

Project Acronym/ Acronimo del progetto:

**INTEGRIDS**

Project title:

***Electric and thermal grids integration  
with energy flexible building***

Titolo del progetto:

***Studio dell'integrazione di reti elettriche e termiche con  
la flessibilità energetica degli edifici***

Deliverable name	Installazione e funzionamento dell'infrastruttura di laboratorio INTEGRIDS
Deliverable N°.	D5.1
Task	5.1
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Due date	30/03/2019

## Table of Contents

<b>Executive summary .....</b>	<b>1</b>
<b>1 Introduction.....</b>	<b>2</b>
<b>2 Single laboratory description .....</b>	<b>3</b>
2.1 Energy Exchange lab .....	3
2.1.1 Producer substations .....	5
2.1.2 Prosumer substations .....	5
2.1.3 Heat rejection Circuit .....	5
2.1.4 Thermal Network .....	6
2.2 PV integration lab .....	6
2.2.1 PV test .....	6
2.2.2 Real-Time simulator for power grids and power electronics.....	7
2.3 Multi-lab .....	9
2.4 Weather station .....	9
<b>3 Integrids laboratory .....</b>	<b>10</b>
3.1 Communication and data infrastructure .....	11
3.2 Plant Control Software .....	13
<b>4 Communication and system design: the weather station example .....</b>	<b>18</b>
<b>References .....</b>	<b>23</b>

## Executive summary

Il progetto finanziato dal Fondo Regionale per lo Sviluppo Economico "Integrids" ha il duplice obiettivo di esplorare l'interazione ed integrazione delle reti elettriche e termiche con la flessibilità degli edifici sia sviluppando modelli appropriati sia tramite la realizzazione di un laboratorio nell'area outdoor dell'Istituto di Energie Rinnovabili di Eurac Research. Il laboratorio Integrids avrà come scopo quello di connettere tramite un sistema di comunicazione dedicato i tre laboratori identificati come PV Integration, Energy Exchange e Multi-lab più una stazione meteo dedicata. Attualmente questi laboratori, già presenti o in fase di costruzione presso l'area outdoor di "advanced energy systems" di Eurac Research sono in grado di generare profili di produzione fotovoltaica, emulare il consumo tramite carichi elettronici, emulare il comportamento di un sistema di teleriscaldamento e teleraffreddamento con pompe di calore reversibili nonché testare condizioni di comfort e domanda per edifici.

Tramite l'infrastruttura che si svilupperà nel progetto Integrids, questi tre laboratori saranno in grado di scambiare dati tra loro sia di grandezze misurate, sia in futuro di controlli, al fine di effettuare test combinando più di un laboratorio alla volta. I dati scambiati saranno gestiti tramite un server centralizzato dove ci sarà un database sia di inviare le quantità di interesse da monitorare e controllare ad un unico database a cui si potrà accedere per effettuare esperimenti off-line. Il medesimo sistema centralizzato ospiterà anche sia tramite un opportuno supervisore centralizzato capace di inviare comandi da un laboratorio all'altro in base a controlli condizionali dipendenti da diversi obiettivi, quali ad esempio la massimizzazione di energie rinnovabili, la minimizzazione dei costi o delle perdite...

In definitiva l'infrastruttura del laboratorio Integrids permetterà ai tre laboratori di creare una sorta di microrete virtuali in cui non saranno possibili scambi di potenza ed energia o di calore, ma la gestione dei flussi avverrà tramite scambio di dati di produzione e consumo.

In questo report vengono descritti i tre laboratori e parte dell'infrastruttura di comunicazione creata, nonché viene presentato anche un esempio del software implementato nella stazione meteo per acquisire le misure dai vari sensori al fine di inviarli nel database centralizzato.

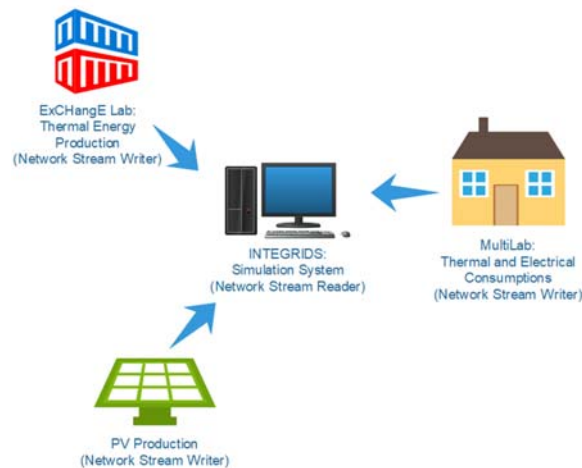
## 1 Introduction

One of the main objectives of the INTEGRIDS project is to build a new laboratory infrastructure which extends the EURAC outdoor energy system facilities in order to test in the future some of the concepts proposed in the project.

The infrastructure will be mainly able to virtually connect the three existing labs, which are:

- *The PV Integration Lab*
- *The Energy Exchange Lab*
- *The Multi-Lab*

Under the framework of the Integrids project, the three existent (or under construction) laboratories are expected to work as a virtual micro-grid able to perform off-line and online experiments.



A proper communication infrastructure will be deployed to share data from one laboratory to one another. The three labs will create a sort of virtual microgrid, where no direct interaction in terms of energy/power exchange will be performed.

A dedicated database will be also developed to store all the data provided by the three laboratories and by a dedicated weather station.

The software part (i.e. controls, communication managers, etc.) of the system will be developed through the programming platform LabVIEW from National Instruments.

A centralized energy management control will send operational signals (e.g. instructions) to the respective control system of each lab to operate for common objectives. On the other hand, the meteo station will provide weather related data to the laboratories to allow them to perform their respective operations.

The core purpose of the INTEGRIDS infrastructure is to be able to simulate as realistically as possible the interaction between the different components of different grids.

In the following section a brief description of the laboratories and the weather station will be presented, as well as the component description of what equipment/system components the INTEGRIDS higher level management system will be signalling or communicating with.

## 2 Single laboratory description

### 2.1 Energy Exchange lab

The Sustainable Heating and Cooling (SHC) Group of the Renewable Energy Institute at EURAC designed this laboratory, with the purpose of carrying out tests on small district heating and cooling (DHC) networks.

The laboratory has been designed to carry out test in conditions as close as possible to real applications. This enables it to reproduce, on a small scale, real-like boundary conditions which affect the operation of the whole DHC system: from production to distribution and utilization of thermal energy.

Characterized by a high level of flexibility from the hydraulic as well as control point of view, due to the high number of sensors, this allows the possibility of studying the performance of single machines and substations at specific interfaces, and the performance of the whole DHC system.

The laboratory's flexible infrastructure allows the connection of producer and prosumer substations in order to investigate different hydraulic solutions on the network side. Moreover, different kinds of circulations with mixing and deviation valves, allow performing tests with different conditions, exploring different subsystem combinations. On the other hand, the data acquisition system and the controllers allow investigating the control strategies at different levels.

This system is a paradigmatic example of the kind of waste heat sources which can be considered in the innovative low-temperature DHC concept. The availability of a trigeneration system allows dealing with real issues, like non-trivial scheduling and variable temperature of the sources. The presence of a refrigeration unit also opens the possibility of stressing the network in cooling mode. A set of heat pumps and heat dissipation systems simulate network users. Reversible water-water heat pumps are used, providing the opportunity to test different load and temperature condition (simulating different types of users possibly connected to the network).

The laboratory can be divided into four subsystems according to the scheme in Figure 1:

1. Producer substations
2. Thermal Network
3. Prosumer substations
4. Heat rejection circuit

The heat generation circuit of the plant has been designed to provide a peak thermal power of about 100 kW to test potential waste heat recovery up to this size. On the other hand, the producer substations and the thermal network have been designed to work with a small temperature difference of about 3 K (between supply and network side). Larger temperature differences, up to 30-40 K, will also be possible in certain configurations. The peak thermal power on the utilization side is about 50 kW.

The small scale DHC plant occupies an area of 2000 m<sup>2</sup> and has the following scheme:

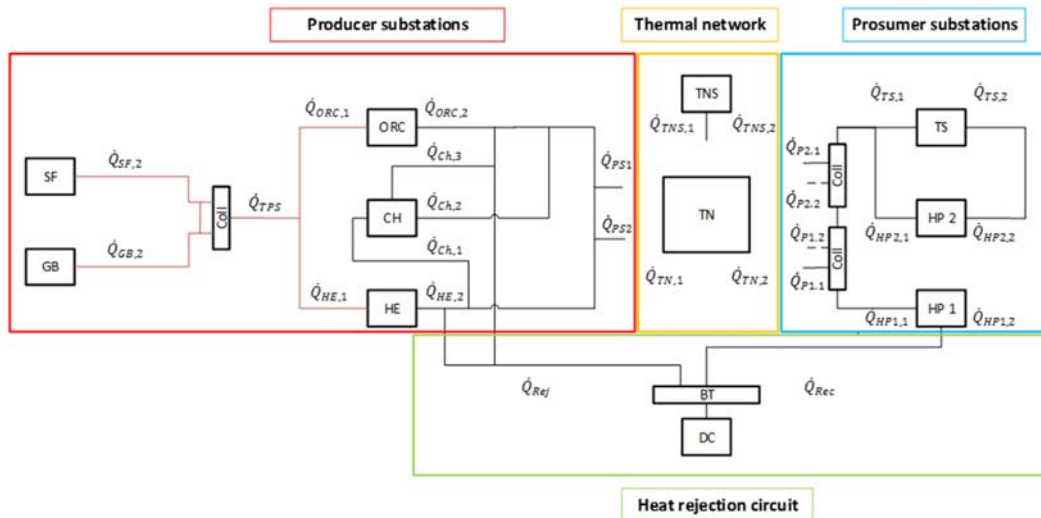


Figure 1 – Single-line diagram of the EURAC pilot. A set of manual valves (not shown in the figure) provides the circuit with the possibility of different configurations.

Component acronyms of the plant in Figure 1:

- SF: Solar Field, 40 kW
- GB: Gas Boiler, 70 kW
- ORC: Organic Rankine Cycle, 40 kWt/4 kWe
- AbC: Absorption chiller, 36 kW cooling
- HEX: Heat Exchanger, 50 kW
- HP: Heat Pump, HP1 = 25 kW, HP2 = 32 kW
- DC: Dry Cooler, 130 kW
- BT/TNS: Storage, both of 2000 l
- Coll: Manifold

A few comments in regard to the plant: the boiler is used in case of insufficient solar irradiation. The produced thermal energy can be converted in different forms and used in different modes: heating only (through the heat exchanger), electricity and heat (cogeneration, through the ORC engine), cooling (through the absorption chiller). The heat input of the solar field and the boiler can be converted into electricity, fed to the internal sub-grid of the plant. An inverter is used to convert the generated electricity to standard grid values. Commonly ORC systems typically benefit of continuous operation, the presence of a back-up boiler is crucial to support the solar field and allow for the execution of tests in stationary conditions. The absorption chiller is supplied through an oil-water heat exchanger, at a temperature of about 95°C. It is operated as an alternative to the ORC cycle.

For the heat pumps, the heating mode typically works on 15-40 °C temperature lift (15 °C within the main water loop, 40 °C for the secondary loop to be heated), with a COP in the order of 5-6; cooling mode typically works on a 10-25 °C temperature lift (19 °C within the secondary loop where heat will be transferred), with an EER (Energy Efficiency Ratio) of the order of 6-7. Part of the electricity required by the pumps can be supplied by the ORC.

The following sections will aim to describe in more detail (with a degree of interest pertaining the project) the different subsystems of the laboratory.

### 2.1.1 Producer substations

The producer substation represents the concept of a highly flexible polygeneration plant which is able to integrate non-programable renewables with thermal, gas and electricity grids. It has the capability to derive different kind of producer substations from the general concept.

The unit is able to represent both a centralized plant managed by a DHC network operator or a distributed substation, which could recycle waste heat from an industrial process with and without electricity production. The plant can supply both heating and cooling to balance the DHC network, but it is not a traditional Trigeneration or combined cooling, heat and power (CCHP) plant.

The circuit is divided into two parts that work with different fluids, and the absorption chiller allows balancing the network during the emulation of “summer conditions”, when there is an overproduction of heat in the network.

Main components:

- Gas Boiler
- Solar Field
- Counter-flow Heat Exchanger
- Organic Rankine Cycle
- Absorption Chiller

Possible operating modes:

- Power station in heating production mode via ORC
- Power station in heating production mode via heat exchanger
- Power station in cooling production mode via heat exchanger and chiller

### 2.1.2 Prosumer substations

Because of the very low temperature of the “neutral” network, reversible water source heat pumps are needed to increase/decrease the temperature of the energy delivered to the final user. On one hand, these machines will work by using the network as a heat source in space heating and domestic hot water production mode. On the other hand, they will use the network as a reservoir when they need to reject heat in space cooling mode. Moreover, prosumer substations will be equipped with thermal storage for what concerns domestic hot water (DHW). This is due to the fact that typically DHW production with heat pumps without storage is not possible.

### 2.1.3 Heat rejection Circuit

The heat rejection circuit includes a buffer tank (BT) of 2000 l and a dry cooler with a heat dissipation capacity of about 130 kW. This part of the plant can be used with different purposes:

- Heat sink for substations during the emulation of “winter” conditions. Particularly, this circuit must emulate the conditions in the distribution circuit of a house which needs heat for space heating and DHW production.
- Heat source for substation during the emulation of “summer” conditions. The buffer tank is used to emulate the conditions of the distribution circuit of a house in need of heat rejection for cooling.

- Waste heat rejection from the ORC or the HE for tests limited only to the generation plant.
- Waste heat rejection from the absorption chiller condenser in cooling production mode.

#### 2.1.4 Thermal Network

The networks allow reproducing different hydraulic solutions by means of appropriate connections with the ports of the producer substations and the prosumer substations, respectively. This part of the circuit includes also a 2000 l, thermal storage. This storage can be connected both in parallel and in series with the network. On one hand, the parallel configuration allows the balancing of the energy flows and investigating different operating strategies for charging and discharging. Furthermore, the thermal storage can be connected as centralised or decentralised storage. On the other hand, the connection of the storage in series with the network can be used to increase the thermal inertia of the whole system.

## 2.2 PV integration lab

### 2.2.1 PV test

The PV Integration laboratory has the capacity to characterize PV modules and systems, both in the open field and integrated within architectural structures, under real conditions (see Figure 2 ). Moreover, it is possible to test systems that are connected to storage systems and verify their impact on electricity networks.

Currently the laboratory is composed of the following subsystems:

- *Rotating roof mock-up*: a 5 x 4 m rotating roof with a maximum tilt of 60° that can reproduce the pitch of a roof or any other type of cover.
- *Façade integrated*: a 4 x 6 m exterior façade structure can evaluate, under real conditions, the electrical yield of PV modules integrated into the systems of active solar facades. It can support heavy loads to better recreate actual conditions of a building in any weather condition. The structure is divided into six 2 x 2 m modules that can simultaneously accommodate various facades blocks.
- *PV Storage Systems and Inverters*: in the case of inverters, efficiency and MPPT control studies to perform tests according to the IEC 50530 standard.



Figure 2 - Different PV solutions present in the outdoor PV Integration lab



No power is defined for this system due to the fact that it is meant to test different types of modules in different conditions, but in practice it can accommodate up to 45 m<sup>2</sup> of photovoltaic modules.

The PV Integration Lab will provide the data of solar power production to the Energy Management system EMS for the simulation's operation.

### 2.2.2 Real-Time simulator for power grids and power electronics

Thanks to the INTEGRIDS project, the PV Integration lab is also equipped with a real-time simulator (OPAL-RT 4510 in Figure 3) which could be used (dependently on the available software) for different purpose such as:

- Development and testing of protection and control system using Hardware in the loop (HIL) simulation;
- Electromagnetic transients required by power grids and complex and fast power electronics and converter systems;
- Real-time transient stability simulation for transmission and distribution grids;
- Phasor domain solver with a typical time-step of few millisecond to compute root mean square values of voltage and current, as well as active and reactive power.



Figure 3 – Real Time Simulator (RTS) OPAL- RT 4510 hardware

The device is the entry-level simulators but has a flexible and expandable architecture which consist of [1]:

- CPU: Intel Xeon E3 4-core
- FPGA: Kintex 7
- I/O: 16 analog channel and 32 digital channel
- High speed optical interface 4 SFP sockets, up to 5Gbps
- Connectivity: Ethernet, USB, VGA, ...

Three different type of simulations can be performed with this RTS:

- 1) *Model-based design simulation*: all the components are simulated, and this typology is particularly useful for proof of concepts of the considered system, functional description and preliminary design phase. The model is implemented in a PC using MATLAB/Simulink® and though the RT lab [2] the model is translated and charged in the RTS for the real-time execution of the models. In this modality a possible application is the study of electric grid stability or EM transient on transmission systems.

## Model-based design

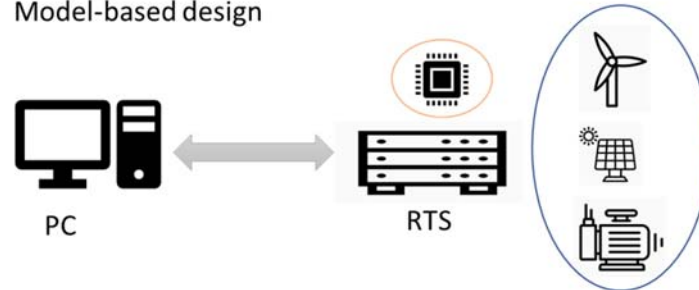


Figure 4 – Conceptual schema of model-based design simulation

- 2) **Hardware in the loop (HIL) simulation:** it is possible to test a real controller with a simulated power plant. In particular, the model and the test are designed in the PC, sent to the RTS where a real controller is connected using the I/O interface. In this case it is possible to directly test the hardware and its logic in a safe and controlled way. A possible application is the test of protection relay or electrical drive.

## Hardware-in-the-loop simulation

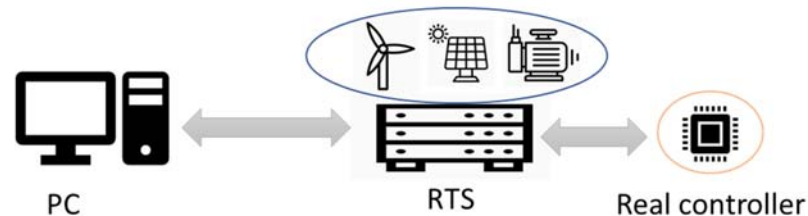


Figure 5 - Conceptual schema of HIL simulations

- 3) **Rapid control prototyping (RCP) simulation:** this operational mode allows us to test the control algorithm with a real power plant (e.g. photovoltaic, motors, wind turbine, ...). The model is developed in a PC using Matlab/Simulink®, the model is transferred to the OPAL-RT and where I/O are connected to a power amplifier (PA) able to transform the low voltage signal to electric quantities comparable with the real device under test (DUT). A possible application is a microgrid integration with power exchanges or inverter test.

## Rapid control Prototyping simulation

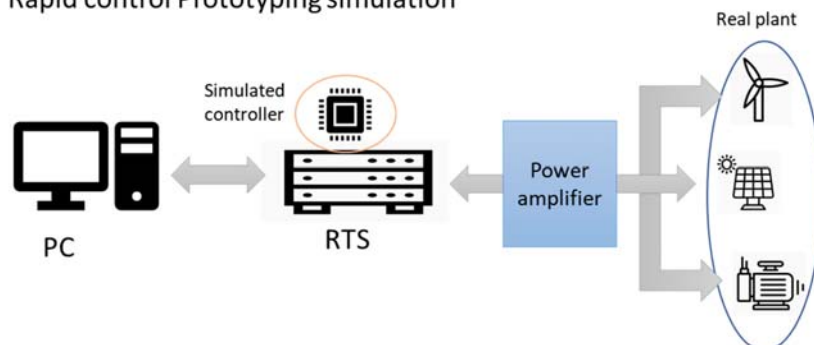


Figure 6 - Conceptual schema of RCP or Power hardware in the loop (PHIL) schema

At the moment, only the simulation 1) and 2) could be performed with the current infrastructure due to the lack of power amplifier. However, the simulation mode 3) will be possible in the future project with the acquisition of the PA.

In the INTEGRIDS framework, the simulator will be mainly used to implement a portion of a test distribution grid where the information about production, demand or HP profile will be possibly sent by the PV installed in the mockup, Multi-Labs and Exchanges respectively.

## 2.3 Multi-lab

The Façade Systems Integration Lab, also called MultiLab, is an experimental facility designed for the testing of building envelope components such as multifunctional façade systems, and for conducting analysis on indoor environmental quality including thermal comfort studies with human participants.

In this lab, there are two identical environmental test chambers (see Figure 7) designed to guarantee an accurate control of the indoor environmental conditions. Furthermore, the whole laboratory can rotate around a central axis enabling the possibility to decide the direction the façade samples face, and therefore to simulate the effect of different orientations. The ventilation system can deliver fresh air at a defined set-point temperature and relative humidity in each test chamber independently. The floor, ceiling, and non-replaceable walls of the environmental chambers cells are equipped with radiant panels to enable the control of the surface's temperature. Depending on the test, an additional optional circuit may be used to control the inner surface temperature of the sample, too.

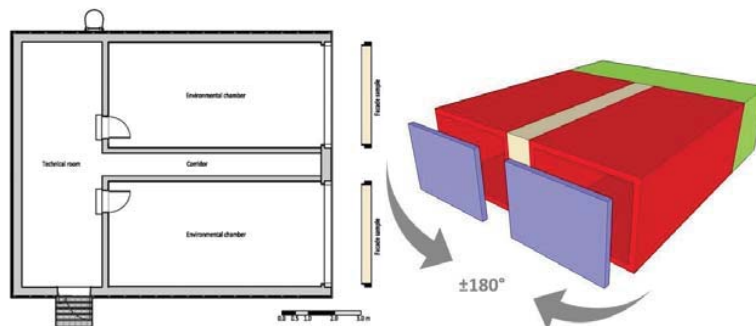


Figure 7 - MultiLab's Floor Plan and 3D View

As this laboratory will be fully operative by the end of summer of 2019, in the meanwhile data that this lab would provide to the simulation will be provided instead by stored consumption profile data, synthetic profiles produced within the simulation software or from external sources.

## 2.4 Weather station

As in any weather station, the locally called “MeteoStation” realizes the measurements of:

- Wind Speed
- Wind Direction
- Ambient Temperature
- Relative Humidity
- Total Irradiation
- Diffuse Irradiation
- Direct Irradiation

The sensor for the first 4 is located on top of the PV Integration Lab (Figure 8a), the pyranometer is located outside the central control room of the outdoor lab (Figure 8b), and the user interface PC cabinet (Figure 8c). These measurements will be distributed to the respective three labs, through the communication system, according to the respective data they require for their operation.



(a)



(b)



(c)

Figure 8 - Wind, Temperature and relative humidity sensor (a); Pyranometer (b) and MeteoStation User Interface Cabinet (c)

### 3 INTEGRIDS laboratory

As it was previously established the aim of INTEGRIDS is to simulate the interactions of a coupled thermal grid and electricity grid. As shown in Figure 9, the main components of the system and their contribution to the simulator will be:

- HP1 of 25 kW: operation under instructions.
- HP2 of 35 kW: operation under instructions.
- CSP field of 45 kW<sub>th</sub>: thermal power production data.
- PV modules: electrical power production data.
- MultiLab: electrical and thermal demand profiles.

- Integrids Server: where the EMS and simulation will be digitally executed.
- OPAL-RT 4510: complex systems simulator.

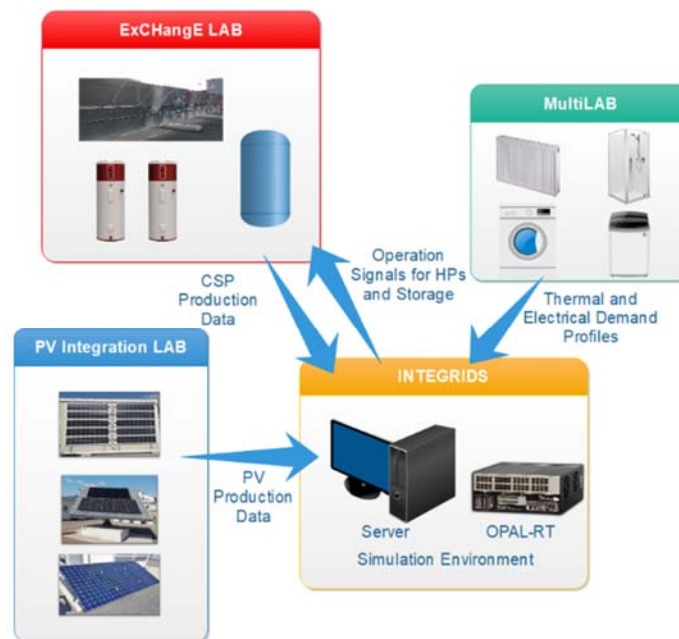


Figure 9 - Scheme of components and their respective physical locations and interactions

The simulation environment of Integrids will be composed of the server where the energy management system will be running, and the OPAL-RT 4510.

As described in previous sections, the components of the system will interact only by communicating information and virtually, through the simulation environment to study and analyse the different scenarios.

The interaction of the physical components with their simulated reproductions will be indirect. When the HPs are operational, the simulation program will signal the HPs when to turn on or off (but no direct control will be exerted), and in cases where they are not operational the program will present a model equivalent of the equipment in order to perform the simulations as accurately as possible. Moreover, as each laboratory already has a defined control system, signals will be sent to each lab to determine the operation of the components, and the internal control system of each lab will react to them.

### 3.1 Communication and data infrastructure

To develop the simulation platform for the project, the first step is to determine the current system components and the needed changes or improvements, that the system will have in order to realize effective communication between the different elements of the system.

The communication system will be comprised mainly of Modbus and TCP/IP communication protocols between the signals acquired by the physical DAQ and the LabVIEW programs. The programs to manage such communication and data management operations will be running one per lab. They will acquire the data, process, transmit to other labs, and store it in the databases accordingly.

On the software side of the system, LabVIEW was used as the platform to develop the program that will acquire, interpret, process and transmit the data from the different sensors and meters to their destinations (labs or simulation environment).

To improve the system performance and simplify data transmission, the Networks Streams method will be used to exchange data between one lab and another (one application to another), for data readout, visualization or storage. This is needed due to the fact that, depending on the lab, it may have interest on data from another lab or the MeteoStation. The advantage of this programming tool is that it is an easy-to-configure and dynamic communication method for transferring data from one application to another without throughput and latency, with characteristics comparable to TCP (transmission control protocol) within the LabVIEW environment. Additional value lies in its point-to-point communication capabilities, involving a writer of data (e.g. the different labs) and a reader of data (e.g. the simulation computer or another lab). In Fig. 9, an illustrative image of the network streams data flow is shown.

In Fig. 10, the different system components of the communication system can be seen, as well as their correspondent laboratory. Even though MultiLab is not physically present at this stage of development of the project its presence will be considered in the scheme.

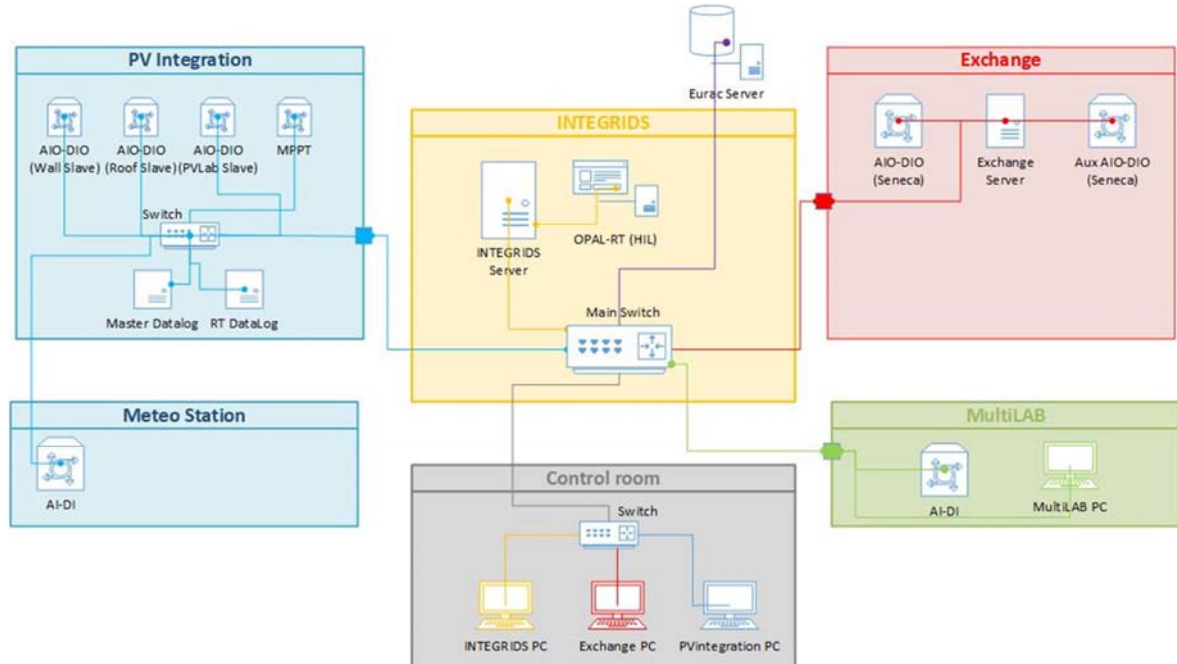


Figure 10 - Communication infrastructure and diagram of connections

From the diagram we can see:

- AIO-DIO: Analog Input/output and Digital Input/output devices.
- Switch and Main Switch: connection stations for wired devices.
- Servers: data storage systems.
- Data Loggers
- PC: viewing systems and programming tools.
- OPAL-RT: real-time simulator of complex systems as distribution grids, or hardware-in-the-loop<sup>i</sup> for inverter simulation and digital prototyping.

All the data produced and received by the different labs, the MeteoStation and the Integrids simulation environment will be stored in a database. The database will be developed in InfluxDB

which allows the storage of large timestamped data and offers the possibility to produce dashboards for data visualization, and it requires SQL for querying the data for extraction.

### 3.2 Plant Control Software

In this paragraph it will be sketched the idea behind the Plant Control Software (PCS), the software already successfully applied in both the Energy Exchange and the new Heat Pumps laboratories, which will be extended also to the Integrids infrastructure. The idea behind PCS is that all control systems are affine between each other, as they normally share a certain number of functionalities and a certain amount of structure (relationships between the elementary components of the architecture). The management of an industrial plant or a research laboratory always involves the setting up of an entire hardware and software infrastructure when the laboratory or manufacturing plant is constructed and the procedure to maintain it when they are operated. The diagram in Figure 11 shows what we call managed plant, a model that captures the essence of such infrastructures. The managed plant is the extension of what is just usually called plant to include the human operator and its relationship with it. This diagram describes the components, their relationship and the information flow. The arrows indicate information flow. They can represent audio, video, verbal and electrical communication<sup>1</sup> or mechanical action, depending on the components involved in the communication. The boxes represent hardware and software components of the managed plant or the actors involved in its operation. The managed plant is a cyber-physical system consisting of men and machines operating together to attain an end and it is operated to obtain one or more products. When the managed plant is a research laboratory (also called experiment), its output is new information about how the object under investigation<sup>2</sup> behaves, when it is a manufacturing plant, the output is the collection of the assembled goods.

The most important components in the diagram are the Plant, which, for the Energy Exchange laboratory, is the collection of the pipes, circulators, temperature and flow sensor and machine making it up, the Plant Control System, which is the collection of all the hardware resources needed to implement a digital control system (industrial computers, programmable logic controllers, input and output modules, monitors, mass storage devices and so on), and human personnel. Personnel is divided in Operators, the people involved in the supervision and control of the plant operations, Blind Operators, people that may happen to take control of the plant without having the knowledge, the expertise or the title to do it, and Observers, people that may look at the monitors or hear the alarms of the plant but will never interact with it. Surely, Blind operation is always to be avoided, and the organization managing the plant needs to take any measures to avoid Blind Operators as this can represent a serious safety and investment protection issue. Also, Observers are likely to be avoided for efficiency reason. What would motivate their salary if they are not going to be part of the feedback loop? If strong motivations can be given to this question, Observers are fine. Care must be taken to avoid the possibility that an Observer becomes involuntary a Blind Operator. For these reasons, Blind Operators and Observers are placed outside the domain of the Managed Plant. Operators, which fully belong to it, are qualified experts which have been properly trained to operate the plant and are in the appropriate phyco-physical conditions to do so. Care must be taken to avoid the possibility that an Operator becomes involuntary a Blind Operator, for example due to lack of training or excess of self-confidence.

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<sup>1</sup> This category includes data movement between different memory locations and between memory and mass storage systems of computing devices.

<sup>2</sup> Which may be a body or a machine not part of the laboratory, the laboratory itself or parts of it.



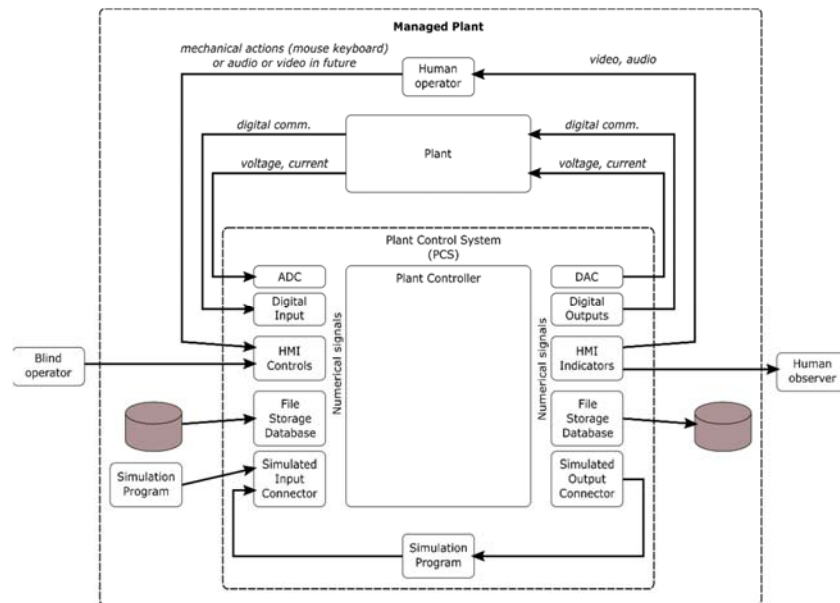


Figure 11 – Elements and information flow in the Managed Plant concept.

Please note that for the sake of simplicity the control system is sketched in this figure as a centralised one. This is not technically the case for the Energy Exchange laboratory and, obviously, for the Integrids infrastructure seen itself as a laboratory. In fact, both are design as hierarchical, distributed control systems involving more control nodes connected in a network. Regarding the control system of the Energy Exchange laboratory, three level can be identified:

1. the field level, where sensors (electrical transducers) and actuators (normally devices transforming electrical energy in kinetic energy) lie;
2. the local control level, where the input and output electronic equipment connected to the lower level lies;
3. the supervisory control level, where the supervisory control and interaction between Operator and Plant take place.

Normally objects at the first (field) level are connected to their controllers (objects at the second level) by galvanic connections where the information is represented by a voltage or a small current of the order of tens of mAmpère. It is possible that complex machines like Heat Pumps or Chillers are connected to their controllers directly via a numerical communication channel using industrial standards like Modbus RTU, CANbus, Serial Communication. This is also how normally objects in the second level are connected to the object(s) of the third level, the supervisory control.

The three laboratories, Energy Exchange, PV Integration and MultiLab, are integrated in the Integrids concept by adding a new processing node in the network (the Integrids server) and fourth level in the hierarchy, the Integrids level. The central, supervisory controllers of each laboratory are connected to the Integrids server via TCP/IP connections.



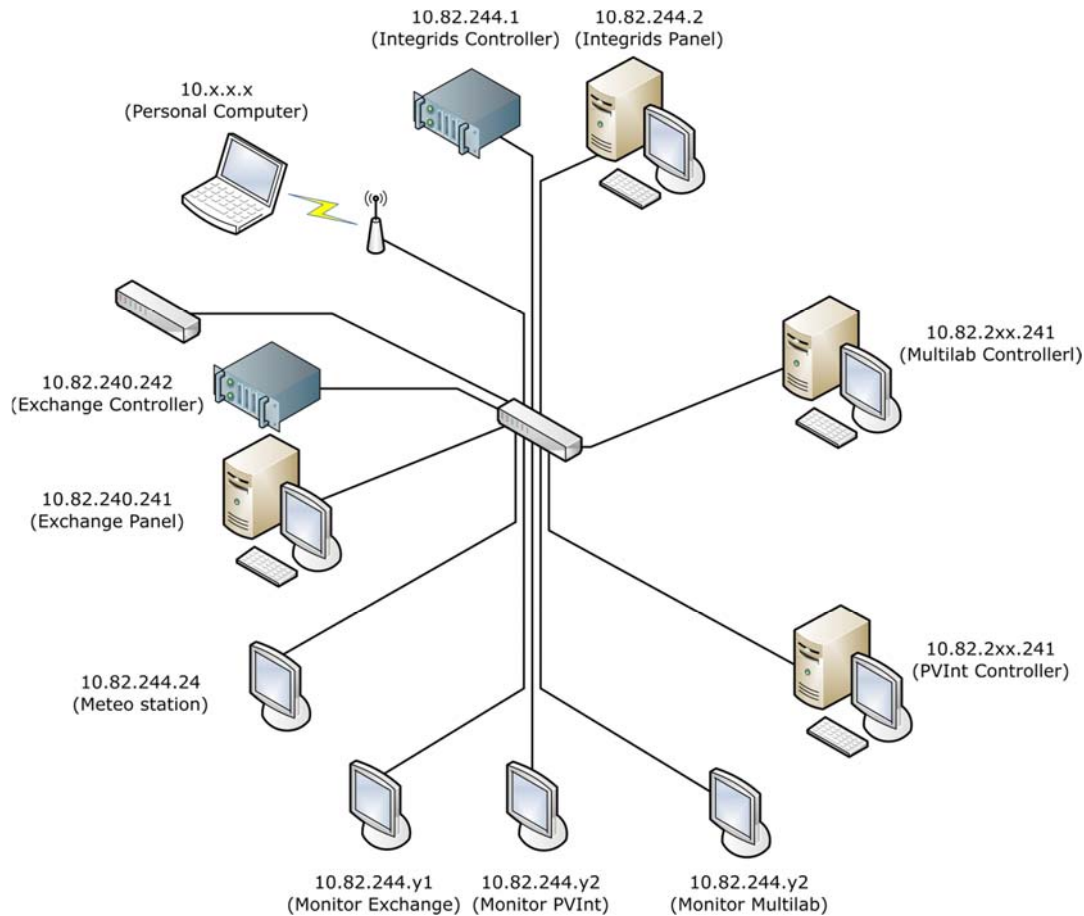


Figure 12 - Relevant nodes in the Integrids network. Please note that the picture does not include all the nodes belonging any of the Integrids laboratory. The Energy Exchange laboratory would require a picture of similar complexity to describe itself. Moreover, the picture is subject to updates as the labs are continuously developed.

Software is implicit in the figure above. Nevertheless, it is an essential component of any digital control system. The implementation of the Integrids concept heavily relies on the control software developed in the past by the experts of the Renewable Energy Institute of Eurac Research and by the software developed within the Integrids project. Overall, the complexity of the software is at least the same level, if not higher than that of the plant itself. Software components belong to three different software libraries, developed as independent projects:

1. BaSyCo (Basic System Control), a container for basic communication tools and control elements such as proportional-integral-derivative (PID) controllers
2. Plant Control Software (PCS), the project containing the software libraries used to implement the controls of the laboratories (Energy Exchange, Integrids and Heat Pumps in particular)
3. IODrivers, the project where low-level software connecting to the hardware is placed.

Note that the acronym PCS may refer to the control system of a generic plant (Plant Control System) or hereafter, to the software run by part of the controllers of the Eurac Research laboratories, including Integrids (Plant Control Software).

For the Integrids project, new and existing software belonging to the PCS project has been re-organized into the following libraries:

1. PCS-Core
2. PCS-Exchange

3. PCS-HPLab
4. PCS-HPLab-A1
5. PCS-HPLab-A2
6. PCS-HPLab-WE
7. PCS-Integrids

PCS is written entirely using the object-oriented programming paradigm of the G graphical language<sup>3</sup>. A small per of the code is written in Python 3.6 for scripting and connection with databases. Connections are with the MDSplus and InfluxDB databases.

The development of the software for a new laboratory, is done by specialisation of key classes contained in the PCS-Core library, which are:

1. Self
2. ErrorLogger
3. Message
4. SystemCommand
5. MDSplusConnection
6. ModbusConnection
7. StreamConnection
8. Event
9. Exception
10. SyncEvent

The Self class is a “partial” class (conceptually virtual, although it can be instantiated) at the very heart of the software architecture. For each laboratory in the Integrids project (and other laboratories outside it) a Controller and a Panel class are derived from it to implement specific controller features. The class self makes use of the classes ErrorLogger, MDSplusConnection, ModbusConnection, StreamConnection, Exception and SyncEvent to provide the following services:

- Global error management, video error visualization and on-disk error logging;
- Automatic connection (configurable via configuration file) to other sibling processes created by deriving from Self;
- Configurable bi-directional communication channel with any such processes in any local network;
- Configurable modbus TCP/IP communication channels;
- Configurable connections to database to store experimental data and configuration data;

Any application created with the above mechanism enjoy the following properties:

- Two instances of the same executable can run on the same machine (can ease debug phases);
- A fault of the physical level does no cause the distributed application to crash. The application can revive if the physical layer is rehabilitated.

The last two properties are extremely important for the robustness of the infrastructure and not easy to achieve on the field. Therefore PCS, with its core libraries PCS-Core, represent a significant value in the project.

During the development of a new application with PCS (that is the development of a distribute controller), apart from the process, also the Message class is likely to be derived. The Message class is the ancestor of any message exchanged by the nodes of the distributed controller.

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<sup>3</sup> In fact, the implementation of it called LabView, provided by National Instruments.

Messages are characterized by a family, a genus and a payload. The currently defined families are:

1. System commands
2. Exchange data frames
3. Exchange commands
4. HPLab data frames
5. HPLab commands
6. Integrids data frames
7. Integrids commands

The System commands family is implemented already at the PCS-Core level as a specialization of the class Message which defines correct enumerative type for the genus of the derived class. Each application must develop its own families and genres. The screenshots of **Error! Reference source not found.** show the structure of the DataMessage class in the PCS-Integrid library and the shape of its meteo-station genus produced by the meteo station.

Early versions of PCS have been tested during its development with a dummy application called ElabNode (from elaboration node) in the two network configurations shown in **Error! Reference source not found.**. The test conducted so far have been successful.

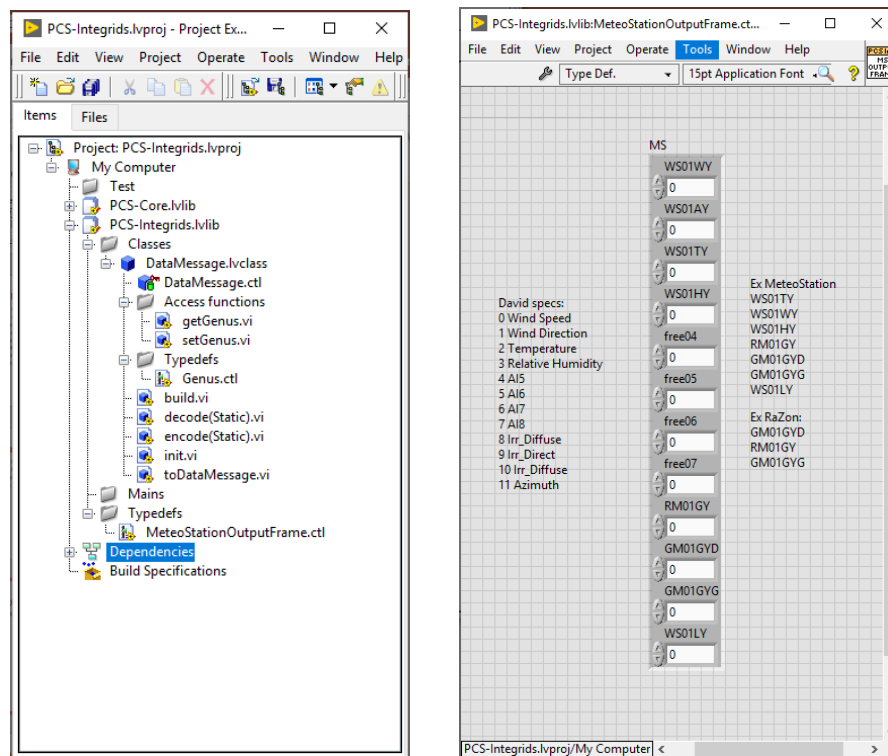


Figure 13- Screenshot of PCS structure for Integrids including only the weather station. On the left the structure of the PCS-Integrids:DataMessage class. On the right the layout of the data in the meteo station genus.

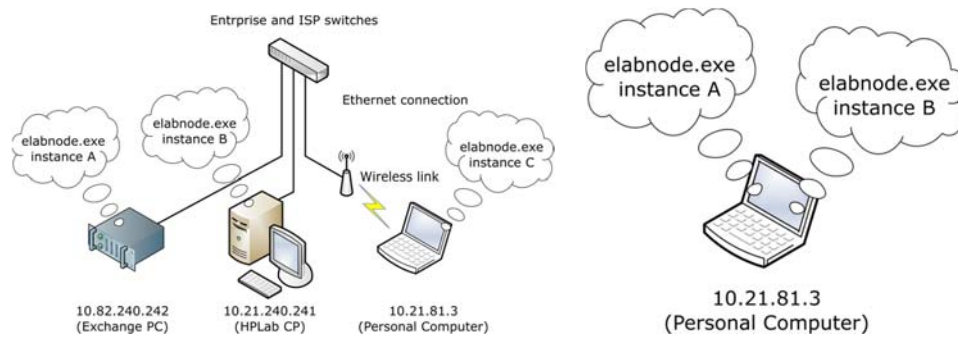


Figure 14- Configuration of test node. On the left three instances of the dummy application running on three different machines (network nodes) communicate over a local network. On the right two instances of the dummy application communicate to each other using the loopback connection.

#### 4 Communication and system design: the weather station example

As it was previously mentioned the development of the software to acquire data, store it and perform the simulations will be performed in the LabVIEW environment, moreover, the hardware of the acquisition system will be composed of cRIOs and Seneca modules. In this section the work developed regarding the design of the MeteoStation will be presented. The data coming from such station will be used in the other labs to perform their operations and the experiments of Integrids, gather relevant weather information, and for future references aid forecasting possibilities in the EMS program.

Mentioned previously, for the simulation environment to operate successfully, a DAQ and management program will be installed in each of the labs. As one example of the programs developed for the Integrids project infrastructure, the main parts of the code developed for the MeteoStation program will be shown and described in regard to functionalities, due to the fact that as the program uses a lot of sub-programs, smaller software applications or programs that are used to operate (in this case they were custom-made), only the first two levels (from top to bottom) were chosen to be presented.

The software for the data acquisition, storage and transmission of each station is composed of 6 blocks, as seen in Figure 15:

- RAM metering: for the computer where the program is being executed, in order to identify if the program is working correctly, using the correct resources or if it is not operating as desired and should be improved.
- Initialization: the connection phase of the program with the different points of the system as the FPGAs or cRIOs where the sensors are connected (Figure 16).
- HMI or human machine interface: visual interface of the program in the computer screen for the user to visualize data or operate, if the program allows it.
- DAQ: data read out or acquisition from the sensors through the physical acquisition system.
- Log: data processing for storing the data in the system, database or its transmission to other labs and the simulation system (Figure 17).
- Close: closing of data communication channels before finalizing the program. If this last part is not designed and executed correctly it will usually generate problems in the moment or reconnecting through the different communication channels that the program uses to connect to the meters or the other labs.

The following images present the code developed to create the data of the MeteoStation. Similar code is and will be developed also for the other labs in order to gather and send data to the

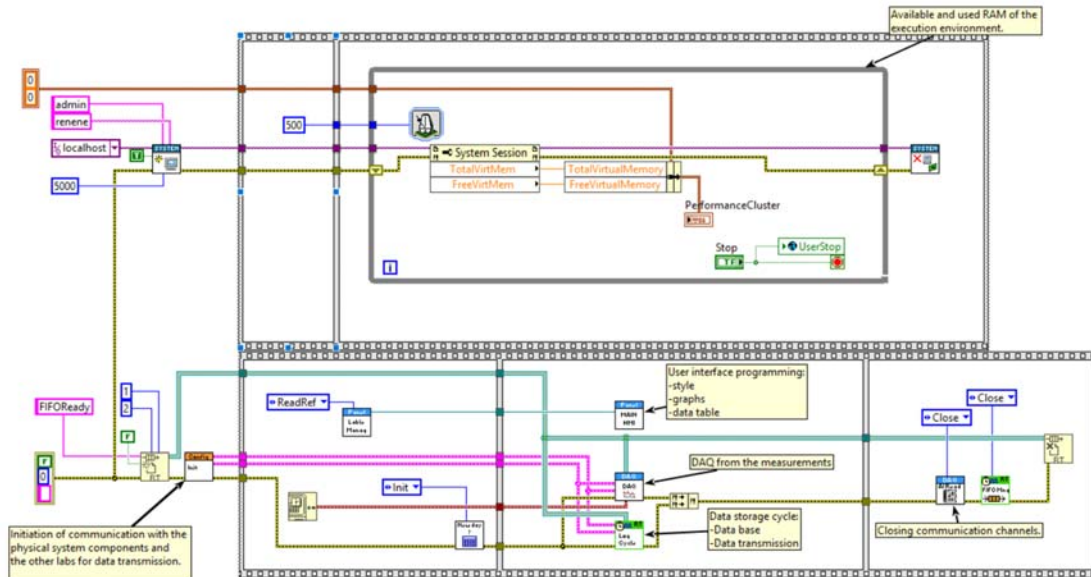


Figure 15 - MeteoStation LabVIEW Code, main level

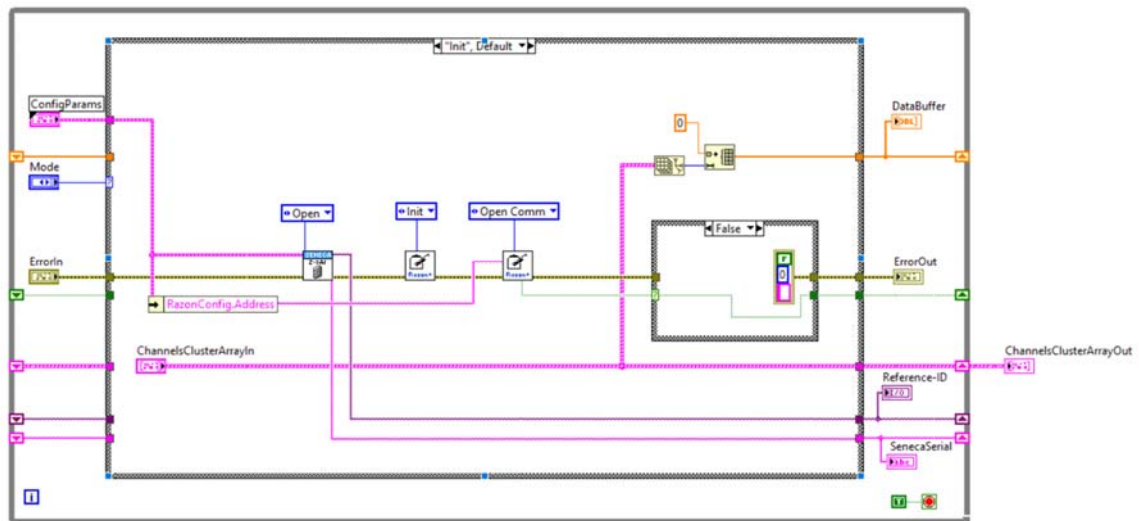


Figure 16 - Initialization of the communication channels with the physical DAQ devices (Pyranometer and Seneca Modules)

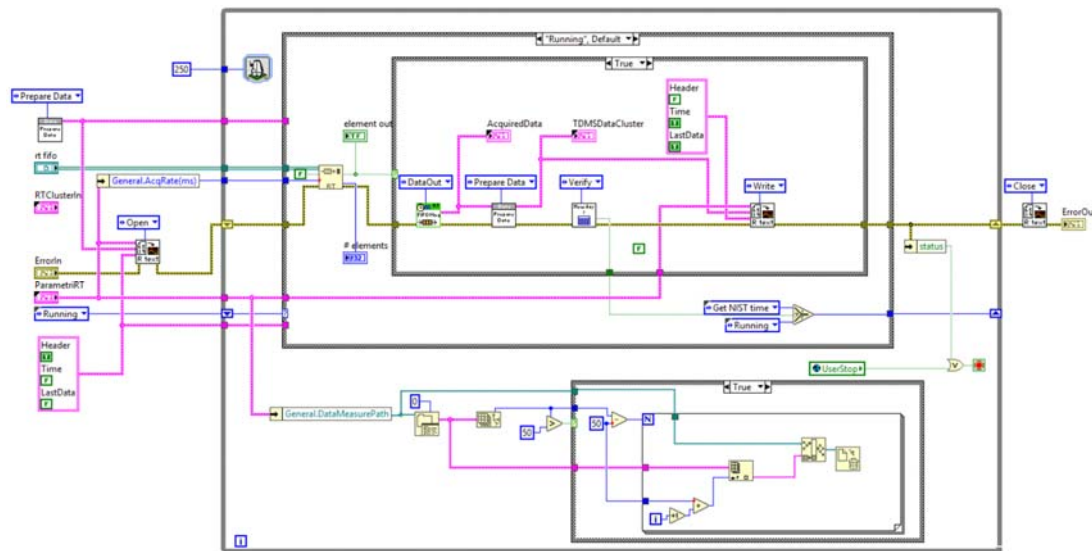


Figure 17 - Data Storage Cycle

As one example of physical data acquisition system, the MeteoStation's communication infrastructure will be described. The physical equipment, without considering wires and antennas, is composed of:

Z-8AI: 8 channel analogue input module, where wind and temperature sensors will be connected.

Z-LINK1: 2 modules, used as transmitter and receiver to transmit the data gathered by the precious Z-8AI.

Z-KEY: transforms the Modbus data transmission protocol from the Pyranometer to TCP/IP.

The set up works as follows. The acquisition module Z-8AI is used to gather the input data (wind speed, wind direction, ambient temperature and relative humidity; seen in Figure 19 a) and as it is connected to the Z-LINK1 module (Figure 19b) it transmits the data to the receiver Z-LINK1 module (Figure 20). The receiver module is located outside the labs, in the cabinet where the user interface PC (with the MeteoStation user interface) is located. Afterwards by use of a Modbus cable and adapter for computer connections, the signals are sent to the computer. On the other hand, the Z-KEY will be receiving the data under Modbus protocol from the pyranometer, in order to transform it to TCP/IP protocol and transmit it via ethernet cable to the PC (Figure 20 and Figure 21). The reason for not simplifying the system, by using only Modbus protocol, was due to the ineffective operation of the data transmission when deploying the communication infrastructure from the pyranometer to the computer. A visual scheme of the situation is presented in Figure 18.



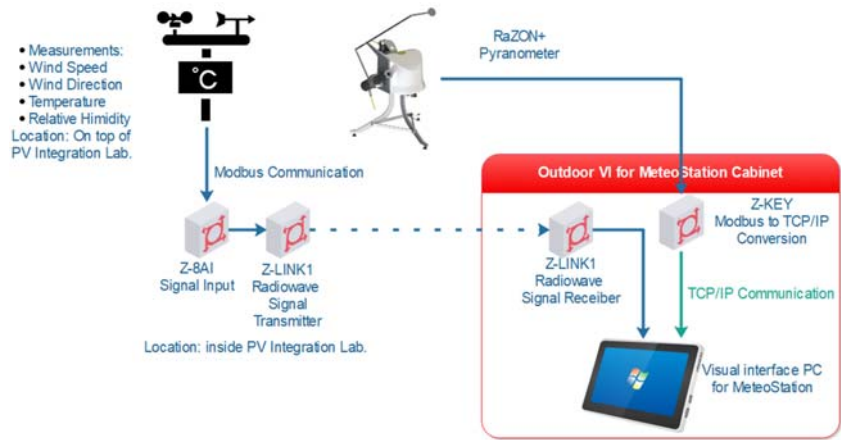


Figure 18 - Scheme of components for MeteoStation



(a)



(b)

Figure 19 - Wires from the sensors (a). Wires connected to Seneca Z-8AI and radio transmitter (b)



Figure 20 - Data reception from Transmitter (z\_Link1) and Pyranometer (Z-KEY)



Figure 21 - Z-LINK receiver and Z-KEY transformer, and the respective connections to the PC



## References

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  - [2] "Software simulation | Real Time applications | RT labs," *OPAL-RT*. .
  - [3] Wikipedia entry for "LabView", <https://en.wikipedia.org/wiki/LabVIEW>
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