of changing the full I/O module.

While ModBus TCP is a native built-in feature using the PLC Ethernet port, the ModBus RTU, if needed, for instance, for the heat pump or the boiler, is available using an external module.

Figure 3.3 shows a summary of the control signal I/O modules and the signals attached to them.

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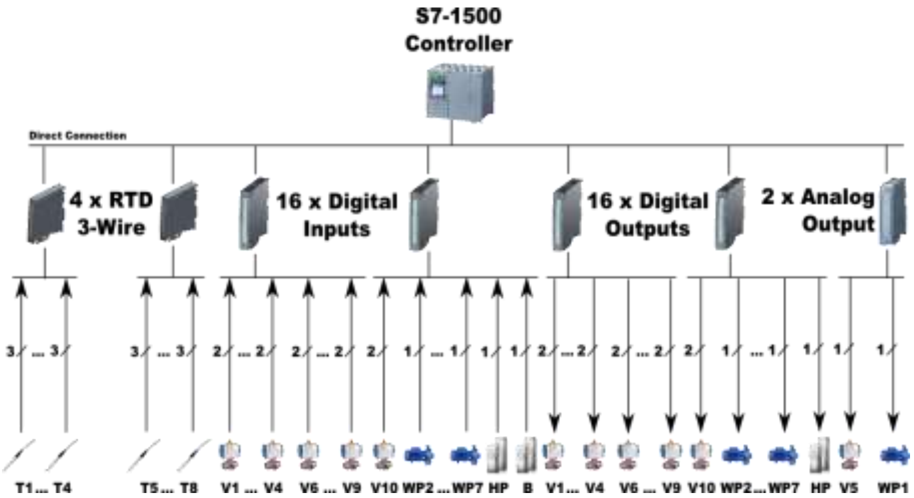

Figure 3.3 Summary of S7-1500 PLC controller and the I/O modules and signals attached to them.

Depending on distances a remote I/O header module such as the S7 IM module or similar will be needed. These IM modules communicate the PLC CPU remotely via Ethernet to an I/O module set. The remote module header (IM) also allows other modules such as the ModBus RTU. **Figure 3.4** depicts the remote module approach.

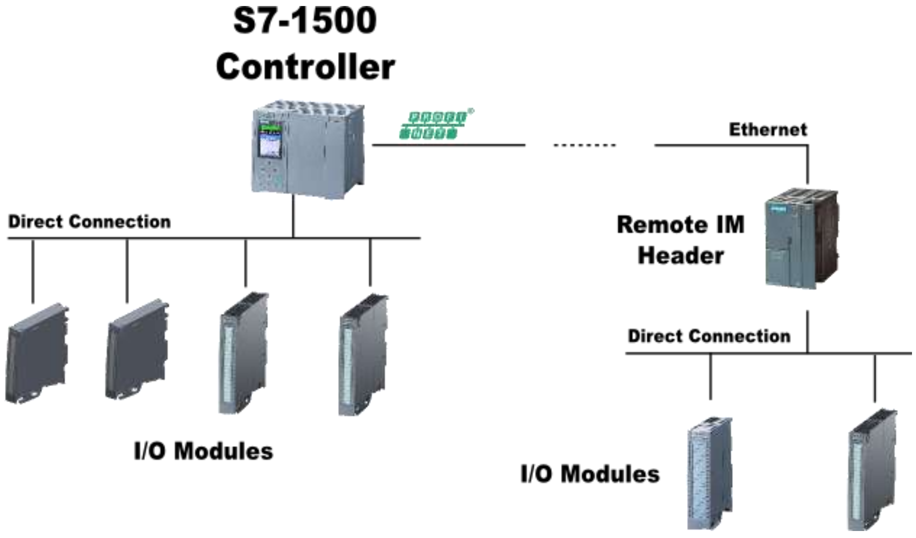

Figure 3.4 Picture shows the S7 remote IM module architecture for external modules. The remote IM header uses ProfiNET protocol over Ethernet I/O communication on large distances.

While **Figures 3.3** and **3.4** show the lower level signals that need to be more robust and attached directly to the controller via I/O modules, **Figure 3.5** shows the higher level monitoring sensors summary for the monitoring variables such as thermal and electrical power and energy or the heat pump and boiler variables and parameters.

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Calorimeters are typically communicated using the M-Bus protocol, therefore a ProfiNET to M-Bus gateway such as ADF-Web or similar that supports up to 20 M-Bus clients must be used.

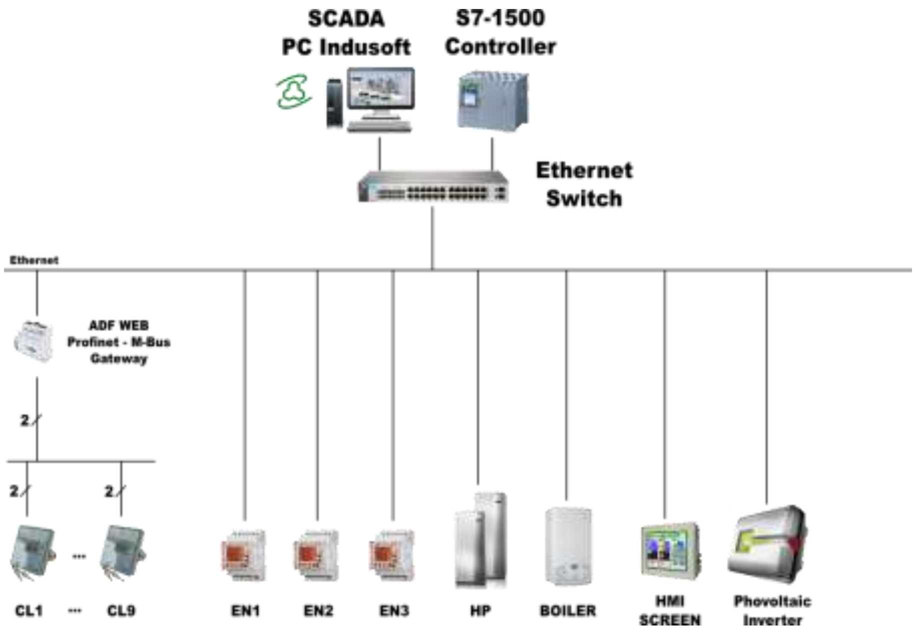

Figure 3.5 Architecture for the monitoring sensors, the visualization HMI screen and the monitoring devices SCADA and PLC. While calorimeters CLi, and the HMI screen are read by the PLC S7-1500 controller the electrical power-meters and the photovoltaic inverter will be read directly by the SCADA tool. If available, the high-level communication to the heat pump and the boiler, they will be connected to the PLC controller.

3.4. System control and data acquisition (SCADA) tool

The main component of the HLCMS will be a commercial SCADA tool. Commercial SCADA tools allow to connect to a wide range of commercial Industrial PLC (Programmable Logic Controller) which is the main controller of the LLCMS. This SCADA software is a generic tool that allows engineers to develop a particular control and visualization project for an industrial problem.

Among others, the main features that a standard SCADA tool such as Indusoft Web Studio will provide to the implementers of the solution are:

- **Graphical design:** Allow the easy creation of graphical interfaces for the operators and users of the system.
- **Graphical symbols and animation:** The tool provides graphs, buttons, pilot lights, tanks, sliders, meters, motors, pipes, pumps and other common objects

that can be animated depending on system variables and parameters to provide an informative set of screen interfaces to the operator users of the system.

- **Events:** Trigger different operations in the case of an event in the system such as variable value changes, an alarm, or any other.
- **Reports:** Create informative reports in any common standard format such as PDF, HTML or CSV.
- **Scheduler:** Allow triggering reports or any other functionality based on a particular time of the day.
- **Scripting:** Usage of an internal script language to provide the needed functionalities by programming them in the system.
- **Database:** Connection to a wide range of standard SQL databases (MS SQL, Mysql, Sybase or Oracle).
- **Device drivers:** Direct drivers to communicate to most of the existing PLCs or the standard OPC for communicating to practically any PLC.
- **Alarms:** Send alarms to a printer a screen or to a mobile phone via e-mail.
- **Multi-language:** The SCADA tool is available in many languages as well as it provides an easy way to develop multi-language solutions.
- **Security:** Support for user and group accounts and screen protection using passwords.
- **Communications:** Communications to external devices and softwares using common standards such as BACNet, ModBus TCP and RTU, CAN, TAP, TCP/IP, .Net, Active X, OPC, ADO/ODBC, COM/DCOM, OLE, DDE, XML, SOAP or HTML.
- **Thin clients:** Automatically provide a HTTP Web Interface for PC, Mobile phones or tablets without any extra programming effort. The same set of screen interfaces that is provided to the local operator PC screen is served as a Web page via Ethernet.
- **Historical data and trends:** Internal module that provides an easy method for plotting graphics and trends Date/Time based or numeric X/Y plots.

Connection to the system

All the components of the HLCMS will be connected to each other by using the standard TCP/IP on top of an Ethernet network.

Depending on the complexity of downloading the external variables (utility grid hourly energy prices or weather forecasts) from the Internet and parsing their content, an external software placed in the same PC than the SCADA software or in an external hardware might be needed.

Figure 3.6 shows all the devices attached to this Ethernet and involved in the HLCMS.

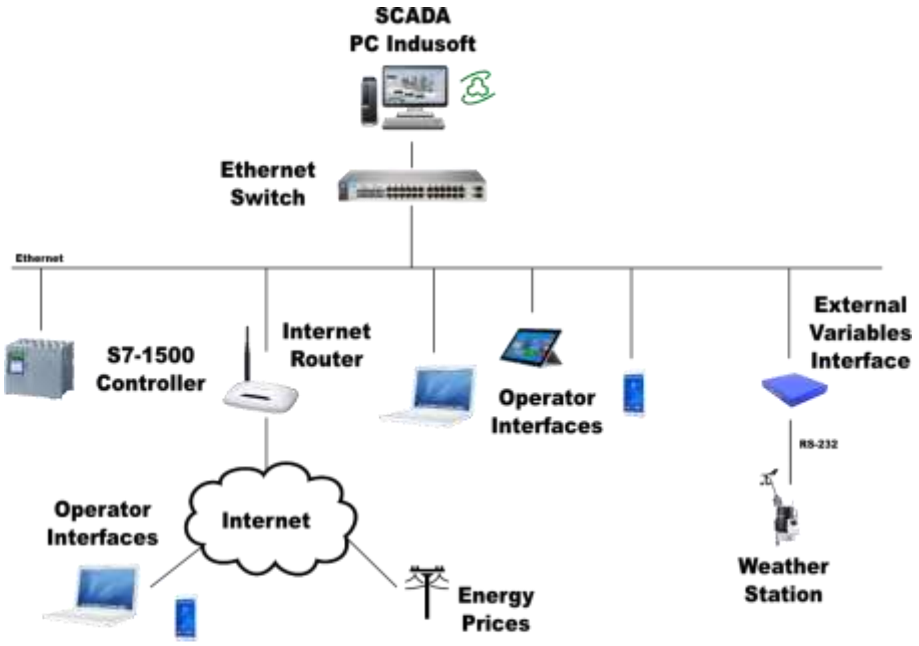

Figure 3.6 The picture shows all the components in the HLCMS connected each other via Ethernet. The SCADA will be periodically polling information from the PLC and the other devices. Operators will communicate to the system by using the local PC screen than runs the SCADA system or using their own thin clients (Laptops, mobile phones or tablets).

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4. Visualization

One of the most important components of the CMS is the visualization since it provides to the operator of the system an easy interface to the whole system in order to detect problems or operate the system in an intuitive and easy way.

The system will provide a single user interface that will be displayed to the local operator screens and served as a web page to remote operators (from the local network or via Internet). This user interface will be composed by a menu and a set of screens that will display different parts or viewpoints of the system. The menu will be used to navigate along the different screens.

4.1. Real-time screens

The real-time screens are those that show the current status of the system. The different screens will contain graphical elements such as valves, water pumps, tanks, etc. animated depending on variables, parameters and alarms. The user will easily see the status of the elements by for example using colours and texts. For instance, a green water pump means that it is working, a grey water pump means it is stopped, and a red water pump means it is in alarm status. Text boxes and combo boxes will be used to define parameters and text labels to show values, for instance, flows, temperatures, powers, etc. **Figure 4.1** shows an example of an application running on top of the SCADA Web Studio.

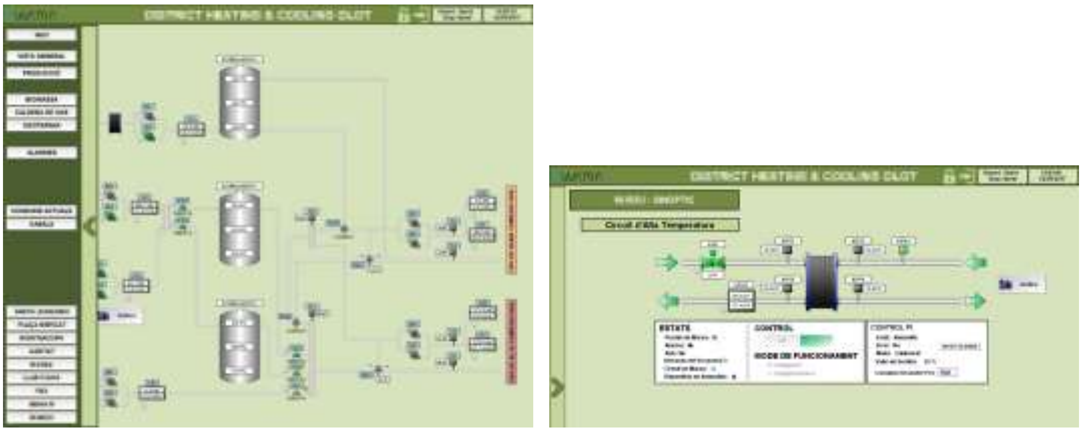

Figure 4.1 The left picture shows sample application main screen with a drop down menu on the left side. The application has 3 energy production sources and the 3 buffer tanks depicted with its own stratification temperature. The picture shows all the circuits involved in the system with all the water pumps and valves. Valves and water pumps in green means they are currently pumping water. The right picture shows a detail of a sub-station that contains a heat exchanger. The control actuates over a proportional valve in the primary and reads a calorimeter in that primary and two temperature sensors and a flow-meter in the secondary.

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4.2. Charts

One of the most powerful tools of the visualization system of the SCADA tool is the possibility of plotting variables in a time or an X/Y chart. This tool allows to verify, for instance, if the regulations perform as it is expected or not. Any variable stored in the database of the system will be available to be displayed in a chart. **Figure 4.2** shows an example chart of a PID regulation.

Figure 4.2 The plot shows the regulation of a PID operating over a proportional valve in the primary of a heat exchanger. The set point is 70ºC at the flow pipe in the secondary. The cyan dots in the picture represent the real value for this temperature in the flow of the secondary and, the yellow dots represent the opening percentage of the valve regulated by the system. As soon as there is a decrease of temperature in the secondary (energy demand by the customer) the regulator opens the valve to increase the amount of energy delivered through the heat exchanger.

Historical Data

The HLCMS will store the variables in the database. The charting engine will be allowed to use any of these stored variables to be plotted against any other using. For instance, represent the current year daily demand against the last year daily demand plus the maximum and minimum daily temperature.

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Moreover, any subset of registered variables can be exported in form of tables in a standard format such as XML or CSV to be used out of the system by any external tool such as Excel or Matlab.

5. Alarms

An important component of the CMS is the alarm management subsystem since it will help to the operator users of the system to deal with the important alarm events which may require a physical intervention by a technician. There is three different user interfaces that will aid the user:

a) **Alarm display.** The CMS system has to display locally (in the HMI screens) the alarms in some way that will be easy to interpret. For instance, using the pictures of the user interface: a red pump or valve will mean an alarm on that device. If the user double-clicks the object a more describe message of the alarm will be displayed. **Figure 5.1.** shows an example of a user interface screen with an alarm.

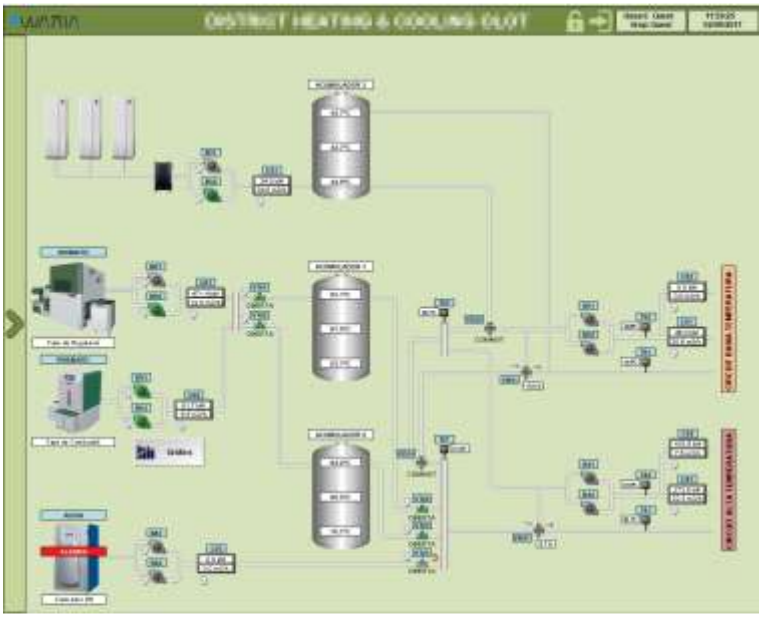

Figure 5.1 The picture shows a typical SCADA user interface where there is an installation depicted. In this case, a gas boiler (a device in the left hand side of the picture) has a red message "Alarm" meaning that there is some problem in that device.

b) **Alarm log.** The alarms have to be logged in order to detect deeper problems. For instance, if a device fails too often or a device fails every day at the same time it might indicate a deeper problem in the system regulation or management. At the same time, many alarms could happen at the same time and it is very informative having the sequence of failures in order to recover from them. Moreover, the alarm recovery typically needs to be confirmed by an operator. If the operator validates an alarm, the system checks again for its persistence and then leaves the alarm log in, for instance, with another colour. **Figure 5.2** shows an example of a user interface screen with an alarm log.

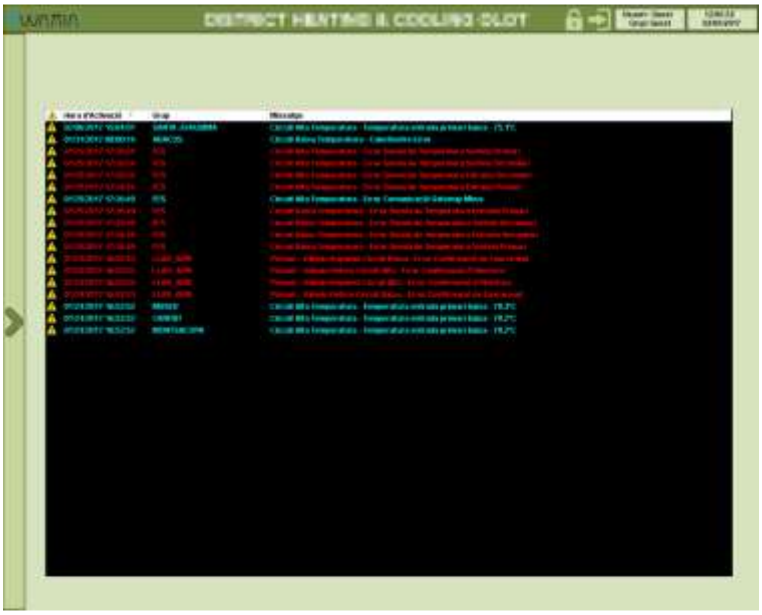

Figure 5.2 The picture shows an alarm log screen where some alarms are still in red meaning that they are still pending to be recovered and confirmed and those in cyan are already validated.

c) **Alarm delivery.** Some of the alarms are urgent enough to be delivered directly to operators by using a messaging system such as SMS or e-mail. In the case of the CHESS SETUP, the more critical alarms will be configured to be sent to a set of users (viewers and operators) via e-mail in order to recover from them.

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6. Pilot Experiences

At the time of writing this report the pilot cases are still being developed which means that the final controls and monitoring may therefore vary from the generic CHESS SETUP case and will be adapted to each scenario accordingly as the project evolves.

Moreover, note that there are variances, for example in the form of the storage being geothermal in Corby's pilot, a large scale pilot in Sant Cugat's pilot and a small scale one in Lavola (Manlleu).

At this moment in time and considering the limitations of the pilots when going on site, the possibilities of optimising the CHESS SETUP system for each scenario are being considered and analysed in more detail.

7. References

[1] http://www.construction21.org/city/es/district-heating--cooling-network-in-olot.html

[2] http://www.diba.cat/documents/479934/63881441/1.2.+Ajuntament+d'Olot+Xarxa+Espavilada+de+clima+d'Olot.pdf/3bd8a530-1b80-4a4e-951d-c085debcec25

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