IEA EBC Annex 67

Laboratory facilities used to test energy flexibility in buildings

A technical report from IEA EBC Annex 67 Energy Flexible Buildings

Laboratory facilities used to test energy flexibility in buildings

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Preface

The increasing global energy demand, the foreseen reduction of available fossil fuels and the increasing evidence off global warming during the last decades have generated a high interest in renewable energy sources. However, renewable energy sources, such as wind and solar power, have an intrinsic variability that can seriously affect the stability of the energy system if they account for a high percentage of the total generation.

The Energy Flexibility of buildings is commonly suggested as part of the solution to alleviate some of the upcoming challenges in the future demand-respond energy systems (electrical, district heating and gas grids). Buildings can supply flexibility services in different ways, e.g. utilization of thermal mass, adjustability of HVAC system use (e.g. heating/cooling/ventilation), charging of electric vehicles, and shifting of plug-loads. However, there is currently no overview or insight into how much Energy Flexibility different building may be able to offer to the future energy systems in the sense of avoiding excess energy production, increase the stability of the energy networks, minimize congestion problems, enhance the efficiency and cost effectiveness of the future energy networks. Therefore, there is a need for increasing knowledge on and demonstration of the Energy Flexibility buildings can provide to energy networks. At the same time, there is a need for identifying critical aspects and possible solutions to manage this Energy Flexibility, while maintaining the comfort of the occupants and minimizing the use of non-renewable energy.

In this context IEA EBC Annex 67 Energy Flexible Buildings was started in 2015 with the aim of gaining increased knowledge on the benefits and services the utilization of the Energy Flexibility in buildings may provide to the future energy networks. The present report is one among several outputs from IEA EBC Annex 67. For further information, please visit http://www.iea-ebc.org/projects/ongoing-projects/ebc-annex-67/.

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1. Introduction

The International Energy Agency (IEA) manages several research programmes, among which the Energy in Buildings and Communities (EBC) programme. The Annex 67 of the IEA EBC focuses on the energy flexibility of buildings, its potential and how to harness it. Sixteen countries have joined this Annex to gather the research efforts towards a better characterization and understanding of energy flexibility in buildings.

The first subtask of the Annex (Subtask A) relates to the definitions, terminology, methodologies for characterization and market analysis of energy flexibility. As for Subtask B, it focuses on implementing flexibility strategies and verifying their performance. In this way, the theoretical flexibility potential can be evaluated against experimental data. Activity B.3. especially consists in laboratory tests of components, systems and control strategies. In this framework, several partners have made their laboratory facilities available for the needs of the Annex 67 as well for the scientific community and the industry. The names and the location of the laboratories included in this report are summarized in the following table:

Name	Managed by	Location
SEILAB	IREC - Catalonia Institute for Energy Research	Tarragona, Spain
Energy Smart Lab	IREC - Catalonia Institute for Energy Research	Barcelona, Spain
NZEB Emulator	VTT / Aalto University	Espoo, Finland
EnergyVille labs	EnergyVille (VITO, KU Leuven, IMEC)	Genk, Belgium
OPSYS test rig	Danish Technological Institute (DTI)	Taastrup, Denmark
ZEB Living Lab	NTNU / SINTEF	Trondheim, Norway
Semi-Virtual Laboratory	Polytechnique Montréal	Montréal, Canada

In order to better understand the capabilities and specificities offered by the available laboratories, the present report draws a description of each test facility. For each one, a general presentation of the lab enables to quickly understand the purpose of the facility. The interested reader then has access to a more detailed description, with the technical specifications of the installation and illustrations. Some examples of previous tests performed in these labs are also presented, along with references to the corresponding publications. The final objective of the report is to provide a clear overview of the potential offered by the testing facilities in the network of Annex 67. In this way, any interested stakeholder, within or without this network, can contact directly the responsible entity in order to perform experimental testing in these facilities.

2. Semi-virtual Energy Integration Laboratory (SEILAB) - IREC

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2.1. General presentation

The Semi-Virtual Energy Integration Laboratory (SEILAB) provides advanced expertise to assess the development and integration of renewable energy solutions and innovative thermal and electrical equipment that are designed to improve energy efficiency in buildings and energy systems. The laboratory is provided with cutting-edge technology comprising systems for energy generation, heat and cool storage and state-of-the-art facilities for testing HVAC equipment and the interaction of energy systems with the grid. The laboratory operation is based on a semi-virtual testing approach, which allows for real equipment to be operated as a function of the behaviour of a dynamic virtual model. The laboratory is pioneer in addressing the smart integration of electrical and thermal components and aims to become a leading experimental facility for improving the development of Net Zero Energy Buildings and Flexible Energy buildings.

2.2. Description of the test facility

2.2.1. General principle and testing possibilities

General testing principles

The general concept of the semi-virtual testing is presented in Figure 1. A real physical device is placed in the lab, where it is studied under specific conditions that are simulated and implemented in the virtual environment. The overall principles are as follows:

- Testing the performance of components or complex energy systems under defined building and environmental conditions
- Development and integration of innovative sustainable, renewable building energy supply systems.
- Analysis of equipment behaviour at particular transitory phases

Detailed testing principles

- Experimental testing of thermal and electrical equipment performance under real-life dynamic conditions, addressing a range of climate zones and thermal building behaviour scenarios.
- Comparison on the performance of equipment provided with particular innovative control concepts to ensure adequate system reliability in real applications.
- Assessment and improvement of innovative efficient energy technologies, such as energy storage systems, photovoltaic and thermal solar systems, nanofluids for HVAC equipment and micro-cogeneration.
- Development of novel measurement methodologies and test protocols to assess realistically the energy performance of thermal and electrical equipment beyond testing methods established in current international standards, including analysis of the Seasonal Performance Factor.
- Optimisation of operation for multiple energy sources and loads for matching energy generation and demand, including microgrid interaction.
- Development of detailed and/or simplified models for use in system simulation software and of learning-method predictive techniques for thermal components performance that are validated using test bench experimental data.

- Research on the integration and effects of local building components in smart energy systems to achieve Zero and Positive Energy Buildings.
- Research on control systems for flexible buildings, including renewables.
- Environmental testing of building components and electrical equipment under realistic climatic conditions in a room-sized climate chamber.

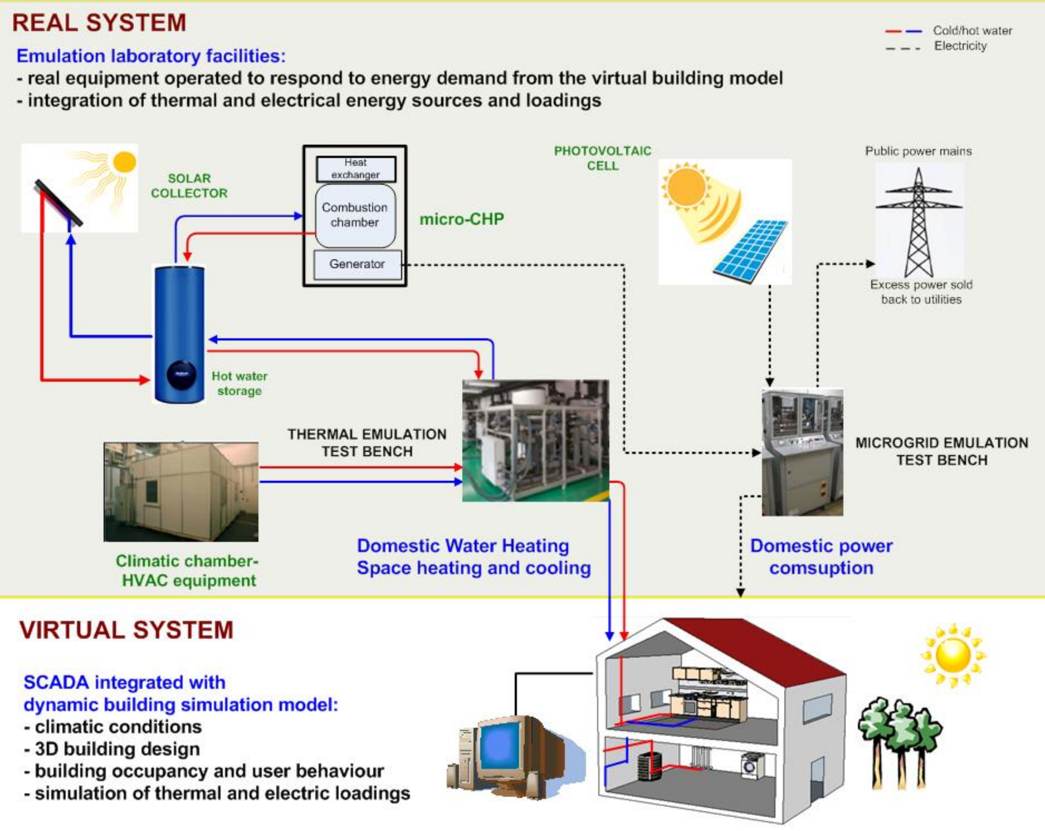


Figure 1. General concept of the semi-virtual testing.

2.2.2. Equipment available and specifications

Climate chamber

The laboratory counts with a walk-in climate chamber (shown in Figure 2) for testing different devices. The climate chamber generates the environmental air characteristics (temperature and humidity) according to the climate conditions in the standards. The chamber is provided with a set of 24PT100 sensors, 2 pressure sensors, 4 humidity sensors and 10 hot wire anemometers for air velocity measurement, which are regularly

Figure 2. Picture of the SEILAB climate chamber.

maintained and calibrated. The climate chamber has a volume of 45 m3, with the following range for temperature, humidity and air flow control:

- temperature range: -30 to +60°C
- RH: 15-98%
- air flow: 8000-10000 m^3/h
- maximum power of condenser: 46.8 kW

Hydraulic thermal test benches

The laboratory counts with a set of thermal test benches for emulating the heat and load source, as specified in standards EN14511, EN16147 and EN14528. The thermal test benches consist of a set of hydraulic loops which are equipped with hydraulic components such as flow meters and motorized valves to control the flow and temperature to the heating/cooling unit under testing. Water circulation is achieved by means of circulating pumps equipped with frequency inverters and high speed modulating control valves provided with magnetic actuators. The hydraulic circuits include expansion vessels and security valves that are installed as standard with piping isolated by means of 30 mm synthetic rubber material. The water used in the installations generally is decalcified and mechanically filtrated. Temperatures are measured with Pt100 in 3 wired circuit sensors with terminal head form B tolerance class A (EN 60 751). Calibration is performed regularly on the flow meters and temperature sensors. Hydraulic pressure is measured in every test bench with digital pressure meters.

Along with measurement systems, the test benches are provided with the following control elements:

- 2 magnetive-inductive flowmeters Endress & Hauser per test bench for volume flow measurement
- 2 precision control valves for flow and temperature control per test bench.

The available thermal test benches have the following characteristic in terms of heating performance:

- water temperature range: -7ºC – 150ºC
- water flow range: 3.5-9 m3/h
- maximum heating power per sample: 30kW
- maximum cooling power per sample: air-to-water 15 kW, water-to-water 30kW

Temperature, flow and pressure measurements in the thermal test benches fulfil requirements specified in the EN14511, EN14528 and EN16147 standards. The instrumentation in the laboratory allows for a very fast control of temperatures and water flows to emulate loads, which allows its application both for emulating steady-state and transient dynamic profiles.

An additional test bench for emulating data centre cooling is also present in the lab.

PV system

A PV system is installed on the roof, summing up to an installed capacity of 3.5 kWp. A photo of the equipment is presented on Figure 3.

Figure 3. PV equipment on the roof of SEILAB.

Other equipment

Several other devices are available in the lab:

- 1 heat pump air-to-water Buderus (7.4 kW heating, 8 kW cooling)
- 1 heat pump water-to-water Dynaciat (40 kW heating, 34 kW cooling)
- Water storage tanks of 1500, 1000 and 300 liters
- Micro data centre of 1.2 kW partially water cooled
- Gas boiler Saunier Duval Themafast 25-A
- 2 electrical test benches (emulated power 5.5 kVA, max generation connected 10 kVA, max consumption connected 10 kVA)

2.2.3. Data acquisition and control

The tests are performed by means of a control system created in the laboratory. The software allows for visualising the operation of the laboratory equipment, controlling the test performance and performing data acquisition. Communications are based on Modbus TCP and RTU industrial protocols, with the laboratory software communicating with actuators and sensors via automatic controllers and data acquisition modules through RS485 connections.

A Labview interface (Figure 4) enables to communicate with the different elements being tested in the lab. This interface can be connected to transient simulation software TRNSYS, where building models can be implemented to simulate the heating or cooling loads of a building or the performance of the virtual part of the system. Other software than TRNSYS, such as Energy Plus or IDA-ICE can be connected with the Labview interface. Remote visualisation of experiments in real time is possible for external collaborators.

In addition, a weather station is placed on the roof and connected to the lab interface. It measures the ambient air temperature, the wind velocity, the relative humidity and the global and diffuse radiation.

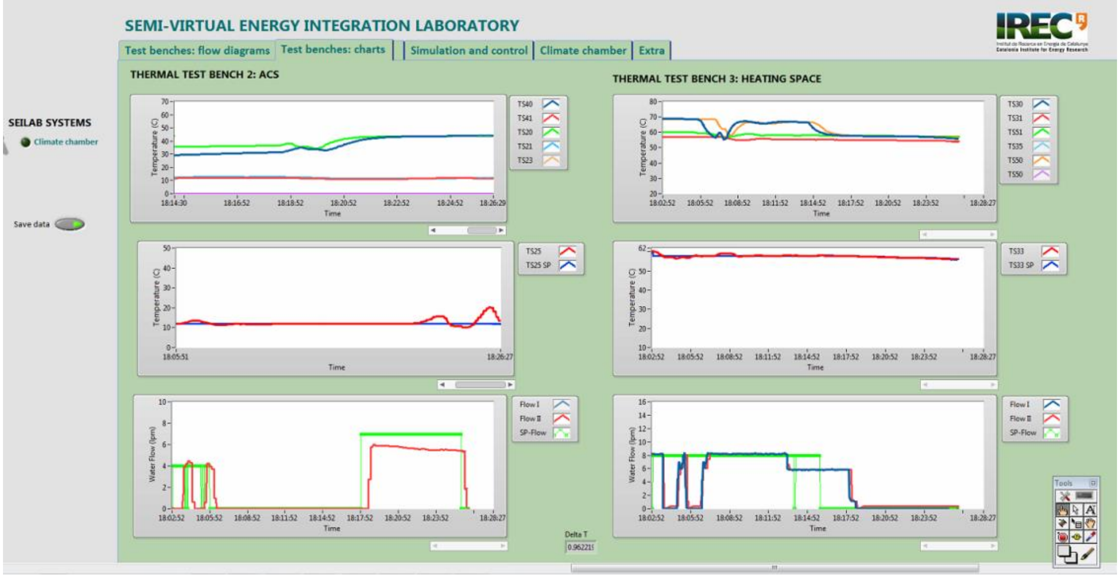


Figure 4. Screenshot of the Labview interface.

2.3. Examples of previous studies

2.3.1. Study 1: Experimental Study of Grid Frequency Regulation Ancillary Service of a Variable Speed Heat Pump

This study (Kim, Fuentes, and Norford 2016) describes an analysis of a variable speed heat pump (VSHP), which responds to direct load control (DLC) signals to provide grid frequency regulation (GFR) ancillary service, while ensuring the comfort of building occupants. A data-driven dynamic model of the VSHP is developed through real-time experimental studies with a time horizon ranging from seconds to hours. The model is simple, yet still sufficiently comprehensive to analyze the operational characteristics of the VSHP. The DLC scheme is then experimentally applied to the VSHP to evaluate its demand response (DR) capability. Two control methods are considered for a practical implementation of the DLC-enabled VSHP and a further improvement of the DR capability, respectively. Additionally, a small-signal analysis is carried out using the aggregated dynamic response of a number of DLC-enabled VSHPs to analyze their contribution to GFR in an isolated power grid. For experimental case studies, a laboratory-scale micro-grid is then implemented with generator and load emulators. We show that the DLC-enabled VSHP can effectively reduce grid frequency deviations and required reserve capacities of generators. The experimental setup used for this study is presented in Figure 5. This experimental study was performed in the framework of a collaboration with MIT (USA) and HITACHI.

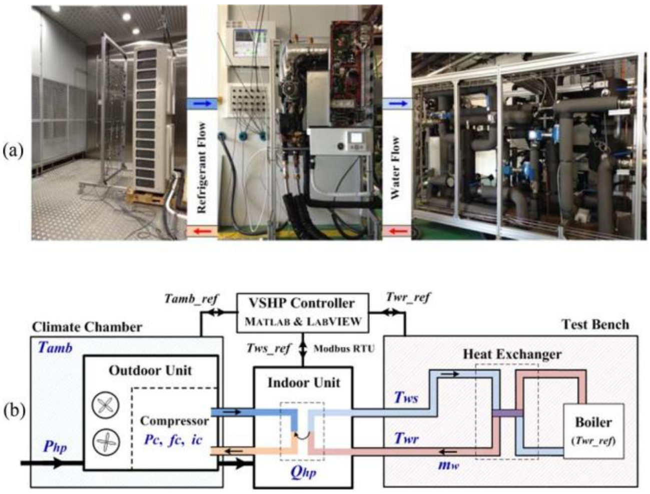
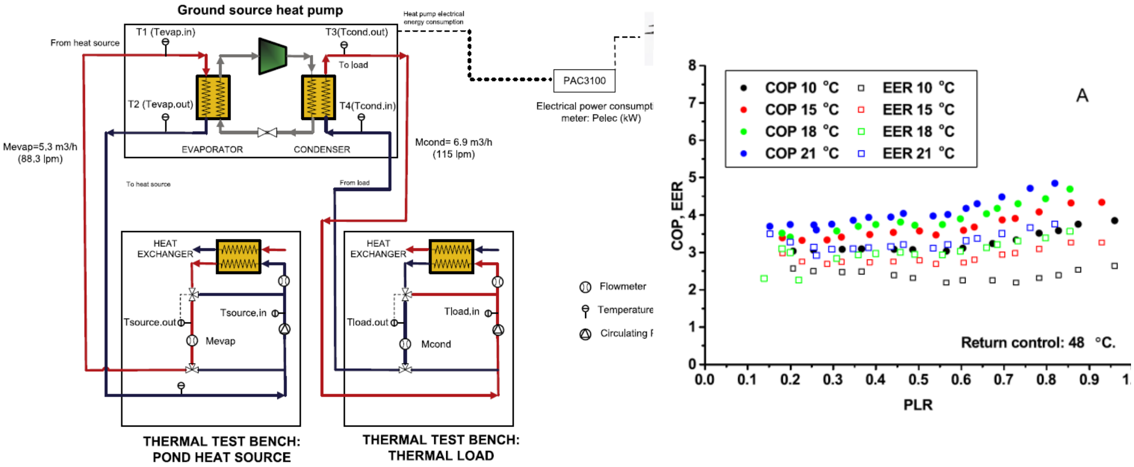


Figure 5. Experimental setup (a) and corresponding diagram (b).

2.3.2. Study 2: Partial load efficiency degradation of a water-to-water heat pump under fixed set-point control



(a) (b)

Figure 6. Experimental setup (a) and graph showing the COP and EER in function of the part-load ratio (PLR) (b).

This laboratory study (Waddicor et al. 2016) was conducted to evaluate the influence of fixed set-point control strategies on the partial load behaviour of a water-to-water heat pump of 40.5 kW heating capacity. Experimental results indicate that the control configuration is highly influential on the heat pump cycling response and efficiency degradation at part load. Deterioration of energy performance occurred mainly during system start-up, with additional efficiency loss caused by short cycling for supply temperature control at low loads. It was concluded that a minimum of 20 min compressor run time is necessary to reduce degradation effects, suggesting that installers and heat pump manufacturers should ensure minimum operation times to improve systems efficiency. Comparison of models and experiments indicate that it is important to adequately account for both stand-by and start-up efficiency losses for improving predictions of part load performance by steady-state heat pump models. The experimental setup as well as one result graph are shown in Figure 6. This project has been done in the framework of EU project TRIBUTE (http://www.tribute-fp7.eu/).

2.3.3. Study 3. Testing of a novel micro-CHP unit for buildings

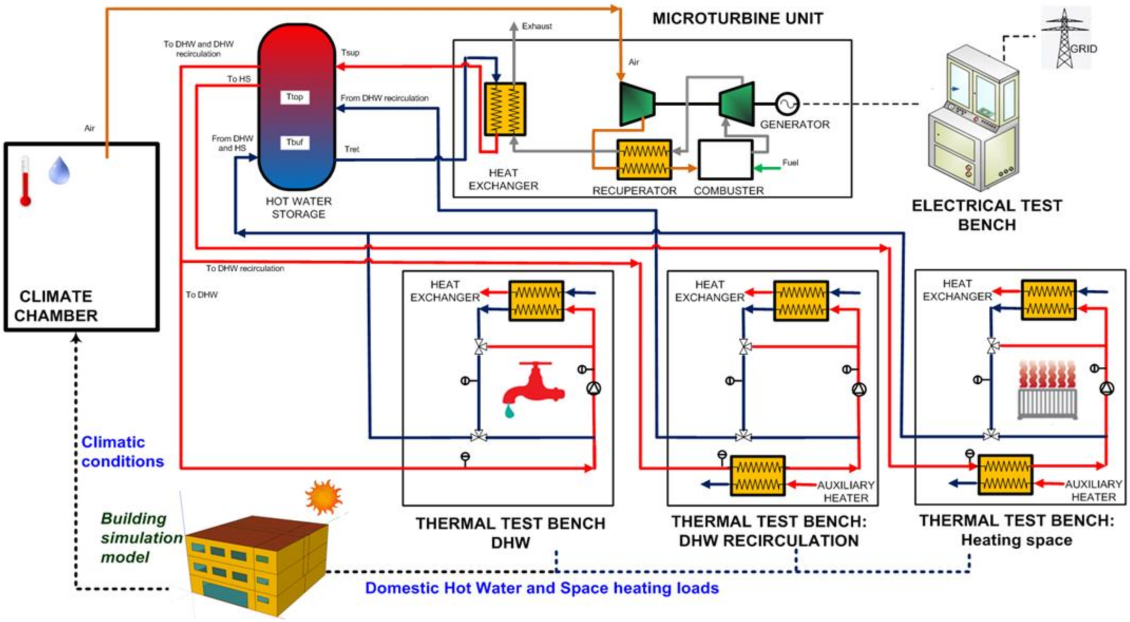


Figure 7. Scheme of the experimental setup for the mCHP test.

The objective of the testing at IREC´s laboratory consists of the determination of the thermal and electrical performance of the MTT micro-turbine CHP under dynamic conditions by means of semi-virtual testing.

This virtual system created with the software TRNSYS has been integrated together with the electrical and thermal test benches configuration in the laboratory to emulate the thermal loads of the building in order to make the mCHP unit to operate as if it was installed in the actual building. The MTT EnerTwin micro turbine-CHP (m-CHP) was installed in the IREC´s test laboratory, which is provided with 164 m2 surface and a 549.73 m3 room volume (ambient temperature between 18 and 24C). The heat and electrical energy production from the m-CHP are measured and controlled by means of high precision measurement and control elements installed in a set of thermal and electrical test benches. The thermal energy from the m-CHP will be used to charge a 1000 l buffer tank, which delivers heat to provide the DHW (Domestic Hot Water) and space heating according to the implemented consumption profiles from a building model. Inlet air to the microCHP is previously conditioned for temperature and humidity control in the climate chamber, which is placed at about 12 m pipe length from the system. The experimental tests consisted of the operation of the microCHP unit under dynamic conditions during 24 h for selected days of the year, in which heating space and domestic hot water consumption were emulated for a hotel building in the BCN and Zurich climates. For the test, the hot water tank was directly connected to a thermal test bench for DHW demand emulation and a second test bench for space heating emulation. A third test bench was employed to emulate the recirculation circuit for DHW. For the conditions in which the thermal energy from the m-CHP is not sufficient to cover the heat demand from the building, a virtual auxiliary heater is implemented in the DHW and heating space circuits, which is emulated with the required heating loops.

The experimental setup is shown in Figure 7. These tests have been supported by KIC InnoEnergy.

2.4. Maintenance and collaborations

The SEILAB laboratory is run and managed by IREC, the Catalonia Institute for Energy Research, which headquarters are situated in Barcelona, Spain. The SEILAB facilities are situated in a branch of IREC in Tarragona. Around five full-time employees are maintaining, organizing and using the lab facilities.

The SEILAB is collaborating in numerous projects with different partners:

- Direct contracts for equipment testing, development of technical solutions, improvement of systems, etc.
- Partnership for national / international R&D projects: EU, KIC-EIT, Horizon 2020
- Donation of equipment for expanding the laboratory structure
- Shared developments for new products

2.5. Additional information

Additional information can be found at www.irec.cat or on demand.

2.6. Relevant publications

Y.J. Kim, E. Fuentes and L.K. Norford. 2016. “Experimental Study of Grid Frequency Regulation Ancillary Service of a Variable Speed Heat Pump.” IEEE Transactions on Power Systems 31(4):3090–99.-

D.A. Waddicor, E. Fuentes, M. Azar and J.Salom. 2016. “Partial Load Efficiency Degradation of a Water-to-Water Heat Pump under Fixed Set-Point Control.” Applied Thermal Engineering 106:275–85. Retrieved (http://dx.doi.org/10.1016/j.applthermaleng.2016.05.193).

E. Fuentes, D. Schaefer and J. Salom. 2014. On the impact of realistic domestic hot water demand profiles on thermal storage stratification and energy efficiency. Eurotherm seminar 99. 28-30 May 2014, Lleida, Spain.

E. Oró, A. Garcia and J. Salom. 2016. “Experimental and Numerical Analysis of the Air Management in a Data Centre in Spain.” Energy and Buildings 116:553–61. Retrieved (http://dx.doi.org/10.1016/j.enbuild.2016.01.037).

3. Energy Smart Lab - IREC

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3.1. General presentation

The Energy Smart Lab is an infrastructure conceived as a flexible and versatile platform for innovative technological developments for both industry and competitive R+D projects. The areas of expertise of this laboratory pivot around the following technologies:

- Power Electronics for the integration and control of the elements within a building or community: Renewable Energy Sources (RES), Energy Storage Systems and Electric Vehicles (EV)
- ICT Platform for smart communications and energy management of systems, building, networks and communities.
- Energy System Integration technologies for smart and flexible buildings and grids including RES and EV

The laboratory operation is based on the hardware emulation approach, which allows for real physical equipment to be operated under a broad range of scenarios without depending on the real occurrence of the boundary conditions suitable for the experimental validation. The laboratory is pioneer in addressing the concept and implementation of Microgrids and aims to become a leading experimental facility for improving the optimal development of Flexible Energy Buildings and Flexibility Aggregation at community level.

3.2. Description of the test facility

3.2.1. General principle and testing possibilities

General testing principles

The Energy Smart Lab test facility is composed of an electricity network which interfaces a set of real devices that inject or withdraw energy to/from it. All such devices include control hardware able to communicate with a centralized system called Building Management System (BMS). The BMS is responsible for the coordination of the power injected/withdrawn into/from the electrical grid in order to ensure power balance at the point of common coupling with the grid supply. The BMS includes an interface with the virtual system, which completes the experimental setup. Virtual components are aimed to provide this facility with the capability to implement a significant number of different testing scenarios, as it includes the following functionalities:

- Building simulation model: thermal inertia and thermal loads of a building or community can be co-simulated with a building model.
- System Operator and Aggregator simulation models: the interaction with remote control actions carried out by electricity System Operators or flexibility Aggregators can be simulated as well.
- Grid simulation model: the physical interaction of the building with the grid power supply can be simulated enabling the experimental validation of flexibility services to the network.

The general concept of the testing facility is summarized in Figure 8.

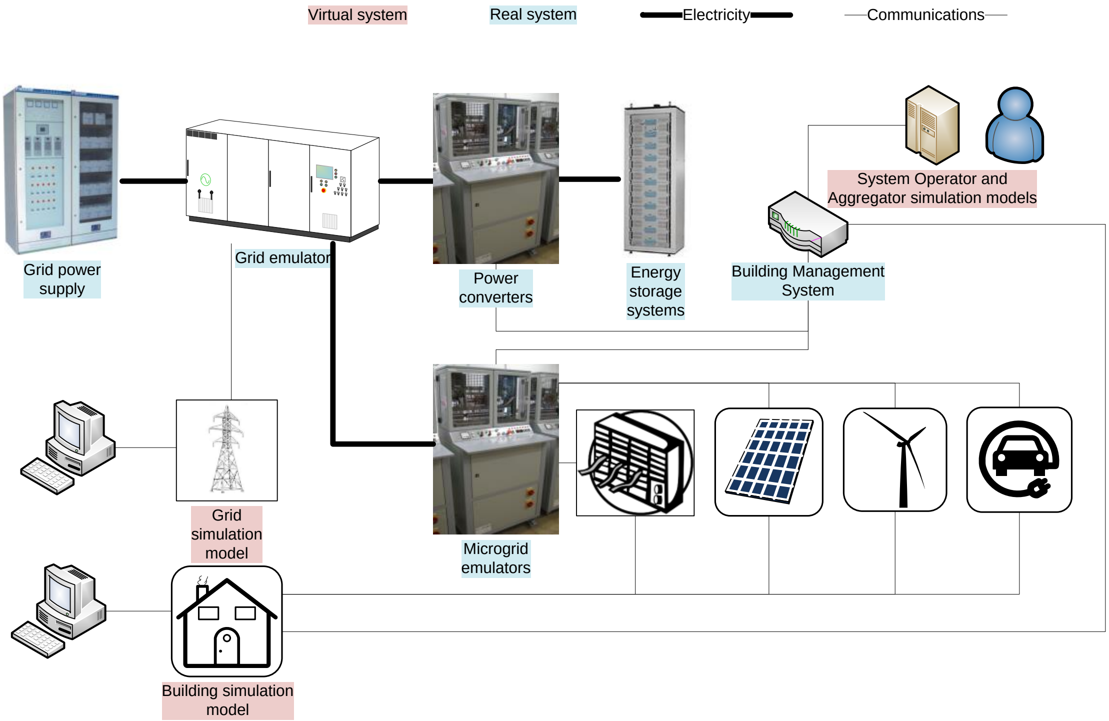

Figure 8. General concept of the IREC Energy Smart Lab testing facilities.

3.2.2. Equipment available and specifications

Energy storage systems

Different energy storage technologies are available in the laboratory, as presented in Figure 9. They are used to conduct experimental research on storage integration in buildings, communities and power grids.

Figure 9. Energy storage systems: flywheel (left), Li-ion battery (middle) and ultracaps (right).

The main specifications are summarized as follows:

- Flywheel: maximum stored energy 15 Wh, rated power 5,5 kW, maximum speed 3000 rpm, motor technology permanent magnet synchronous machine, efficiency 85-90%

- SAFT Li-ion battery: maximum stored energy 20000 Wh, rated power 150 kW, rated discharge current 200 A, rated charge current 34 A, operating voltage 189 V – 227 V – 254 V, capacity 82 Ah
- Ultracapacitors: maximum stored energy 57 Wh, rated power 10 kW, rated current 20 A, peak current (<1s) 200 Apk, operating voltage 250 V – 500 V, capacity 1,65 F
- Electric vehicle second life battery: maximum stored energy 23300 Wh, rated power 40 kW, rated current 150 A, operating voltage 240 V – 400 V, capacity 32 Ah

Power converters / Microgrid emulators

It is possible to emulate the electrical behavior of different Renewable Energy Sources and building or community demands through the so-called Microgrid emulators (see Figure 10). Emulation is the ability to reproduce power profiles with the aim of obtaining the same output than the real element, such as PV units, electric vehicle charge events or household appliances. Microgrid emulators are power converters with the following specifications:

- Total available Microgrid emulators: 5 cabinets
- Rated power: 4 kVA
- Configuration: back-to-back converters, bi-directional power flow
- Operation mode: active and reactive power set point following

Figure 10. Overview of the microgrid: microgrid emulators (back), electric vehicle (right) and data acquisition and control system (front).

Figure 11. Grid emulator.

Grid emulator

The Microgrid elements can be directly connected to the laboratory power supply or to the so-called Grid emulator (see Figure 11). This device is a configurable voltage source used to emulate a set of power network conditions impacting on the building or community. In particular, it can be configured to simulate rural networks (weak grids) as well as different power quality issues including frequency excursions or voltage harmonics (non-exhaustive list). The main technical specifications are summarized as follows:

- Rated power: 200 kVA
- Rated current per phase: 350 A
- Rated current per neutral conductor: 35 A

Other equipment

Other devices are available in the lab:

- One 9-phase motor-generator test bench (30 kVA)

- Three 3-phase motor-generator test benches (3 x 5 kVA) of different generator technologies: permanent magnet synchronous generator, doubly-fed induction generator and squirrel cage generator.

3.2.3. Data acquisition and control

The control and communications architecture of the microgrid is composed of three layers, as can be observes in Figure 12. In the top one, called service layer, the microgrid can interact with high-level control and management systems, either locally or remotely. In the middle layer, the low-level control takes place in the so-called local concentrators. Such concentrators are data gateways to enable operability of storage systems and emulators with the service layer. Finally, the bottom layer, called configuration layer, aims at providing a means to configure and monitor all devices before and during the execution of tests.

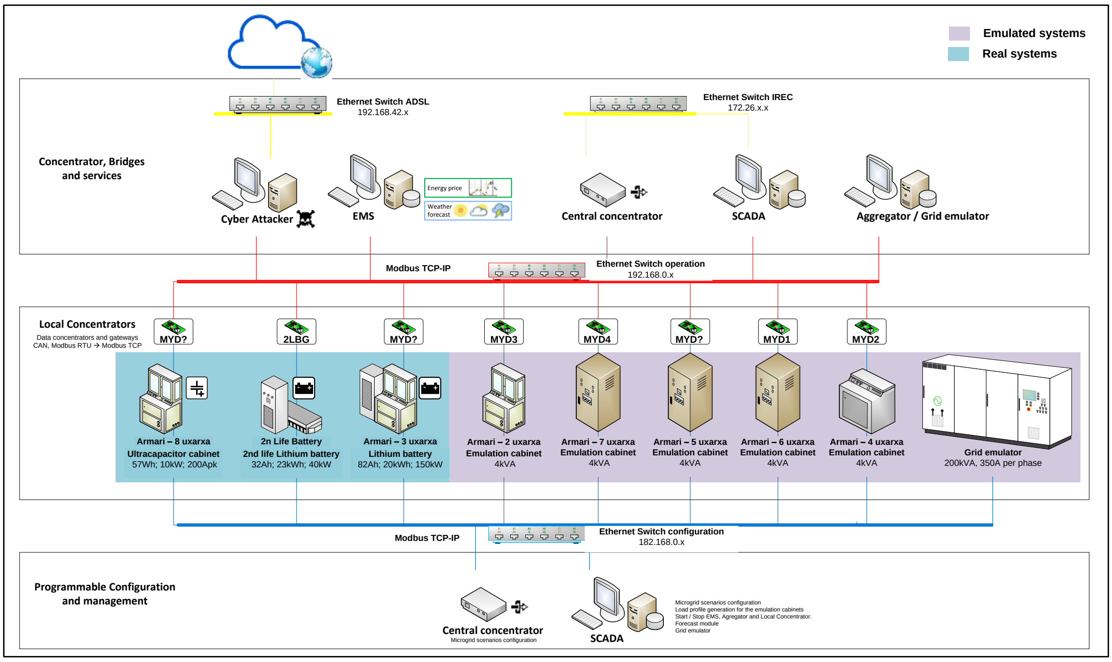

Figure 12. Data acquisition, control and communications architecture of the microgrid.

3.3. Example of previous studies

3.3.1. Study 1: Analysis and Experimental Implementation of Grid Frequency Regulation using Behind-the-Meter Batteries Compensating for Fast Load Demand Variations

This study (Kim, Del-Rosario-Calaf, Norford 2017) proposes a new grid frequency regulation (GFR) scheme using behind-the-meter battery energy storage systems (BESSs). The fast dynamic responses of the electrical BESSs enable buildings to compensate for the high-frequency components of load demand variations, through direct load control (DLC). An electrical system in a building, along with its building-level and device-level controllers, is considered to address the difficulties in the application of DLC, especially in communicating with several small-scale BESSs. A small-signal analysis is carried out using the aggregated responses of the generators and the DLC-enabled buildings to investigate the proposed GFR scheme, particularly with respect to the feedback controllers for the buildings. Simulation studies are performed using a test grid for various penetrations of the DLC-enabled buildings, and the test grid is implemented using a laboratory-scale microgrid. The proposed GFR is effective in reducing the frequency deviations and required reserve capacity of the generators, which is achieved by making small variations in the state-of-charge of the behind-the-meter battery. The experimental setup utilized in this study is presented in Figure 13.

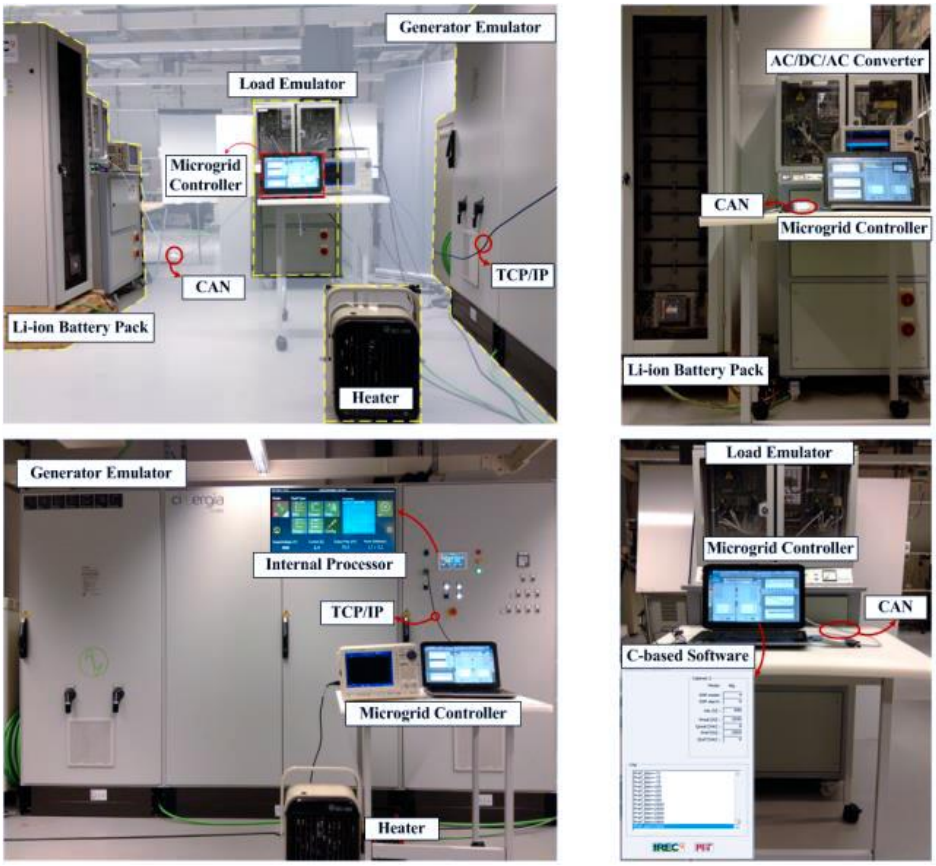

Figure 13. (a) Experimental setup for the implementation of the test grid including (b) a generator emulator, (c) a Li-ion battery pack, and (d) a load emulator.

3.3.2. Study 2: A Real-Time Commercial Aggregator for Distributed Energy Resources Flexibility Management

The paper (Lipari, Del-Rosario-Calaf, Corchero, Ponci, Monti, in press) describes the implementation of a real-time Commercial Aggregator, that pools the generation and/or consumption flexibility offered by its customers to provide energy and services to actors within the system. Results of the emulations carried out in the scope of the FP7 European project IDE4L are presented, highlighting the effects of the participation of DERs and Microgrids to the congestion management by offering flexibility products through the involvement of the Commercial Aggregator (CA).

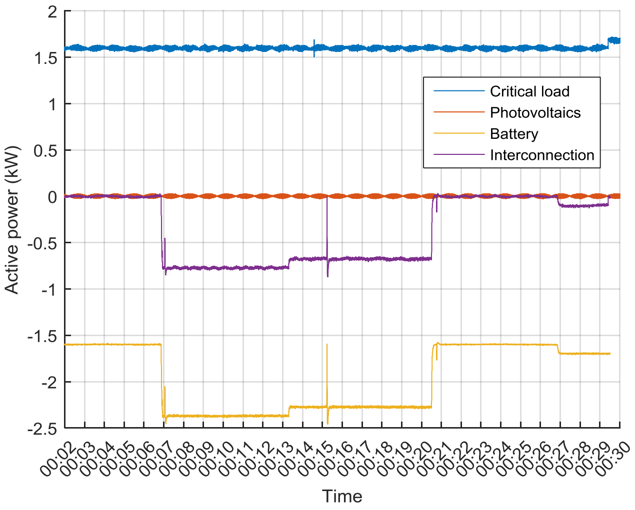

Figure 14. Active power measurements during flexibility delivery at customer's premises.

3.4. Maintenance and collaborations

The Energy Smart Lab is run and managed by IREC, the Catalonia Institute for Energy Research and its facilities are located in Barcelona, Spain. Seven full-time employees are maintaining, organizing and using the lab facilities on average.
The Energy Smart Lab is collaborating in numerous projects with different partners:

- Direct contracts for equipment testing, development of technical solutions, improvement of systems, etc. Example: pre-certification tests of Electric Vehicle charging infrastructure
- Partnership for national / international R&D projects: EU, KIC Innoenergy -EIT, Horizon 2020. Example: laboratory-scale tests for the validation of ICT platforms for the optimal management of Microgrids
- Donation of equipment for expanding the laboratory structure. Example: integration of a Second Life Electric Vehicle Battery for stationary applications in the Microgrid
- Experimental test site for researchers. Example: development of a proof-of-concept setup for novel applications of Flywheels to expand Wind Power Plant capabilities
- Joint research with other laboratories. Example: development of tests in coordination with SEILAB laboratory to validate Building and Aggregator control implementations.

3.5. Additional information

Multimedia
A video presenting the lab can be found at the following address:
https://vimeo.com/111393514

More details can be found at the following address:
http://www.futured.es/en/capability/?prettyUrl=irec

3.6. Relevant publications

Y.J. Kim, G. Del-Rosario-Calaf and L.K. Norford. 2017. “Analysis and Experimental Implementation of Grid Frequency Regulation using Behind-the-Meter Batteries Compensating for Fast Load Demand Variations” IEEE Transactions on Power Systems, vol.32, no.1, pp.484-498.

G. Lipari, G. Del-Rosario-Calaf, C. Corchero, A. Monti and F. Ponci. In press. “A Real-Time Commercial Aggregator for Distributed Energy Resources Flexibility Management”, in Sustainable Energy Grids and Networks.

L. Igualada, C. Corchero, M. Cruz-Zambrano and F.J. Heredia. 2014.” Optimal Energy Management for a Residential Microgrid Including a Vehicle-to-Grid System” IEEE Transactions On Smart Grid, vol. 5, no. 4, pp. 2163-2172.

G. Del-Rosario-Calaf, M. Cruz-Zambrano, C. Corchero and R. Gumara-Ferret, "Distribution network congestion management by means of electric vehicle smart charging within a multi-microgrid environment," Electric Vehicle Conference (IEVC), 2014 IEEE International, Florence, 2014, pp. 1-8.

4. Nearly-zero Energy Building Emulator – Aalto University

Institution / Department
Aalto University
School of Engineering
Department of Mechanical Engineering
Laboratory of Energy Efficiency and Systems

Location of the test facility
Aalto University, building K4
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4.1. General presentation

The nearly-zero energy building (nZEB) emulator is a platform for studying the performance of a building with different renewable energy production and storage equipment fitted into a fully functional system operating in Finnish climate conditions. The platform is based on a semi-virtual approach comprising of real components for energy generation, conversion and storage connected with a simulated building and a ground source heat pump borehole. This arrangement makes the system very flexible as different types and sizes of buildings may be studied by simply changing the simulation model. The system is also equipped with an energy management system (EMS) developed at VTT which can direct energy flows in an optimal way by assessing the current and future energy status as well as the availability of renewable sources (sun, wind). The nZEB emulator platform is a unique facility for assessing the real-time performance of advanced energy solutions and investigating the energy-flexibility in buildings towards achieving set targets in the building and requirements by the grid.

4.2. Description of the test facility

4.2.1. General principle and testing possibilities

General operation principles

The general operation concept of the nZEB emulator is presented in Figure 15. The platform is designed to resemble a single-family house with respect to component sizing but the operation can be scaled to match different building types. The actual building is a TRNSYS simulation running in a computer and the physical devices are operated according to electricity and heating demands given by the simulation at six minute (changeable) intervals. The physical part of the system is operated in real-time and according to real weather conditions as there is no weather chamber. The platform is equipped with an energy management system (EMS) which optimizes the energy use and flows by assessing the energy prices and weather. The general uses for the platform are as follows:

- Analysis of local energy matching in buildings
- Performance evaluation of different control strategies for achieving optimal use of energy resources
- Gathering of high-resolution data from the various components for validating component models used in simulations and optimizations

Examples of research possibilities

- Experimental testing of novel energy solutions related to local production and storage of electricity and heat such as PV panels, solar thermal collectors, microwind turbines, heat pumps, batteries and heat storages
- Development and testing of new control strategies for energy systems in smart buildings
- Monitoring and recording the behaviour of different components present in the system
- Using the data to calibrate the models for building simulation tools

- Optimization of energy flows in order to improve energy generation/demand matching and interactions with bidirectional future hybrid smart grids of electricity and heating
- Evaluation of modelled electric/hydrogen vehicle as a part of the nZEB concept
- Evaluation of the energy flexibility performance of building’s energy systems e.g. for minimizing operating energy costs, environmental impacts or responding to grid requirements.

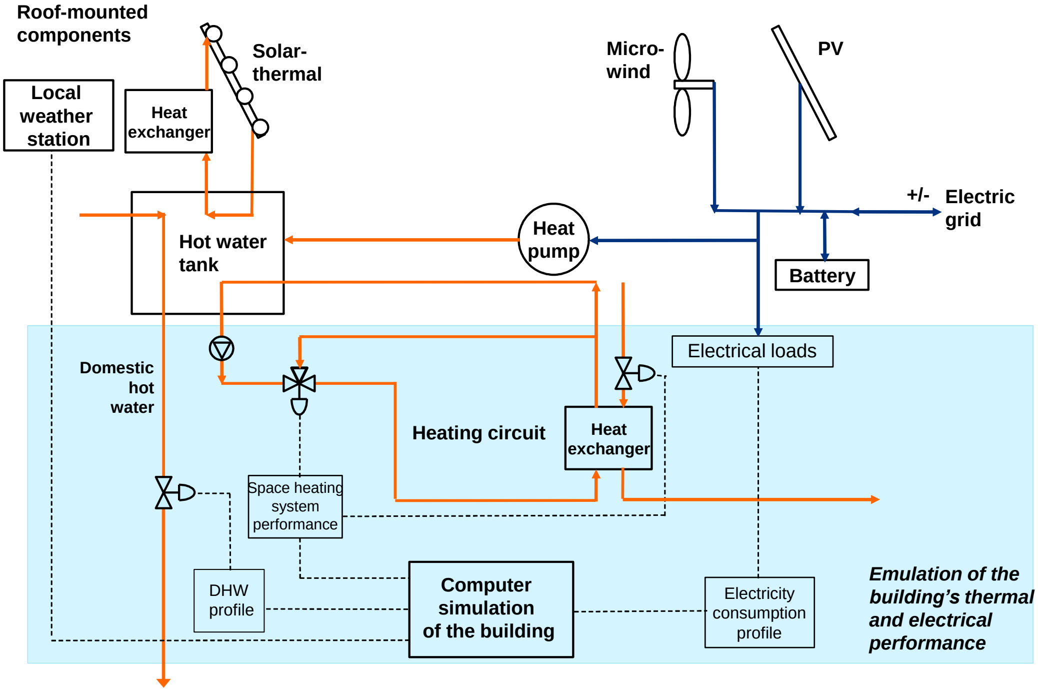


Figure 15. Operation and basic component diagram of the emulator platform.

4.2.2. Equipment available and specifications

PV panels

Figure 16. PV panels and microwind turbine on the roof of the K4 building.

A PV plant consisting of 18 panels in two rows is installed on the roof of the lab (Figure 16). The panels have a nominal capacity of 240 Wp each, totalling 4.32 kWp. Both panel rows are equipped with separate SMA Sunny Boy 2000 HF inverters, and the production is monitored at one minute resolution via a Bluetooth interface.

Microwind turbine

In addition to PV panels, a Finnwind Tuule E200 microwind turbine with a rated capacity of 4 kW has been installed onto the roof (Figure 16). The turbine is located at the top of a 9 meter high steel mast, accounting for a 25 meter total distance from the ground level. The turbine automatically rotates towards the wind direction and is equipped with storm protection which turns it away from the wind if the gusts become too powerful. The wind plant is equipped with an SMA Windy Boy 3600 TL inverter which, like its PV counterparts, is monitored at one minute resolution via Bluetooth.

Island electricity network

The PV panels and the wind turbine are connected to an island electricity network via an SMA Sunny Island 6.0H inverter (Figure 17). The island network is equipped with a 48 V, 200 Ah battery (four 12 V 200Ah lead acid batteries in series), and also contains ten 600 W electric heaters which emulate the electricity loads of a house according to the simulation’s load profiles. The battery state-of-charge is monitored by the inverter and communicated to a computer via an Ethernet cable.

Figure 17. PV and island network inverters.

Figure 18. Flat-plate solar collectors on the roof of the K4 building.

Solar thermal collectors

For heat production, two sets of four solar thermal collectors have been installed on the roof (Figure 18). One of the sets consists of Oilon Solarpro flat-plate collectors whereas the other one contains AMK-Solac OWR 12 evacuated tube collectors. Each set has a capacity of ~4 kW at typical Finnish summer conditions and is equipped with a Sonnenkraft SKSC3+ controller/pumping station which controls the brine flow rate in the circuit.

Ground source heat pump (GSHP)

The other method for heat production in the platform is an Oilon Geopro GT 5 ground source heat pump with a nominal capacity of 5 kW (Figure 19). There is no real ground borehole so a hydraulic circuit including a 500 liter buffer tank filled with brine is used as a heat source for the GSHP. The brine flowrate and return temperature are emulated according to the borehole output results from the TRNSYS simulation. The buffer tank is heated up by the rejected heat from the system that would normally be used for the space heating of the building.

Figure 19. Ground source heat pump.

Hot water storage

The emulator platform is equipped with three Akvaterm Akva Solar hot water storage tanks (Figure 20). Two of the tanks have a capacity of 500 liters while the third is slightly smaller at 300 liters. Each tank is equipped with three heating coils (solar thermal, DHW pre-heating, DHW heating). There is a plate with a small opening in the middle of the tank for separating the top and bottom parts from each other. The temperature stratification is monitored by five thermocouples placed inside the tank at different elevations. One of the 500 liters tanks is equipped with a 6 kW electric heater and the 300 liters tank is prepared for the future implementation of phase-change materials as a heat storage. The storage tanks have flexible connections so it is possible to have them in a series or a parallel configuration, or a combination of the two.

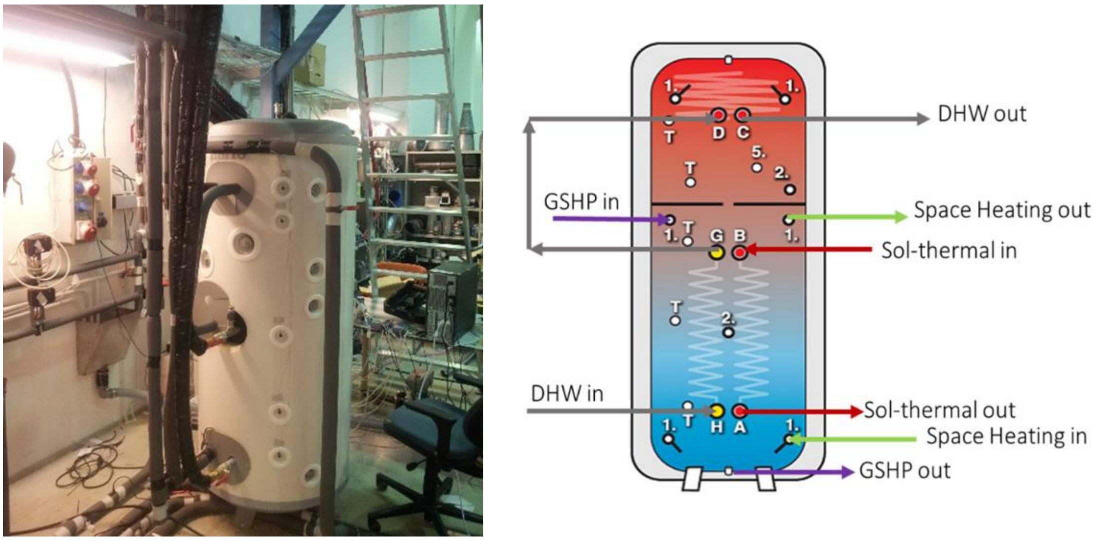


Figure 20. One of the hot water tanks, and schematic of the storage tank connections.

Other equipment

- Vaisala AWS330 weather station for measuring temperature, humidity, wind speed/direction and solar irradiance
- Water-to-air heat exchanger on the roof for emulating export of excess solar thermal heat into district heating network

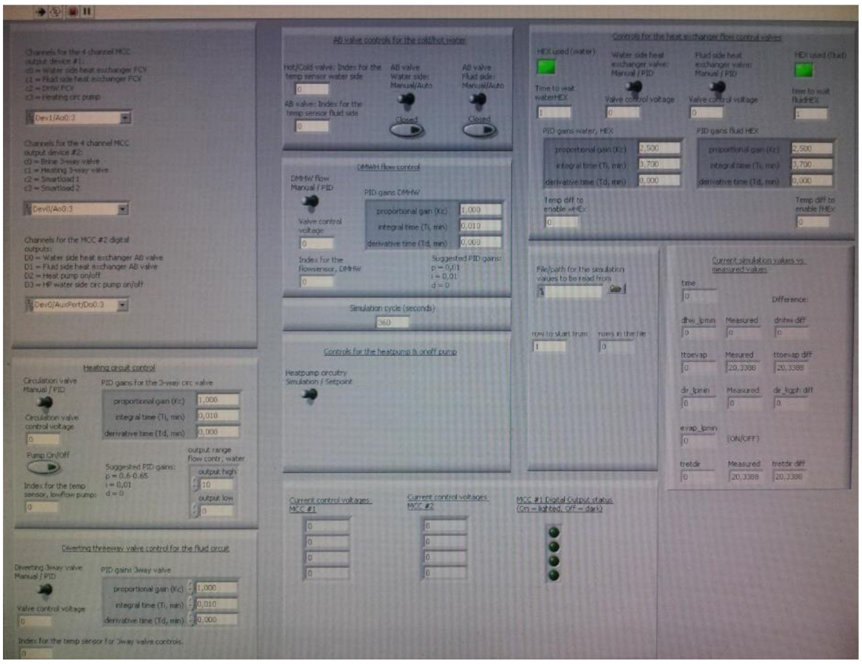
4.2.3. Data acquisition and control

The majority of the components in the emulator platform are controlled by a Labview-based software developed at Aalto University (Figure 21). This software is also used for data acquisition from the roughly 100 thermocouples, resistance temperature detectors (RTDs) and flow sensors the system is equipped with. The sensor data is collected mainly via National Instruments DAQ modules connected to the computer via USB ports.

The production facilities (PV, wind turbine, solar thermal collectors) are operated by their own factory-supplied controllers and their data is acquired via dedicated software, written into CSV files and then read into the Labview main program.

The rest of the system is controlled with PID and on/off controllers written into the Labview program. For supplying control voltage (0-10V) to the various actuators, pumps etc., Measurement Computing USB analog voltage modules are used.

Besides acting as the data acquisition and control hub of the system, the Labview program also acts as an user interface for operating the system, and communicates with the simulation software (TRNSYS) containing the building and the GSHP borehole as well as with the energy management system which gives decisions on how to direct the different energy flows in the system. The communication between Labview and the other software is done via text files.


Channels for the 4 channel MCC output device #1:
c0 = Water side heat exchanger FCV
c1 = Fluid side heat exchanger FCV
c2 = DHW FCV
c3 = Heating circ pump
Dev1/Ao0:3

Channels for the 4 channel MCC output device #2:
c0 = Brine 3-way valve
c1 = Heating 3-way valve
c2 = Smartload 1
c3 = Smartload 2
Dev0/Ao0:3

Channels for the MCC #2 digital outputs:
D0 = Water side heat exchanger AB valve
D1 = Fluid side heat exchanger AB valve
D2 = Heat pump on/off
D3 = HP water side circ pump on/off
Dev0/AuxPort/Do0:3

Heating circuit control
Circulation valve Manual / PID
Circulation valve control voltage: 0
Pump On/Off
Index for the temp sensor, lowflow pump: 0
PID gains for the 3-way circ valve
proportional gain (Kc): 1,000
integral time (Ti, min): 0,010
derivative time (Td, min): 0,000
Suggested PID gains:
p = 0.6-0.65
i = 0,01
d = 0
output range flow contr, water
output high: 10
output low: 0

Diverting threeway valve control for the fluid circuit
Diverting 3way valve Manual / PID
Valve control voltage: 0
PID gains 3way valve
proportional gain (Kc): 1,000
integral time (Ti, min): 0,010
derivative time (Td, min): 0,000
Index for the temp sensor for 3way valve controls: 0

AB valve controls for the cold/hot water
Hot/Cold valve: Index for the temp sensor water side: 0
AB valve: Index for the temp sensor fluid side: 0
AB valve Water side: Manual/Auto
Closed
AB valve Fluid side: Manual/Auto
Closed

DMHW flow control
DMHW flow Manual / PID
Valve control voltage: 0
Index for the flowsensor, DMHW: 0
PID gains DMHW
proportional gain (Kc): 1,000
integral time (Ti, min): 0,010
derivative time (Td, min): 0,000
Suggested PID gains:
p = 0,01
i = 0,01
d = 0

Simulation cycle (seconds): 360

Controls for the heatpump & onoff pump
Heatpump circuitry Simulation / Setpoint

Controls for the heat exchanger flow control valves
HEX used (water) 🟩
Time to wait waterHEX: 1
Water side heat exchanger valve: Manual / PID
Valve control voltage: 0
Fluid side heat exchanger valve: Manual / PID
Valve control voltage: 0
HEX used (fluid) 🟩
time to wait fluidHEX: 1
PID gains water, HEX
proportional gain (Kc): 2,500
integral time (Ti, min): 3,700
derivative time (Td, min): 0,000
PID gains fluid HEX
proportional gain (Kc): 2,500
integral time (Ti, min): 3,700
derivative time (Td, min): 0,000
Temp diff to enable wHEX: 0
Temp diff to enable fHEX: 0

File/path for the simulation values to be read from
row to start from: 1
rows in the file: 0

Current simulation values vs. measured values
time: 0
Difference:
dhw_lpmin: 0 Measured: 0 dmhw diff: 0
ttoevap: 0 Mesured: 20,3388 ttoevap diff: 20,3388
dir_lpmin: 0 Measured: 0 dir_kgph diff: 0
evap_lpmin: 0 (ON/OFF)
tretdir: 0 Measured: 20,3388 tretdir diff: 20,3388

Current control voltages: MCC #1
0
0
0
0

Current control voltages: MCC #2
0
0
0
0

MCC #1 Digital Output status (On = lighted, Off = dark)
●
●
●
●

Figure 21. Screenshot of the Labview interface.

The heat and electricity demands of the building under investigation are calculated at fixed time intervals (currently six minutes) by the TRNSYS simulation program and then supplied to the physical part of the system via Labview. While the simulation calculates the heating demands and the space heating water return conditions, it uses typical profiles for the household electricity consumption and domestic hot water DHW, along with the prevalent weather conditions. In addition to providing energy demands, TRNSYS also simulates the GSHP borehole and gives Labview the temperature of the brine returning from the ground to the heat pump.

The energy management system (EMS) is a Matlab-based program which optimizes the energy flows in the system based on a successive linear programming (SLP) approach (Ruusu et al., 2016). While nonlinear methods are generally preferable, this approach works well here since the problem set is mostly linear and the real-time operation of the system calls for a fast algorithm. With the help of real-time and forecast energy pricing and weather data, EMS can instruct the system on how to deal with locally produced and imported energy i.e. to cover the demand, convert or store the energy in the same or another form (e.g. electricity to heat), or to export/import to/from the connected networks. The EMS is connected to the online Nordpool spot electricity pricing database as well as to online weather forecast from the Finnish Metrological Institute. In its current iteration, EMS manages the temperature set points for the GSHP, electric heater and excess solar heat export, as well as decides when and at what portion to import/export/store electricity in the batteries.

4.3. Example of previous studies

The first task of the emulator platform is to provide experimental data for a joint Aalto/VTT Finnish Academy project dealing with nearly-zero energy buildings and supply/demand matching. In this project, the emulated building is a 150 m2 well-insulated Finnish single-family house with four occupants. The emulator is operated for two full calendar years with the first one having finished in spring 2016 and the second one to finish in late 2017.

In the first year, the system was run with its original components and settings, and the results were analysed both to study the operation and performance of the different components, and to come up with ideas of improvement for the second year of operation. In general, the system performed reasonably well. There were a couple of issues with the most notable one being the poor performance of the batteries in the PV/wind system. To give an example of the data analysis, Figure 22 shows the monthly onsite energy fraction (OEF) and onsite energy matching (OEM) indices for electricity during a six-month period from Sep 2015 to Feb 2016. The OEF (demand cover factor) is the portion of the total electricity consumption covered by local production whereas the OEM (supply cover factor) is the portion of self-consumption from the total local electricity generation. As can be seen from the figure, OEF is high during autumn when there is still PV generation whereas OEM is better in winter when the constant electricity demand due to heating is high.

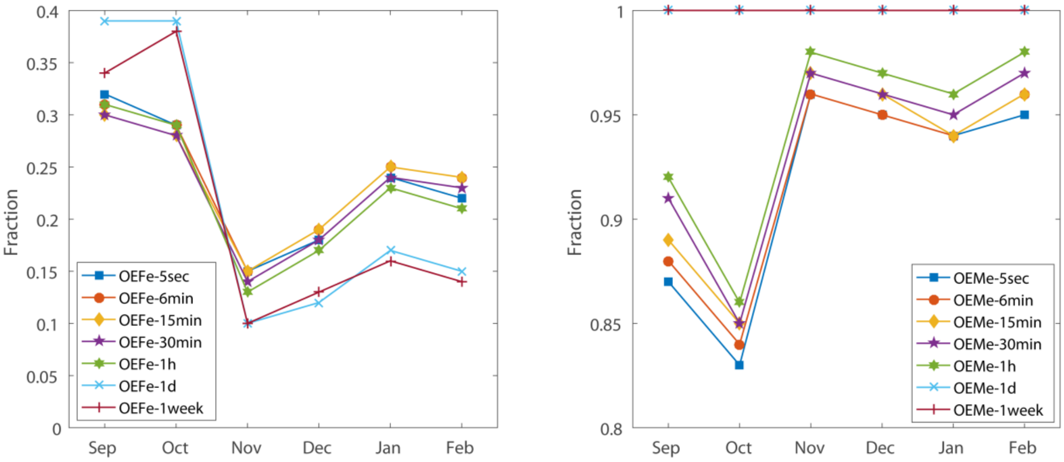


Figure 22. Monthly average matching indices OEFe and OEMe at different time averaging intervals.

After year one was finished, some modifications and additions were made for the second year during a maintenance break lasting several weeks. The most notable changes were the additions of the intelligent EMS software as a master controller of the system (done in early 2017), and a heat exchanger on the roof for emulating heat export from the solar thermal system to the district heating grid. The batteries of the PV and wind plants were replaced as the original ones had reached the end of their lifetime. On the simulation side, TRNSYS was set to use real-time weather data from the weather station instead of a weather profile from the past.

The extensive analysis of the data from year two will be done later but the preliminary results show that the issues that were present in the first-year data are resolved. The EMS seems to be performing according to expectations although it won’t be put into a real test until summer 2017 when it has more options to consider.

4.4. Maintenance and collaborations

The nZEB emulator is run and maintained by the Laboratory of Energy Efficiency and Systems at Aalto University. Currently, the operation is mainly handled by Dr. Kilpeläinen, with a laboratory technician helping with maintenance and new hardware installations

Currently, the emulator is operated year-round for providing data to a Finnish Academy research project dealing with nearly-zero energy buildings and supply/demand matching. In the future, research projects in collaboration with companies developing new technology for renewables and/or control systems, as well as international partners dealing with similar topics can be expected.

4.5. Relevant publications

R. Ruusu, S. Cao, A. Hasan, J. Kortelainen and T. Karhela. 2016. “Developing an Energy Management System for Optimizing the Interaction of a Residential Building with the Electrical and Thermal Grids”. CLIMA 2016 – Proceedings of the 12th REHVA World Congress: Vol 10 (2016).

5. Labs in EnergyVille

Institution
EnergyVille
KU Leuven – VITO – IMEC
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Marcel Stevens
marcel.stevens@vito.be

5.1. General presentation

The EnergyVille laboratory facility provides a modern, high-end environment for testing and developing solutions for renewable energy integration in electrical and thermal systems. The EnergyVille laboratory facility consists of 5dedicated laboratories which are linked to specific domains of expertise: Battery Testing Lab, Home Lab, Polyline Medium-Voltage Smart Energy System Lab, Matrix Lab and Thermo-technical Lab.

Each of the laboratories is equipped with state-of-the-art measurement equipment and data-acquisition systems to facilitate high-end research in the specific sub-domains. Moreover, all laboratories are physically interconnected to enable the integrated testing of innovative technologies for electrical and thermal systems. As such the entire EnergyVille building with its laboratories and offices can act as an integrated test facility.

5.2. Description of the test facility - Battery Testing Lab

5.2.1. General principle and testing possibilities

EnergyVille has one of the most extensive battery testing labs in Flanders, consisting of multiple battery and cell testers and a flexible setup. EnergyVille uses its infrastructure to evaluate ultra-capacitors, battery cells, battery components and materials. Also, systems using batteries or battery management systems can be evaluated.


Figure 23. Illustration of battery testing.

General testing possibilities

Batteries and ultra-capacitors exist in many types. Selecting the optimal one for an application is a complex matter, moreover since within each chemistry type (Lithium-Ion, Nickel-metal hydride...) exist several subtypes. The actual performance and lifetime of a specific application can only be determined by testing.

EnergyVille can perform tests according to any customer specified profile. We have elaborate experience in developing custom efficiency test procedures that are equivalent to actual application cycles (electric vehicles, solar batteries…).

EnergyVille offers performance and lifetime tests according to international standards:

- Static capacity tests at various discharge currents
- Constant power discharge tests
- Hybrid pulse power characterisation tests
- Self-discharge tests
- Cold cranking tests
- Thermal performance tests
- Energy-efficiency tests
- Charge sustaining cycle life tests
- Charge depleting cycle life tests

- Calendar life tests

Each of these tests can be performed at various temperature profiles. Batteries and battery components can also be subjected to several current ripple profiles.

5.2.2. Equipment available and specifications

- **2 PEC SBT8050 battery testers (36kW)**
    - 24 channels in total
    - maximum voltage: 80V per channel
    - maximum current: 600A, max. 12 channels of 50A each
- **2 PEC SBT0550 cell testers (6kW)**
    - 48 channels in total
    - maximum voltage: 5V per channel
    - maximum current: 600A, max 12 channels of 50A each
- **1 PEC ACT0550 cell tester (16kW)**
    - 40 channels in total
    - Maximum voltage: 5V per channel
    - Maximum current: 250A, max. 5 channels of 50A each
- **Triphase 75kW inverter**
    - maximum voltage: 700V
    - maximum current: 160A nominal, 200A peak
- **Triphase 30kW inverter**
    - maximum voltage: 700V
    - maximum current: 96A nominal, 144A peak
- **1 VMP3 from Biologic with 8 independent potentiostat/galvanostat channels including electrochemical impedance spectroscopy (EIS) measurement.**
    - Current ranging from 10 µA up to 5A with a resolution of 0.0033% of FSR
    - Voltage ranging from 0 to 10V with a resolution of 0.0033% of FSR
    - Frequency range 1 MHz to 10 µHz (accuracy: 1%, 1°)
        - Amplitude potentio: 1 mVpp to 1 Vpp
        - galvano: 0.1% to 50% of the current range
- **Associated temperature chambers**
    - temperature range: -20°C – +55°C

5.2.3. Data acquisition and control

Data-acquisition is performed by the battery and cell testers. The voltage-, current- & temperature measurements of each individual test channel are logged on 1 second base. The Battery Testers are periodically calibrated according to the ISO 9001 Quality Management System.

5.3. Description of the test facility – Home Lab

5.3.1. General principle and testing possibilities

The EnergyVille Home Lab is a real life test infrastructure for home energy management systems, residential demand response technologies and in home communication systems. Specifically, the Home Lab enables the testing of residential energy management systems, communication systems, novel optimization algorithms etc. in real life conditions.

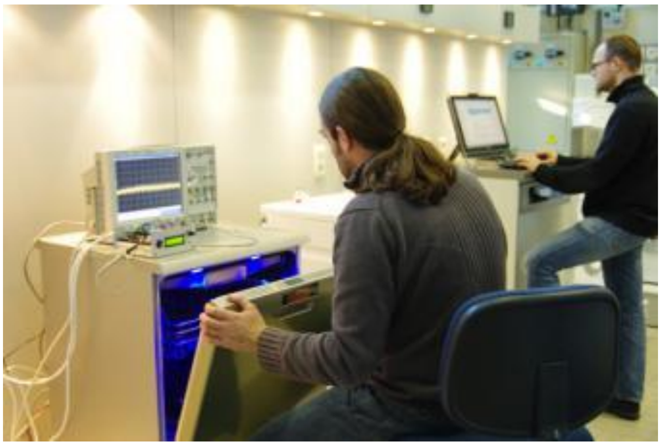


Figure 24. HomeLab.

For example, the demand response technologies which were developed in the Linear project were first tested in our Home Lab before integrating them in the participants' houses. Business cases such as maximization of self-consumption, peak shaving, wind balancing and Time Of Use tariffs, etc. were tested.

General testing possibilities

There are two electrical distribution boards, each representing one residential house. A flexible connection system facilitates the configuration of the available appliances, such as a smart washing, a dishwasher, a tumble dryer, a domestic hot water heater etc., in these two houses. Apart from this, there is also the possibility to connect solar panels through a residential PV invertor but also devices from all the other labs in the building can be physically connected to a house in our Home Lab through our Smart Test Grid. This way we are able to integrate a smart charging station, a smart heat pump, microCHP,, batteries etc. For example a small LV distribution grid can be set up in which the charging of electrical cars is coordinated, on a parking lot with smart charging stations, based on the production of a central PV station in combination with battery storage. This gives us the opportunity to test systems on the distribution level but also test power quality problems, voltage droop control, etc.

5.3.2. Equipment available and specifications

The EnergyVille Home Lab enables the integrated testing of products and services that are key to the implementation of Smart Grids, such as home energy management systems, residential demand response technology and in-house communication technology.

Peripherals:

- a programmable load (10kW) with a dedicated interface that allows for easy configuration of consumption profiles
- a PV inverter simulator (2.5 kW)
- a PV panel simulator (2 kW)

- multiple types of smart meters, energy management systems, smart plugs
- multiple smart appliances, including state of the art smart washing machines, dishwashers, tumble dryers, air-conditioning and domestic hot water (DHW) buffers
- various battery packs

Inter-lab connections:

- The Home Lab can be connected to the smart grid infrastructure to set up low voltage distribution grid tests.
- The Home Lab can be connected to the Thermo Technical Lab in order to include (smart) heat pumps, µCHPs and thermal storage components.

5.3.3. Data acquisition and control

The energy consumption of the individual loads is measured with dedicated power meters. The active/reactive power, voltage, current, cosΦ,… are logged.

5.3.4. Example of previous studies

The Linear research project examined various methods to tailor a household's energy consumption in function of the available wind and solar energy. These methods included new technologies and user interfaces. The major research questions were:

- How does a change in behaviour benefit both households and the industry?

- How are the costs and benefits distributed among the parties involved?

- Which solutions result in sufficient motivation and convenience to prompt a change in behaviour?

- To what extent are households willing and able to adjust their behaviour?

More info:
http://www.linear-smartgrid.be

5.4.Description of the test facility – Smart Grid Infrastructure

5.4.1. General principle and testing possibilities

In the Smart Grid Infrastructure Lab, our highly experienced team executes tests and validates:

- power line communication systems in distorted grids.
- long-term automated cycling of Li-ion batteries and reference performance tests.
- research on low voltage distribution grids with a high amount of renewable energy sources
- development & test of VITO Intelligator®: an agent based control algorithm to match supply and demand of energy.
- power quality: voltage dips, phase unbalance, harmonic distortions.
- voltage droop control: taking grid constraints into account by power adjustments.

- inverter control algorithms for unbalanced grid conditions.
- data analysis:
- different energy flows (V, I, cosφ ,..) are logged in a dedicated SCADA system.
- accurate high speed PQ measurements according to EN 50160.

5.4.2. Equipment available and specifications

The EnergyVille Smart Grid Infrastructure consists of:

- a 150 kVA low voltage AC-grid , connected to:
    - the EnergyVille Home Lab with test facilities for energy management systems and smart domestic appliances.
    - the EnergyVille Thermo Technical Lab with test facilities for heat pumps, μCHP and thermal storage.
    - extra cable loops.
    - PV systems & simulation equipment
    - EnergyVille's Battery Testing Lab.
- charging station for plug-in hybrids, electric vehicles & electric scooters
- dedicated programmable inverter and converter equipment:
    - 70 kVA inverter as three-phase grid connected inverter, with or without neutral line.
    - inverter as grid independent voltage source that reproduces voltage/frequency.
    - deviations and harmonic distortions.
    - two dedicated 100 A DC-DC converters.
- reconfigurable programmable inverter and converter equipment.
- possible configurations:
    - two 11 kW grid-connected inverters with neutral line
    - three three-phase 11 kW grid-connected inverters
    - one 11 kW grid-connected inverter with three 32 A DC-DC converters
- a 700 V low-voltage DC-grid connected to:
    - a DC-DC converter with battery storage and/or supercapacitor storage.
    - DC-sources such as fuel-cells and PV.
- a 150kW bidirectional DC module, useful to simulate batteries or PV installations as source or batteries or other DC devices as load.

5.4.3. Data acquisition and control

The branches in the test grid are equipped with current and voltage sensors which are connected to a high speed data-acquisition system.

5.5. Description of the test facility – Polyline Medium-Voltage Smart Energy Lab

5.5.1. General principle and testing possibilities

This facility enables to test medium-voltage smart-grid equipment in a three-phase synthetic grid up to the 50th harmonic in realistic condition.

Figure 25. Polyline Medium Voltage Smart Energy Lab.

General testing possibilities

In the EnergyVille Medium-Voltage Smart Energy System Lab, our experienced team offers:

- measurement of voltage and selected current levels on a 36kV 3-phase / 100 kV 1-phase installation
- surge voltage measurements
- partial discharge measurements of components (AC + DC)
- custom measurements and experimental configurations for cases of out of the ordinary use
- pre-certification testing to the applicable standards

The PolyLine system consists of two synergetic facilities:

- a traditional, single-phase AC (50/60 Hz, 100 kV)/DC (100 kV) + impulse (200 kV) facility
- a three-phase synthetic grid up to 36 kV/1000A (5kVA per phase for voltage and current injection), with wide bandwidth (25Hz to 5 kHz) to capture complex system transient and non-ideal behaviours unavailable in traditional testing facilities. It allows equipment, sensors, and protection devices to be exposed to fully user-programmable situations of: unbalance, harmonics, transients, reproduction of recorded grid faults, fluctuations in fundamental frequency, interaction with simulations, etc.

5.5.2. Equipment available and specifications

Equipment

- two mono-phase, partially discharge-free, Haefely transformers of 220V/100kV, 5kVA and 9kVA
- wide-band voltage transformer, 3*36kV/5kVA, separate cores, 25 Hz – 5 kHz
- wide-band current-injection transformers, 1000A, isolated to 36 kV, 5 kVA/core, 25 Hz – 5 kHz (3X)

- power amplifier, tri-phase, 10 Hz - 5 kHz bandwidth, 110 V output
- Marx multiplier for creation of surge voltages up to 200kV
- Saturn Flat isolated measurement system for multi-channel, wide-band registration of low-voltage sensor signals in the high-voltage section
- DMI 551 for measurement of DC, AC and peak voltages
- partial discharge measurement equipment (AC + DC, 3-phase multiplexed capability)
- wide selection of ancillary measurements, such as temperature, current, etc.
- the system can be fed from a local generator, offering exceptionally clean 50/60 Hz wave forms

Extra features
The EnergyVille Medium-Voltage Lab can be connected to EnergyVille's Matrix Lab, Smart Grid Infrastructure Lab, Home Lab and Thermo Technical lab.

5.6.Description of the test facility – Matrix Lab

5.6.1. General principle and testing possibilities

The Matrix Lab enables to measure the electrical and mechanical characteristics of electro-technical equipment, power electronic devices and solar panels.

General testing possibilities
In the EnergyVille Matrix lab, our experienced team executes tests on and validates:

- solar panels and their ancillaries, in controlled climate and irradiation conditions.
- electrical motor, transformer or generator behaviour and efficiency that is subject to variable power and load curves
- measurements on power electronic devices and converters
- interaction between multiple devices and energy modalities
- calibration of power meters
- customised experiments and measurements

5.6.2. Equipment available and specifications

- Multiple, multi-modal sources and loads can be interconnected as desired
- Standard, industrial power available up to 45kW/100kW
- Atlas SolarClimatic Test Cabinet Type SC 2000 MHG
- Test benches for electric motors/generators from 500W to 45/90kW
- Various AC and DC generators
- Controllable sources to generate outputs 0-400V at 64A / 200A
- Various bi-directional, programmable power electronic sources
- Various resistive loads
- Power calibration table with precise three-phase voltage and current control (up to 600A)
- Precision voltage, current, torque, speed, temperature and power measurements
- Remote-controllable using local Ethernet or over the Internet
- Many more capabilities at user's request

5.7.Description of the test facility – Thermo-technical Lab

5.7.1. General principle and testing possibilities

The Thermo-Technical Lab is one of the major research facilities of the EnergyVille knowledge center. It is a multi-functional laboratory infrastructure in which static and dynamic tests on thermal systems (heating and cooling) can be performed.

Figure 26. Thermo-technical lab.

Testing possibilities

- highly accurate measurements of:
- relevant emissions
- energetic performance
- fast response dynamic measurements
- dynamic tests of:
- boilers, burners, control systems, hot tap water appliances...
- cogeneration units: engines, turbines, μCHP's, ORC's,...
- heat pump systems
- thermal energy storage systems (both sensible and latent heat)
- combinations of systems: heat pumps and thermal energy storage, combined heat and power and thermal energy storage, distributed thermal energy storage, sorption systems
- energy system combination: f.i. a boiler combined with cogeneration and a storage tank
- including renewable energy sources
- including gas, oil, biogas and electricity

5.7.2. Equipment available and specifications

- thermal power up to 1000 kW
- electrical feed-in power to 500 kW (such as CHP, Turbine)
- temperature from 3 °C to 90 °C
- temperature 1/10th DIN 3 point calibration certificate (4-20 mA)
- connection gas or gas mixture through own gas station
- high-end electromagnetic flow measurements with 3 point calibration certificate (4-20 mA)
- logging of all measuring points and control parameters can be set individually (abs, avg, ...)
- both fixed set points as a dynamic profile to 200 ms selectable

- direct coupling with external datasets or dynamic simulation software
- electrical connection of devices with other laboratories using their own lowvoltage test grid
- a modular construction for easy monitoring and control can be added

5.7.3. Data acquisition and control

The laboratory is controlled and measured by an industrial PLC infrastructure, linked to a SCADA package. The devices can be connected directly to the EnergyVille Smart Grid Infrastructure Lab.

5.7.4. Example of previous studies

- Lab testing as part of national and European research projects (FP7 E-hub, Linear, etc.)
- Efficiency testing of gas heaters
- Energy performance testing of micro-turbines
- Boiler characterization
- Comparative testing of latent energy storage
- Intelligent control of heat pump for smart grid peak shaving
- Intelligent distributed thermal energy storage

5.8. Maintenance and collaborations

The EnergyVille laboratories are available for our own experts to conduct experiments for you, or you can get in contact with EnergyVille experts to rent (a part of) the laboratory facilities for your project.
Access to the EnergyVille Laboratories can only be obtained when an EnergyVille representative is present. Access is also limited to persons familiar with the infrastructure. The required test and set-up will always be designed in collaboration with an EnergyVille expert.

5.9. Additional information

Additional information on the EnergyVille laboratory facilities as well as related projects can be found at the EnergyVille website:
www.EnergyVille.be

5.10. Relevant publications

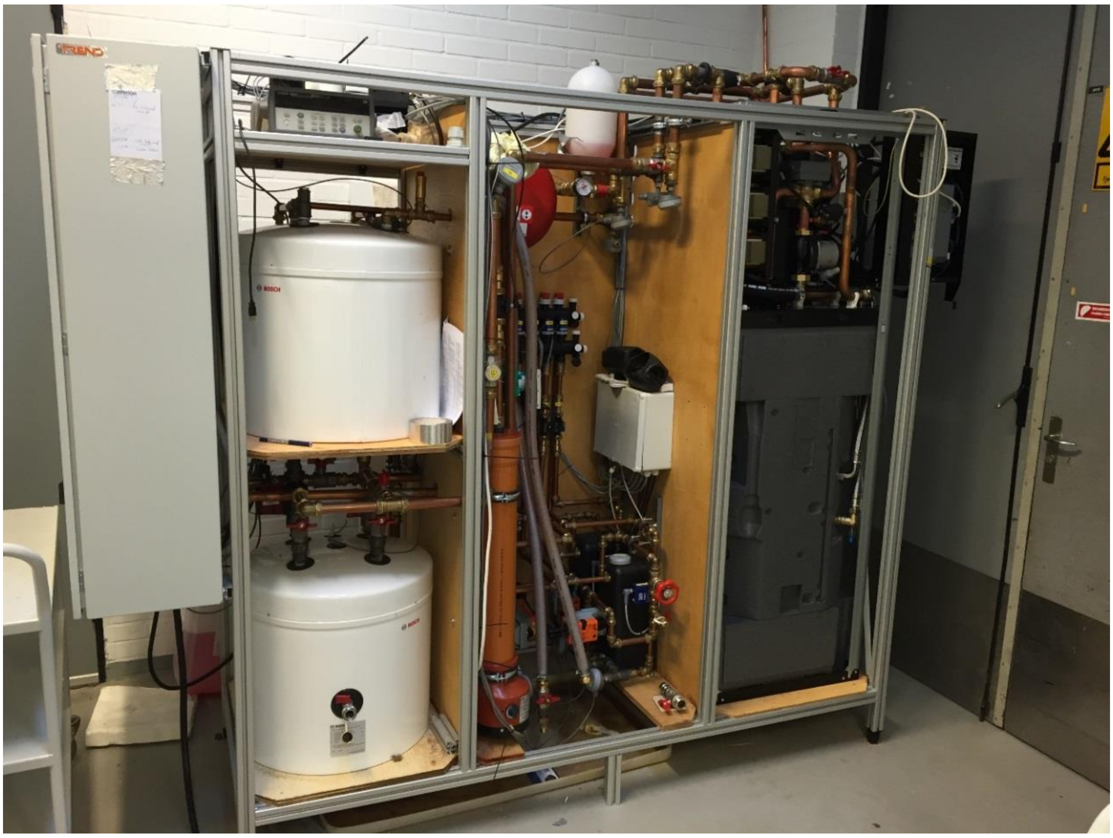
Linear consortium. (2014). *LINEAR - Demand Response for Families*. Genk. Retrieved from http://www.linear-smartgrid.be

Vanhoudt, D., Geysen, D., Claessens, B., Leemans, F., Jespers, L., & Van Bael, J. (2014). An actively controlled residential heat pump: Potential on peak shaving and maximization of self-consumption of renewable energy. *Renewable Energy*, *63*, 531–543. http://doi.org/10.1016/j.renene.2013.10.021

Beerten J. 2013. Modeling and Control of DC Grids (Modellering en controle van DC netten). PhD Dissertation, KU Leuven, Department of Electrical Engineering, Belmans R. (supervisor)Title of Chapter

Costanzo, G. T., Iacovella, S., Ruelens, F., Leurs, T., & Claessens, B. J. (2016). Experimental analysis of data-driven control for a building heating system. *Sustainable Energy, Grids and Networks*, *6*, 81–90. http://doi.org/10.1016/j.segan.2016.02.002

6. The OPSYS test rig - DTI



Institution / Department
Danish Technological Institute
Energy and Climate
Refrigeration and Heat Pump Technology

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6.1. General presentation

The OPSYS test rig emulates a house with an underfloor heating system to which a ground source heat pump can be connected. Figure 27 shows a principle sketch of the system. The system has two main elements denominated the hot side and the cold side, seen from the heat pumps point of view (cold side = evaporator side, hot side = condenser side).

The hot side emulates the underfloor heating system (can also emulate a radiator system) with the possibility of using a buffer tank. The underfloor heating system is emulated via a series of parallel-connected heat exchanges resembling each room in the house. Hot water draw off may also be emulated, but this is at the moment not part of the test setup.

The heat consumption is programmable in order to simulate different sized rooms of a house with different load conditions. The controller of the experimental setup is running a simulation program that calculates the heat consumption of the rooms and provides an emulated room temperature and an emulated return temperature of the water from each “room” as input to the control of the manifold. In this way it is on one hand possible to control an underfloor heating system like in an ordinary home while on the other hand different more advanced control strategies may also be tested. The size and function of the “rooms” can easily be changed by changing the load pattern and heat loss of the “rooms” in the simulation program.

The cold side of the experimental setup (see Figure 27) emulates a heat source, e.g. the ground. This is an electric heater, which is controlled in order to obtain a brine temperature defined by the simulation program. With this method, seasonal variations of the ground temperature and different length of tubes in the earth can be emulated as well.

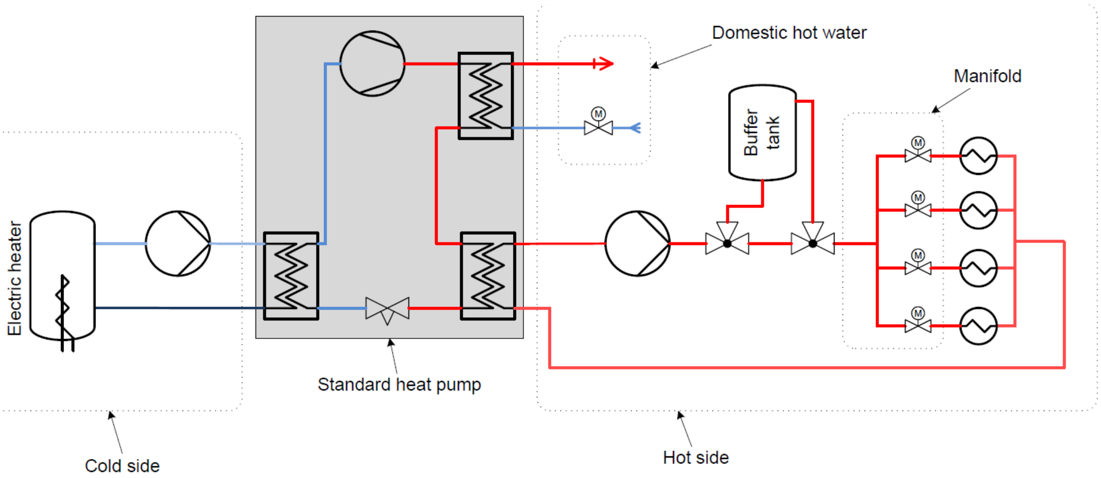

Figure 27. Principle sketch of experimental setup.

6.2. Description of the test facility

6.2.1. General principle and testing possibilities

General testing principles

The general concept of the semi-virtual test rig is presented in Figure 28. A real physical device (heat pump or control of the thermostats in the heating system) is placed in test rig, where it is studied under specific conditions that are simulated and implemented in the virtual environment. The overall principles are as follows:

- Test of the components under defined building and environmental conditions
- Development and integration of innovative control of heating systems.
- Analysis of equipment behavior at particular transitory phases for performance improvement.

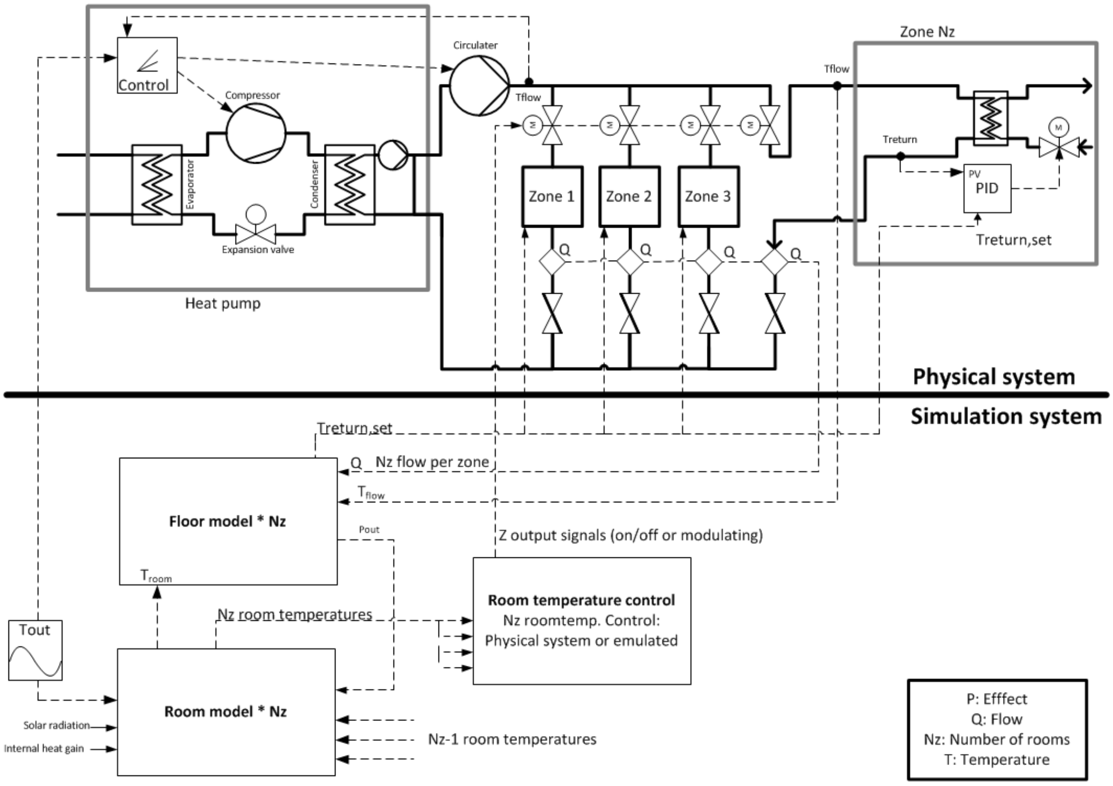

Figure 28. General concept of the semi-virtual OPSYS test rig.

Detailed testing principles

- Experimental testing of control of the forward temperature of a heat pump.
- Experimental testing of control of the water flow through a heat pump and through the different circuits of a heat emitting system.
- Demonstration of optimal combined control of a heat pump and the heat emitting system in a house.
- Demonstration of advanced control of a heat pump and the heat emitting system in a house for optimization of the efficiency of the complete system and/or for providing energy flexibility to the surrounding grid.

6.2.2. Equipment available and specifications

Heat emitting system

The heat emitting system consists of four heat exchangers emulating the heat demand of the house – see Figure 29. If necessary, more heat exchangers may be added to the test rig.

The virtual heat load on each heat exchanger is simulated by a house model developed in Dymola (Modelica) and embedded in the control system of the test rig as an FMU (Functional Mock-up Unit). The physical heat loads on the heat exchangers are created by the central cooling system at Danish Technological Institute, Energy and Climate Division. The flow rate of the cooling water is for each heat exchanger determined by the return temperature of the warm water leaving the underfloor heating simulated by the house model

The hot water flows in the heat exchangers are controlled by traditional actuators for underfloor heating systems consisting of a valve controlled by a wax motor – see Figure 29. When heating the wax with an electric current the valves open. The valves close again when the current is turned off. The valves may either be on/off controlled or be kept partly open by pulsing the current through the wax motors. The position of the actuators is determined by the simulated room temperature and the implemented control algorithms for controlling the actuators.

The test rig is developed in a Danish project with the aim of increasing the Seasonal Performance Factor of heat pumps by optimization of the forward temperature from the heat pump and the flow rate through the heat pump (Jensen et al, 2017). However, as the control of the system is on the PC of the test rig, many different control options may be tested. One option being controlling the heat pump according to the need of the surrounding power grid in the terms of providing energy flexibility. Traditionally energy flexibility of heat pumps have been tested by switching the heat pump on and off, however, increased energy flexibility may be achieved by pre-heating the building within the comfort limits of the room temperature before the heat pump is switched off due to a period with limited power in the grid. This demands for more advanced control including forecast of the future power level in the grid and heat demand of the house. As the control of the test rig is implemented on the controlling PC very advanced control scenarios may be tested in the test rig and following transferred to commercial control devices.

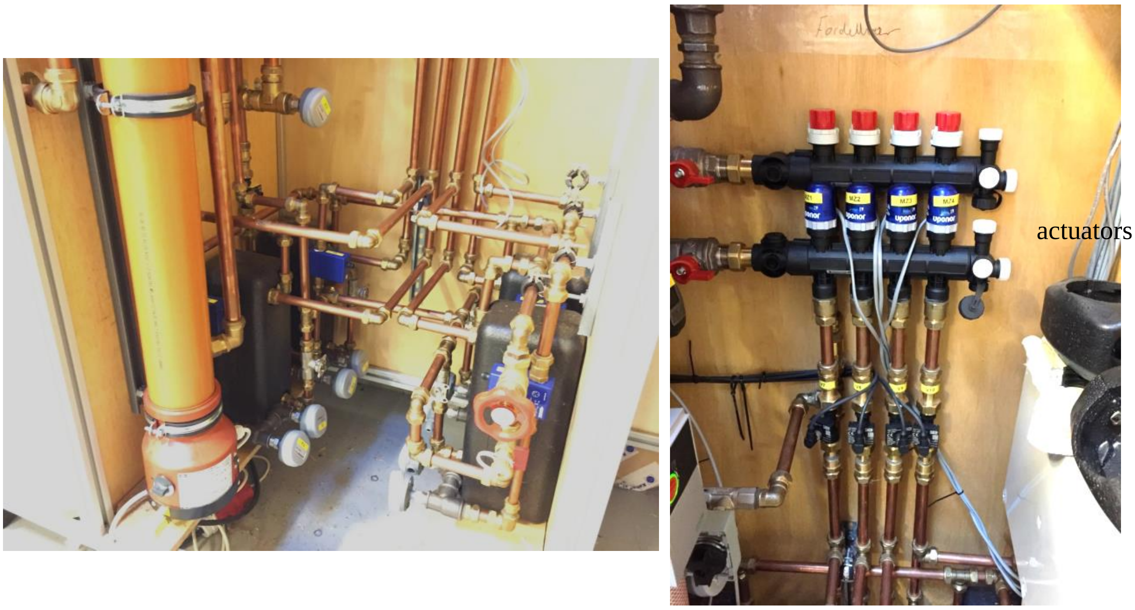

Figure 29. The heat exchangers emulating the heat emitters in a heating system (left). The actuators of the heating system (right).

- the heat exchangers are Reci PHE-TYPE: LP80Tx40 with a capacity of 8 kW
- the actuators are from Uponor. Running time from fully closed to fully open and vice versa is 300 seconds

Brine circuit

The brine circuit consists of a heating element in series with a 300 litre insulated buffer tank. The heating element is controlled in order to give the heat pump the desired brine temperature. The simulation program control the brine temperature so that it matches the time of the year the simulation program is running.

The buffer tank smoothens out any temperature variation of the brine temperature created by the control of the heating element, which has a capacity of 7 kW.

The test rig is originally designed for testing of ground source heat pumps, which is the most commonly used type of heat pump in Denmark. If an air to water heat pump needs to be tested in the test rig, the outdoor unit of the heat pump should to be located in one of the climate champers at the Energy and Climate Division.

Heat pump

The first heat pump installed in the OPSYS test rig was a ground source heat pump from Bosch: Bosch Compress 7000 LWM 3-12 kW (Bosch, 2017). The heat production can be varied continuously between 3 and 12 kW. Below 3 kW on/off control is necessary.

The heat pump may be controlled by five input and five output in the control of the test rig. The simplest way to control the forward temperature of the heat pump is to manipulate the ambient temperature the heat pump “senses”. For the above mentioned heat pump from Bosch the ambient sensor of the heat pump was replaced with at controllable voltage signal, which - when knowing the heating curve of the heat pump - may be adjusted to trick the heat pump to delivering the desired forward temperature.

6.2.3. Data acquisition and control

The test rig is controlled by a Python script running on a PC and a BMS system on the test rig. Figure 30 shows the connections between:

- the PC running the Dymola house model (as a FMU), the interface to the Trend BMS (CTS 963 software) and the control of a separate data logger (Agilent DAQ)
- the Trend controllers (BMS) via the sip
- the data (Agilent) logger

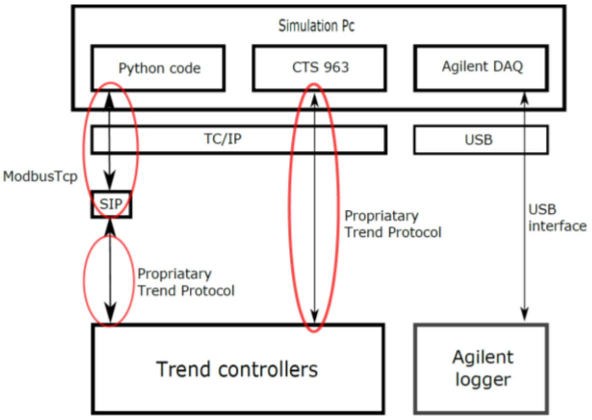

Figure 30. The connections between the test rig, the simulation PC and the data logger.

The BMS system of the test rig is composed of modules from Trend: one IQ4E and four 8UIO modules. The BMS is developed and interfaced by the Trend 963 software. Trend 963 is a Windows based software package, which provides a management interface between the user and the Trend IQ building control system.

The Trend BMS modules communicate with the components of the test rig via a sip ModBus/vIQ module. The sip is an interface between the BMS and the components of the test rig using the serial ModBus protocol.

The heart of the virtual part of the test rig is the FMU running a simulation of the heat demand of a typical Danish house. Three typical Danish houses from four time periods has been developed (Jensen et al, 2017):

- a house from the 70's
- a house build according to the Danish Building Regulation 2010
- a house build according to the Danish Building Regulation 2015

The house models contain typical free gains from persons, appliances and solar radiation. The house models are using typical Danish weather conditions and an annual profile for the temperature of the brine to a ground source heat pump.

The parameters and values of the house models may be changed to reflect other building types and weather conditions.

The house models simulate the heat demand of the rooms of the house and transfer the room temperatures and return temperature of the underfloor heating system of the rooms to the control script also running on the PC.

Figure 31 shows a screenshot of the interface of the BMS showing the four heat emitting systems. The test rig can either be controlled by the Python control script running on the PC or manually – the latter for e.g. performing step response tests.

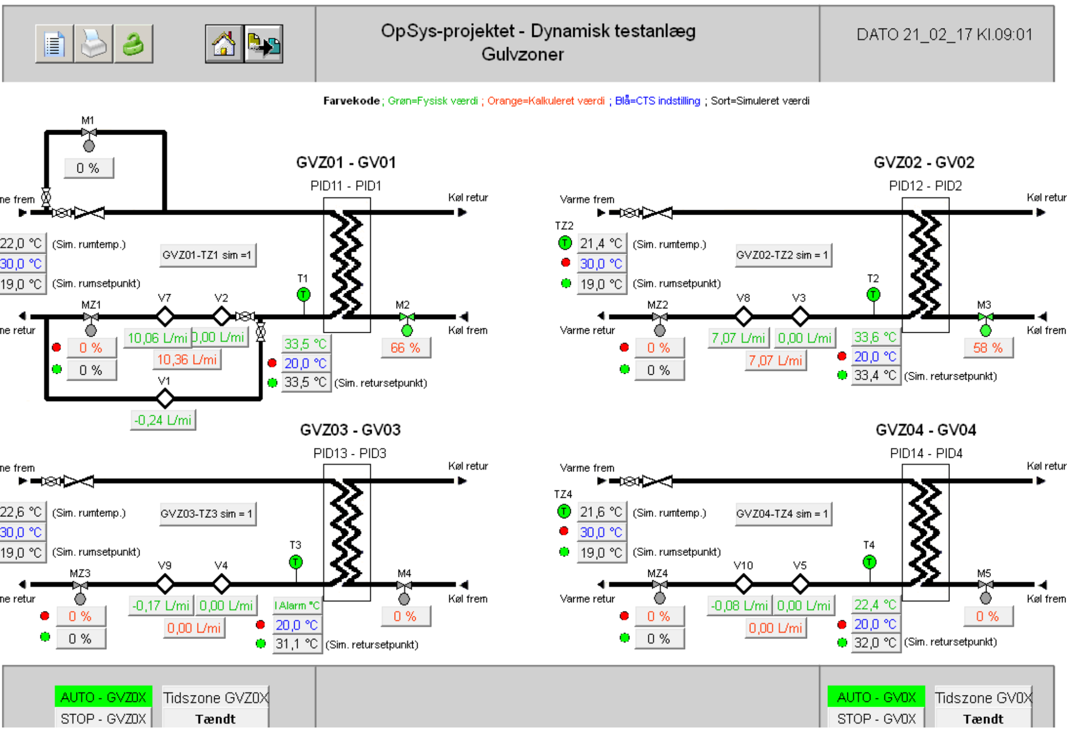

Figure 31. Screenshot of the BMS interface showing the heat emitting system.

The test rig is equipped with several physical and virtual sensors measuring temperature, flow, energy and actuator positions – please refer to (Jensen et al, 2017) for a description of the applied sensors. The measurements is collected by the BMS, the data logger and the house model and transferred to a database on the PC running the test rig.

Special purpose Python scripts have been developed for extracting and aligning the measured data from the database.

6.3. Example of previous studies

6.3.1. Study 1: Underfloor heating and heat pump optimization

The OPSYS test rig has been developed as a central part of the Danish research project: Underfloor heating and heat pump optimization (Jensen et al, 2017). The project will run until September 2017.

The purpose of the project was to minimize the gap between the accredited efficiency of domestic heat pumps and the actual efficiency when installed in a house. Unfortunately, measurements on existing heat pump installations has shown Seasonal Performance factors (SPF: mean annual efficiency) well below expectations as the heat pump and the heat emitting system are rarely properly adjusted at the installation of the heat pumps, and the operating parameters are not continuously adjusted according to the actual operating conditions. The supply temperature is e.g. often set too high in order to guarantee sufficient space heating. A supply temperature higher than needed results in a lower SPF.

Typically, an increase of 1°C in the temperature difference between the cold and hot side of a heat pump leads to a decrease of 2-3% in the COP (instant efficiency of the heat pump). For most heat pumps, the only control and means of reducing the supply temperature is a simple ambient temperature correction, which, however, rarely leads to an optimal supply temperature. A too high supply temperature also has consequences for the heat emitting system. The volume flow through the system fluctuates due to uncoordinated opening and closing of valves in the system, e.g. manifold valves for an underfloor heating system. The higher the supply temperature is above the minimum required supply temperature, the more the amplitude of the fluctuations increases. The fluctuating flow causes the heat pump to fluctuate in produced heat power resulting in a reduced COP compared to the optimal COP at the actual temperature level. The larger fluctuations, the higher decrease in efficiency.

The aim of the project was to minimize the above problems, so that end users receive the expected efficiency from their heat pump installations. This has been done by developing integrated controllers for the heat pumps and the heat emitting systems in order to reduce the supply temperature and volume flow fluctuations.

Preliminary results from a study financed by the Strategic Research Centre on Zero Emission Buildings (Jensen, Olesen and Paulsen, 2014) indicated a theoretical potential for improving the COP of an installed heat pump by approx. 15 % by optimizing the volume flow. The study showed an equal large improvement when keeping the forward temperature as low as possible. A detailed theoretical study including tests in the OPSYS test rig will be reported by the end of 2017 (Jensen et al, 2017).

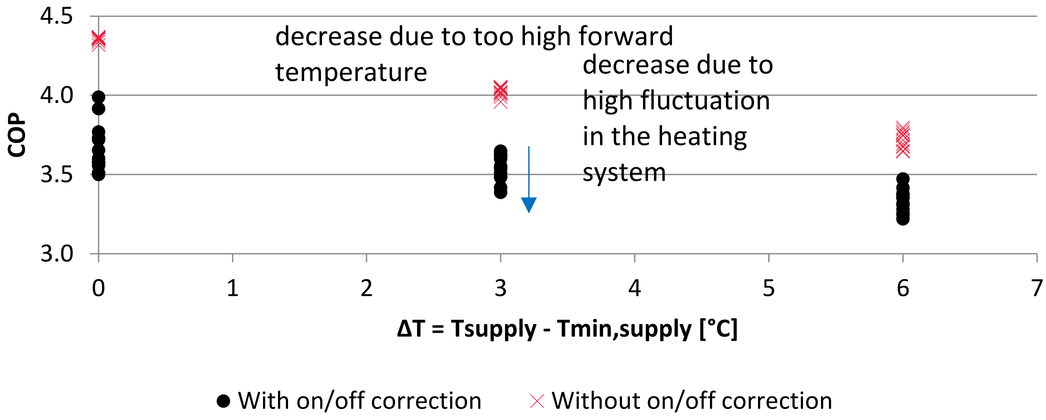

Figure 32. Results from simulation of the efficiency of a heat pump dependent on the forward temperature and fluctuation of the flow rate though the heating system (Jensen, Olesen and Paulsen, 2014).

- ● With on/off correction: the heat pump is frequency controlle except for below 30% of the nominal heating power, where is is on/off controlled.
- X Without on/off correction: frequency controlled in the whole area of the heat production.

6.3.2. Study 2.

A first study with a simple control in order to obtain energy flexibility to support grid operation is aimed to be conducted during the second half of 2017. The results of simulations and tests in the OPSYS test rig will be reported in (Jensen et al, 2017).

6.4. Maintenance and collaborations

The OPSYS test rig is run and managed by Refrigeration and Heat Pump Technology at the Danish Technological Institute. Refrigeration and Heat Pump Technology has laboratories in both Taastrup and Aarhus, Denmark. The OPSYS test rig situated in Taastrup. Around 30 full-time employees are maintaining, organizing and using the lab facilities in Taastrup and Aarhus.
Refrigeration and Heat Pump Technology performs:

- certified tests according to international standards on refrigeration and heat pumps systems
- research and development in the fields of not only refrigeration and heat pumps but also in the areas of solar energy, energy demand of buildings and smart grids

6.5. Additional information

Danish Technological Institute offers lab testing services in the area Eco design (Directive 2009/125/EC) and energy labelling (Directive 2010/31/EU) in the following categories; Commercial refrigerated cabinets, condensing units, domestic ovens and hobs, electronics for household, office and professional use, heat pumps, household refrigerating appliances, electric motors and drives, water pumps and circulators, fans, ventilation units - RVU/NRVU, range hoods. Cross-product services include testing of sound and acoustics.
For further information: www.dti.dk/testing/ecodesign-and-energy-labelling/37224.

6.6. Relevant publications

Bosch, 2017. http://dk.documents.bosch-climate.com/download/pdf/file/6720813696.pdf

S.Ø. Jensen et al. 2017. “Combined optimization of heat pumps and heat emitting systems". Danish Technological Institute and Aalborg University. December 2017. In process.

Jensen, Olesen and Paulsen, 2014. “Lightweight underfloor heating system and the impact on the efficiency of heat pumps (partly in Danish, however, not the part containing Figure 32)”. Danish Technological Insitute, February 2014. ISBN: 978-87-93250-01-7.

7. ZEB Living Laboratory - NTNU / SINTEF

Institution / Department

Norwegian University of Science and Technology, NTNU
Department of Architecture and Technology

SINTEF Building and Infrastructure

NTNU – Trondheim
Norwegian University of Science and Technology

SINTEF

Location of the test facility

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7.1. General presentation

The ZEB Living Laboratory test facility is a single family house with a gross volume of approximately 500 m^3 and a heated surface (floor area) of approximately 100 m^2. The building is realized with state-of-the-art technologies for energy conservation measurements and renewable energy source exploitation, and was designed to carry out experimental investigations at different levels, ranging from envelope to building equipment components, from ventilation strategies to action research on lifestyles and technologies, where interactions between users and low (zero) energy buildings are studied. The building is equipped with different, redundant energy systems and monitoring technologies, and is controlled by an on-purpose developed system, which allow different types of tests to be conducted, among them tests on energy flexibility in buildings.

7.2. Description of the test facility

7.2.1. Architecture and building technology

The Living Laboratory is a single family house with a gross volume of approximately 500 m3 and a heated surface (floor area) of approximately 100 m2. It is realized with state-of-the-art technologies for energy conservation measurements and renewable energy source exploitation. The plan of the Living Lab (Figure 33) is organized in two main zones: a living area facing south and a working/sleeping area towards the north. The entrance is located in the southwest corner, and through a filter space, that hosts a wardrobe, the user gets access to the living room. The kitchen is located at the opposite end of the living room. An automated double skin (ventilated) window is installed in the living room, covering the largest part of the south facade. At the centre of the north zone, there is a shared studio area, equipped with a long writing desk and with an automated window.

Two bedrooms (one facing east and one facing west) are located at the two sides of the studio room. The technical room (accessible from outside the building), bathroom (accessible from the studio room) and the kitchen are placed all along the central spine of the building in order to optimize the distribution of the technical equipment. A small mezzanine is placed above the west bedroom, and it is equipped as sleeping area for guests or as play area for children.

The building construction has been optimized through a set of preliminary simulations, and resulted into a highly insulated envelope characterized by a glass ratio of around 20%. Walls, floors and roofs are made out of a conventional wooden-frame structure with a double layer of rock wool insulation for a total of 40, 40, and 45 cm respectively (and a U-value of 0.11, 0.10 and 0.11 W/m2K, respectively). All the windows are characterized by low u-value (in a range from 0.65 W/m2K – south window – up to 1.00 W/m2K – for the roof windows).

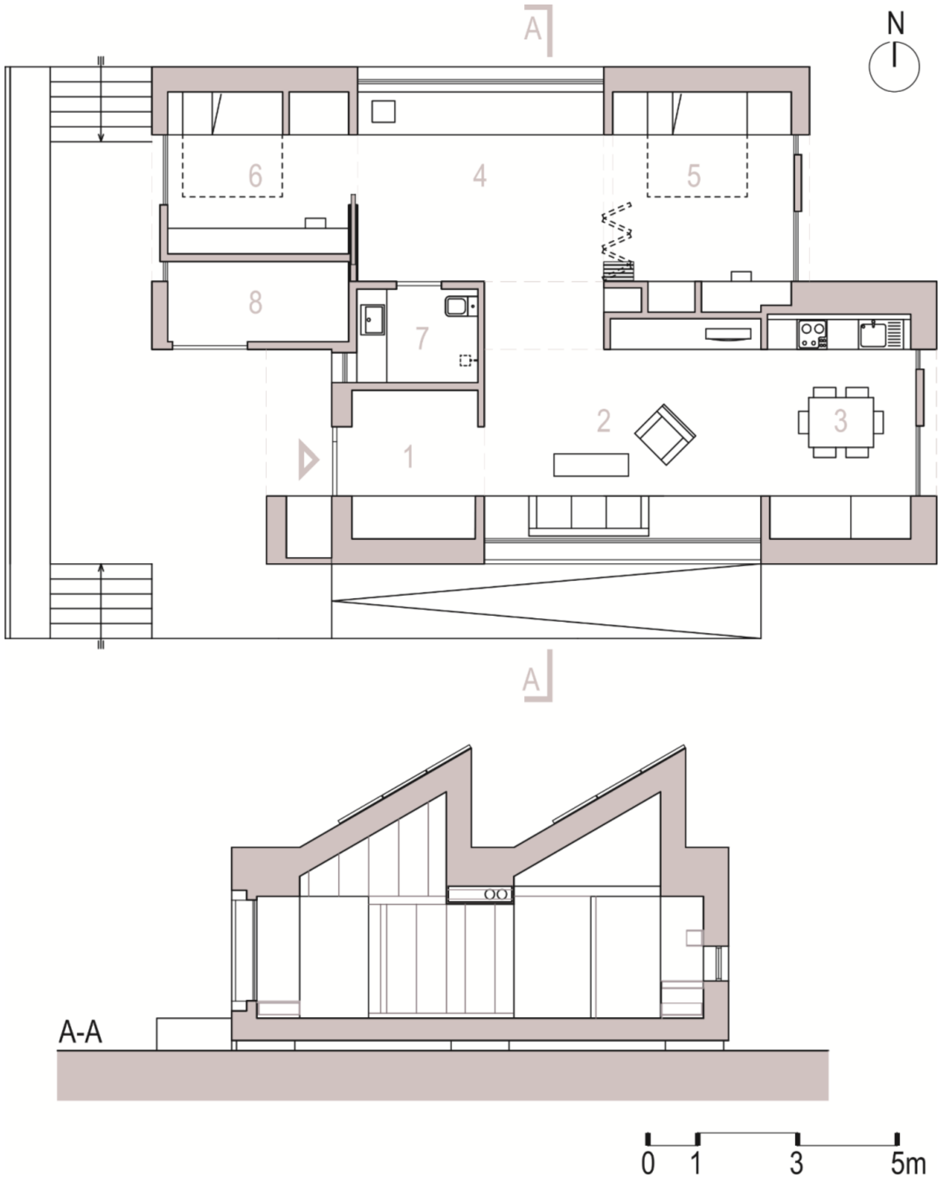

Figure 33. Plan and vertical section of the Living Laboratory (1: entrance; 2: living room; 3: kitchen; 4: studio room; 5,6: bedroom; 7: bathroom; 8: technical room). Original Figure in Goia et al. 2015.

7.2.2. Building equipment

The Living Lab is designed to minimize energy demand for its operation and to harvest solar energy to such an extent that converted solar energy (both through passive measures and active technologies) is larger, on a yearly basis, than the building energy demand, and even compensate embodied emissions in the constructions by avoiding greenhouse gasses emissions during the life of the building. The energy flow within the building plant, including on-site renewable energy supply, is schematically illustrated in Figure 34.

The thermal energy necessary to cover heating, ventilation and domestic hot water demands is primarily planned to be obtained by a fix speed scroll compressor ground source heat pump (GSHP in Figure 34), which is connected to a surface collector field (total length of the approximately 150 m) located in the back-yard (north of the building side) of the Living Laboratory. The heat pump has a nominal output of 3.2 kW (with B0W35) and a nominal COP of 3.7. In case of thermal output at a higher temperature level (55 °C), the nominal COP is 3.0 (B0W55) and the nominal thermal power is 2.6 kW. The heat pump has a very simple control logic, which turns on the compressor full power when a heating (thermal output at 35 °C) or domestic hot water (thermal output at 55 °C) load is received by the controller, and turns it off when the load signal is over. Control of the signals for heating or domestic hot water load is achieved through the building level control system, integrated in the building monitoring and control system.

The plant-side of the heat pump is connected to an integrated tank (IWT in Figure 34) that combines a buffer tank (BT) for the heating circuit (160 l) and a domestic hot water tank of 240 l (DHTW). The lower, buffer tank, has with two coils: one connected to the thermal panel circuit, and the other connected to the domestic hot water circuit for preheating of the sanitary water. After flowing in the coil of the lower tank, the domestic hot water is stored in the upper tank, equipped with a coil connected to the heat pump output. Two auxiliary electric coils (3 kW each) are installed in the integrated water tank, one for each of the two vessels.

For research purpose, two different terminal units for the heating system are available in the building and planned to be operated independently: a floor heating system and one, 2kW high-temperature (55 °C) radiator. Underfloor heating panels are located under the entrance, the living room, the kitchen, the studio room, the bedrooms, and the bathroom. The sole radiator is instead installed in the living room, approximately at the centre of the building. It is also possible to use a combination of these two systems (e.g. the radiator can be used in combination with the floor heating in the bathroom).

Heating through ventilation air (ventilative heating) can be also exploited to cover heating demand in combination with fresh air supply need. In this case, underfloor heating in bathroom is expected to operate in combination with the overheated fresh air supply.

The building is equipped with a balanced mechanical ventilation plant with nominal air flow of 120 m^3/h, and possibility to regulate the airflow up to 360 m^3/h. Air diffusers are evenly distributed in the building (living room, studio room and two bedrooms), while extract takes place in the kitchen (to a small extent) and in the bathroom (to a larger extent). Fresh air supply is managed by a compact air handling unit that integrates a heat recovery system with rotatory wheel. The nominal efficiency (with a flow rate of 250 m^3/h) of this system is 85%. The unit is equipped with an electric coil (1.2 kW) capable of heating up the supply air up to 40 °C (for ventilative heating purpose). A water coil (2 kW) is also available for post-heating of supply air and it is connected to the buffer tank. The unit can effectively control only the sensible temperature, while active control of relative humidity is not possible.

The air handling unit has an integrated controller that handles the equipment independently by the centralized control/monitoring system. The unit is however connected to the (upper) building level control system, which can therefore manage the unit. Hybrid ventilation strategies (combination of mechanical and natural ventilation) can also be exploited thanks to the possibility offered by some of the windows in the building, which are equipped with electric driver to allow automated opening.

The artificial lighting plant of the Living Laboratory is based on an extensive use of LED strips and LED luminaires. Conventional LED strips (12 V DC) with nominal power input of 4.8 W/m, 9.6 W/m and 14.4 W/m are installed according to locations and the required luminous flux.

Floor lamps and a pendant lamp above the dining table complete the lighting plant. All the luminaires are controlled by the building level control system and can be dimmed from 0 to 100% of the power through both both physical (pulse switches) and virtual (on touch screen) interfaces. The central building control system records the status of the physical and virtual signals and consequently acts on 24 fast-response solid state relays to manage the LED stripes and lamps. Total installed power (including outdoor lighting) of the lighting plan is 1.2 kW (DC side). The AC to DC conversion is assured by a transformer with an efficiency of 87%.

Technologies for onsite renewable energy harvesting

Two façade-integrated solar thermal panels are installed on the south-facing façade of the building. They cover a total area of little more than 4 m^2, have optical efficiency of 0.82, and are connected to the buffer tank and to the GSUH-SCF circuit. A series of dedicated valves can change the direction of the flow of the heat carrier fluids in these circuits and different paths are therefore possible.

A total of 48 PV modules are installed on the two roof slopes of the building, 24 modules for each slope. Each PV module has a nominal power (values at STC) of 260 W, and the efficiency is just below 16%. The total installed power (DC) is thus approximately 12.5 kW_P for both the roofs. Each PV roof is connected to a power inverter with a nominal AC rated power output of 4.6 kW (single-phase, 230 V line), with an efficiency (European weighted efficiency) of 96.5%. An electric battery is not installed at the moment, it is planned to add a battery with a capacity of around 20 kWh.

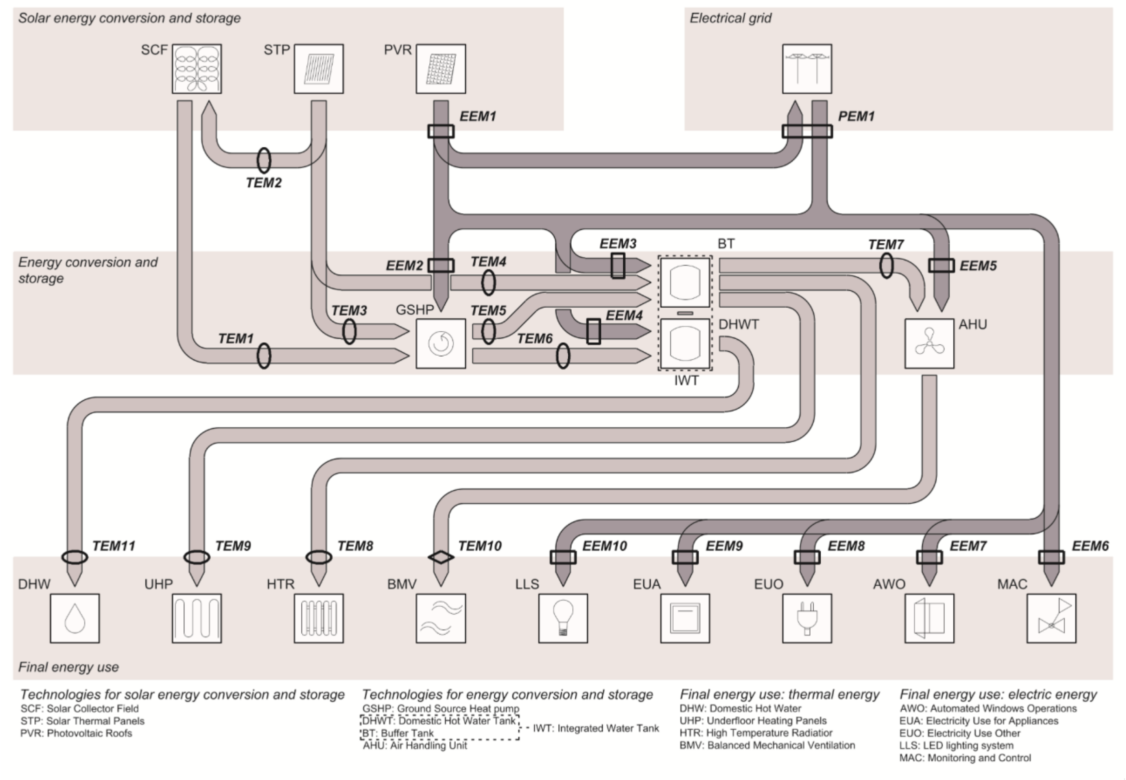

Figure 34. Thermal and electrical energy/power flow in the Living Laboratory; technologies and devices for energy conversion and storage and associated monitoring system. Original figure in Goia et al. 2015.

7.2.3. Monitoring and control systems

Aim and requisites of the monitoring system

The monitoring system in the Living Laboratory has been developed in order:

- to monitor the most relevant environmental quantities, both indoor and outdoor;
- to record users patterns and occupants' habits;
- to measure energy use for heating, ventilation, domestic hot water, artificial lighting, appliances and other uses;

- to quantify solar energy exploitation and energy from the grid; and
- to assess efficiency in conversion and storage of energy for different uses, as well as energy flexibility.

Starting from these aims, the requirements for the selection of the components of the monitoring system were set considering that:

- a compromise between accuracy, number and type of the sensors should be found – i.e. to reach the same measurement accuracy as in a laboratory test facility was out of the scope;
- sensors should be integrated in the building as it would be in a real house, and they should be chosen among those that can be installed in a conventional application;
- though, for research reasons, more sensors can be installed than in a conventional building, the number and location of the sensors should be as close as possible to that which would occur in a real, occupied building;
- the measurement system should be very flexible and allow a following upgrade to be easily realized;
- the characteristics of the sensors should be so that measurements and data analysis can be performed according to the relevant technical standards for energy and comfort assessment (e.g. EN 15251, IEC 62053).

Sensors and transducers

The building is equipped with a weather station that integrates sensors for measurements of outdoor air temperature (Pt 100; accuracy: ±0.3 °C), relative humidity (thin film capacitive sensor%; accuracy: ±3%), barometric pressure (piezoresistive sensor, accuracy: 50 Pa), wind velocity (ultrasonic sensor, two axes; accuracy speed: ±3%; accuracy direction: ±2 deg), global solar irradiance on the horizontal plane (thermopile; accuracy: II class pyranometer). The weather station is installed above the roof of the building. A luxmeter is installed on the roof to record global (direct, diffuse, reflected) illuminance ln the horizontal plane (thermopile; accuracy: ±5%). Global solar irradiance measured in two other locations as well: on the roof slope plan and on the south façade, both by means of thermopiles (raccuracy: II class pyranometer).

Outdoor air temperature is also recorded by means of two additional sensors located on the south- and north-exposed façade (Pt 100; accuracy: ±0.1 °C). Both sensors are suitable protected from the influence of direct solar irradiation.

Indoor air temperature values are measured in every room of the Living Laboratory, at the height of 1.6 m from the floor. In the living room and in the studio room temperature stratification is also measured at 5 levels (0.1, 0.8, 1.6, 2.4, 3.2 m from the floor) by means of a wall mounted sensors with PT100 probe (accuracy: ±0.1 °C). Relative humidity is recorded thanks to a wall mounted capacitive probe (accuracy: ±3%) integrated in a multi-sensor element, in all the room of the building. The relative humidity sensor comes in combination with a temperature sensor (Si band-gap; accuracy: ±0.8 °C) which is used as temperature signal for the controller.

Air temperature and relative humidity values are also measured near each diffuser of the ventilation plant (i.e. living room, kitchen, studio room and two bedrooms) though duct sensors that integrate a band-gap temperature sensing elements (accuracy: ±0.8 °C) and a capacitance probe for relative humidity measurement (accuracy: ±3%).

CO_2 concentration values are recorded by means of a non-dispersive infrared sensor (accuracy: ±70 ppm + 5% MV), one sensor in each room, located close to the correspondent temperature sensor.

A combined ceiling mounted sensor measures in each room diffuse illuminance level and people presence. The sensor contains a probe for light intensity (digital sensor for illuminance; accuracy: ±5%) and a sensing element for motion detection (infrared sensor). Users' behaviour is also monitored by recording position (open/closed) of all the windows (both automated windows and manually-operated windows) by means of a simple magnetic contact sensor, as well as artificial light use down to every single LED luminaire.

Thermal energy demand for heating purpose is measured for two independent terminal configurations (high temperature radiator, TEM8 in Figure 34, and low temperature underfloor heating panel, TEM9 in Figure 34). For both the circuits, a thermal energy meter calculator is used in combination with PT500 temperature probes and ultrasonic flow meters, resulting in an accuracy of 2%. Monitoring of energy demand when underfloor heating panels are in use is split in three different zones: living room, kitchen and studio; bedrooms; and bathroom. Energy demand for domestic hot water (TEM11 in Figure 34) and waterborne energy demand for ventilation (when the water coil is activated, TEM7 in Figure 34) are also monitored by means of similar configuration. Sensors used to monitor thermal energy use are different from those used to control the plant.

Airborne thermal energy demand for ventilation (TEM10 in Figure 34) is calculated from measurement of air speed, of temperature and of relative humidity in ventilation ducts. For this purpose, two sensors that integrates a PT100 probe (accuracy: ±0.3 °C) and a capacitive probe (accuracy: ±3%) are installed, one in the supply main duct and one in the extract main duct. Air speed is measured by means of one hot-wire sensor (range: 0.1…30 m/s; accuracy: 10%) in each of the two main ducts.

Electric energy use for heating ventilation and domestic hot water is monitored by means of several electric energy meter located on the (single-phase) lines that powers different building equipment components, all having a resolution of 1 Wh and an accuracy of 2%.

Electrical energy use in the building that is not related to heating, ventilation and domestic hot water can be grouped in five categories: energy use for lighting (EEM10 in Figure 34), for appliances (EEM9), general electricity for other uses (EEM8), energy use for use and control of automated windows and shading systems (EEM7) and energy use for monitoring and control of the building (EEM6).

The electric energy monitoring system measures 25 power lines independently monitored (single-phase energy meter with 1 Wh resolution and 2% accuracy), and allows a high level of detail to be achieved, being able to discriminate electrical energy use a single appliance (i.e. fridge; hob; oven; extraction hood; dishwasher; washing machine; tumble dryer), for groups of sockets (i.e. sockets in living room and entrance; sockets in kitchen; sockets in studio room; sockets in bedrooms and sockets in bathroom), for line to power shading devices, for line to power automated windows and their controllers. The power line for lighting is independently monitored and, as previously mentioned, through data post-processing based on control signals counters it is possible to assess lighting energy use down to luminaire level.

Energy for auxiliaries is also monitored so that components are coherently grouped. Several power lines related to electric coils or to the heat pump, as well as auxiliary lines for power in the technical room and for the DAQ are monitored too.

Power converted by means of PV roofs is monitored both by means of two energy meters (EEM1; resolution: 1 Wh; accuracy: 2%.), one for each PV roof, and by means of data retrieved from the inverters. Among others, data retrieved from power inverter include: operating hours; DC current input and voltage; DC power input; AC voltage and current output; AC active, reactive and apparent power.

Three-phase electrical energy/power supply from the grid is monitored by means of a power meter (63rd harmonic, 128 samples per cycle), which records, for each phase, current (accuracy: ±0.5%), voltage (accuracy: ±0.2%), power factor (accuracy: ±0.002), active power (accuracy: ±0.2%), frequency (accuracy: ±0.01 Hz), active and reactive energy (accuracy: IEC 62053-23 Class 2 and IEC 62053-23 Class 0.5, respectively). The meter is designated with the code PEM1 in Figure 34.

Thermal energy/power output from the solar thermal panels is calculated starting from measurement of heat carrier fluid (water-glycol) flow rate (electromagnetic flow meter; accuracy: ±5%) and temperature (of flow and return), the latter one by means of PT100 probes (accuracy: ± 0.1 °C). Due to flexible use of solar thermal converted energy, this thermal output can be diverted to the surface collector field (TEM2 in Figure 34) for ground regeneration, or to the heat pump (TEM3) or to the buffer tank (TEM4).

Similarly to the solar thermal panel circuit, thermal energy/power extracted from the surface collector field (TEM1 in Figure 34) is calculated starting from monitoring of flow rate and temperature of flow and return. Flow rate is measured by means of an electromagnetic flow meter (accuracy: ±5%) and temperatures with PT100 probes (accuracy: ± 0.1 °C).

Additional temperature and humidity measurements are also performed in several other locations of the plant for different purposes (e.g. control, energy conservation equation, in-depth analysis of components). In general, temperature measurements in water or water-glycol heat carrier fluids are carried out by means of PT100 class I probes, while J/T type thermocouples (accuracy: ± 0.5 °C) are used to perform additional temperature measurements in air or on surfaces. Relative humidity measurements are done through capacitive sensors with accuracy ± 3%.

Data acquisition and control system

Acquisition of signals from sensors and transducers is carried out by a National Instrument system based on the CompactRIO platform. This is a modular structure, where controllers, expansion chasses, input/output modules can be freely combined in order to suit the requirement of the measurement layout. One of the main advantages of this system is that future expansion and modifications of the measurement system can be realized in a relatively easy way.

The chosen starting configuration for the Living Laboratory includes one controller and two expansion chassis. A total of 19 different input/output signal modules are installed, ranging from current to voltage signals, from resistance to digital signals. Modbus communication protocol is widely used to connect transducers and components with serial communication features.

Signals sourcing for building equipment control are generated by data acquisition hardware. Most common control signals are 0…10 V, digital signals (24 V logic) and Modbus serial communication.

The integrated data acquisition system and control system is controlled by means of the National Instrument LabVIEW programming code. This is a graphical programming environment specifically developed for sophisticated measurement and tests. User interfaces will be developed to allow users controlling (some) of the features of the building. One of the main advantages of this system is that the degree of control that is handed out to the users can be relatively easily changed from one experiment to the other. Dedicated user interface will be developed for each experiment in order to allow occupants to control only some of the fea-

tures of the building. A more comprehensive user interface handling the whole building components is developed and is used by researchers to control the building when not occupied.
It is worth mentioning that, due to its configuration and particular features, such as centralized management of the entire building equipment, including control of power lines, actuators, artificial lighting, windows and shading system, the building can be completely operated without users living in it, using schedules so that ideal occupancy can be also experimented.

7.3. Example of previous studies

7.3.1. Study 1: Making a home in Living Lab: the limitations and potentials associated with living in a research laboratory.

The first qualitative experiment in Living Laboratory (Woods et al., 2016) took place from September 2015 to April 2016, when six different resident groups comprising of two to four people, lived in the Living Laboratory as if it were their home for a period twenty-five days each. The resident groups were chosen because they are associated with three basic demographic categories; students under 30 who are already cohabiting, families with small children and couples around the age of sixty. During the resident periods, the Living laboratory functioned as a home outside their actual homes for each of the six groups. The insight gathered in Living Laboratory provided an understanding of how a concept of home is established within a highly technical setting, and the implications this has for the use of the technology being tested in Living Laboratory.

7.3.2. Study 2: Daylighting availability in a living laboratory single family house and implication on electric lighting energy demand

The aim of this study (Lobaccaro et al. 2017) was to analyse the correlation between natural light availability and use of artificial light in a residential building located in the Nordic climate. Experimental data and numerical simulations were used to compare the use of artificial light (and the correlated electric energy demand) against the daylighting availability, in Living Laboratory, considering the six groups of resident involved in the experiment previously described. During the building occupation by the 6 different groups of people, electrical energy use for artificial lighting was continuously recorded, together with outdoor environment conditions (irradiance and illuminance on the horizontal plan). Through advanced daylighting simulations carried out with DIVA-for-Rhino, the availability of daylight (illuminance level) during the periods of occupancy has been reconstructed, using as input data the outdoor environmental variable recorded during the experimental analysis. The results, based on the analysis of the outcomes of five groups, show that the coefficient of correlation between daylight availability and energy saving (measured thorough the artificial light energy demand) is low, and it appears that the use of artificial lighting is little dependent on the availability of natural light.

7.3.3. Study 3: Energy performance assessment of a semi-integrated PV system in a zero emission building through periodic linear regression method

The aim of this study (Goia and Gustavsen, 2017) was to assess the performance of the photovoltaic (PV) system installed on the Living Laboratory.The building has a semi-integrated PV plant installed over two slopes of the building’s roofs. The total installed power (DC) is approximately 12.5 kWP. Each PV roof is connected to a power inverter with a nominal AC rated power output of 4.6 kW, based on a layout that optimize energy conversion, given the fact that shading over the two roof slopes is different.

In this paper, the performance analysis of the PV system is carried out considering the six months in the first year of operation of the system. A graphical analysis based on the linear regression method is presented and the array yield is compared against the reference yield (Performance Ratio). The analysis gives a general overview of the performance of the system, and a focus is then placed on the understanding of the system's output in relation to the undersizing of the PV inverters.

7.4. Maintenance and collaborations

The ZEB Living Laboratory is run and managed jointly by the Norwegian University of science and Technology, NTNU, and SINTEF Building and Infrastructure, and it is part of the ZEB Laboratories system, which includes also the ZEB Test cell Laboratory, and the ZEB Advanced Materials and Component Laboratories.

The ZEB Laboratories system is involved in numerous projects with different partners:

- Direct contracts for equipment testing, development of technical solutions, improvement of systems, etc.
- Partnership for national / international R&D projects
- Shared developments for new products

7.5. Additional information

Multimedia

The ZEB Laboratories system can be found here:
http://www.zeb.no/index.php/en/laboratories

7.6. Relevant publications

F. Goia, L. Finocchiaro and A. Gustavsen. 2015. The ZEB Living Laboratory at the Norwegian University of Science and Techonology: a zero emission house for engineering and social science experiments. Proceedings of 7PHN Sustainable Cities and Buildings. 21-21 Aug 2015, Copenhagen (Denmark).

F. Goia and A. Gustavsen. 2017. Energy performance assessment of a semi-integrated PV system in a zero emission building through the periodic linear regression method. Proceedings of NSB 2017 – The 11th Nordic Symposium on Building Physics. 11-14 June 2017, Trondheim (Norway).

G. Lobaccaro, S. Esposito, F. Goia and M. Perino. 2017. Daylighting availability in a living laboratory single family house and implication on electric lighting energy demand. Proceedings of CISBAT 2017 - International conference on Future Buildings & Districts – Energy Efficiency From Nano to Urban Scale. 6-7 Sep. 2017, Lausanne (Switzerland).

R. Woods, T. Berker and M. Korsnes. 2016. Making a home in Living Lab: the limitations and potentials associated with living in a research laboratory. Proceedings of the Demand Centre Conference 2016.

8. Semi-virtual Laboratory – Polytechnique Montréal

Institution / Department
Polytechnique Montréal
Department of Mechanical Engineering
Building Energy Efficiency (BEE) Research Group

Location of the test facility
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POLYTECHNIQUE
MONTRÉAL

8.1. General presentation

The Semi-Virtual Laboratory at Polytechnique Montréal allows to test hydronic (water-side) heating and cooling equipment in highly dynamic conditions. Active (e.g. heat pumps) and passive (e.g. storage tanks) equipment can be tested thanks to auxiliary loops capable of producing and rejecting up to 100 kW of heat simultaneously. A key feature of the Semi-Virtual Lab is to perform Hardware-In-the-Loop testing, where HVAC equipment is tested in realistic operating conditions provided by a full system dynamic simulation with the TRNSYS program. The 2-way data exchange between LabVIEW and TRNSYS is performed at every time step through shared variables, allowing direct feedback from the experimental performance on the simulation results and vice-versa.

The objective of the Semi-Virtual Lab is to develop and validate detailed dynamic models of HVAC equipment including detailed controls, and to test new prototypes or existing equipment in realistic dynamic conditions to improve their design and standard testing methods.

8.2. Description of the test facility

The concept of semi-virtual testing for a water-to-water heat pump is represented in Figure 35.

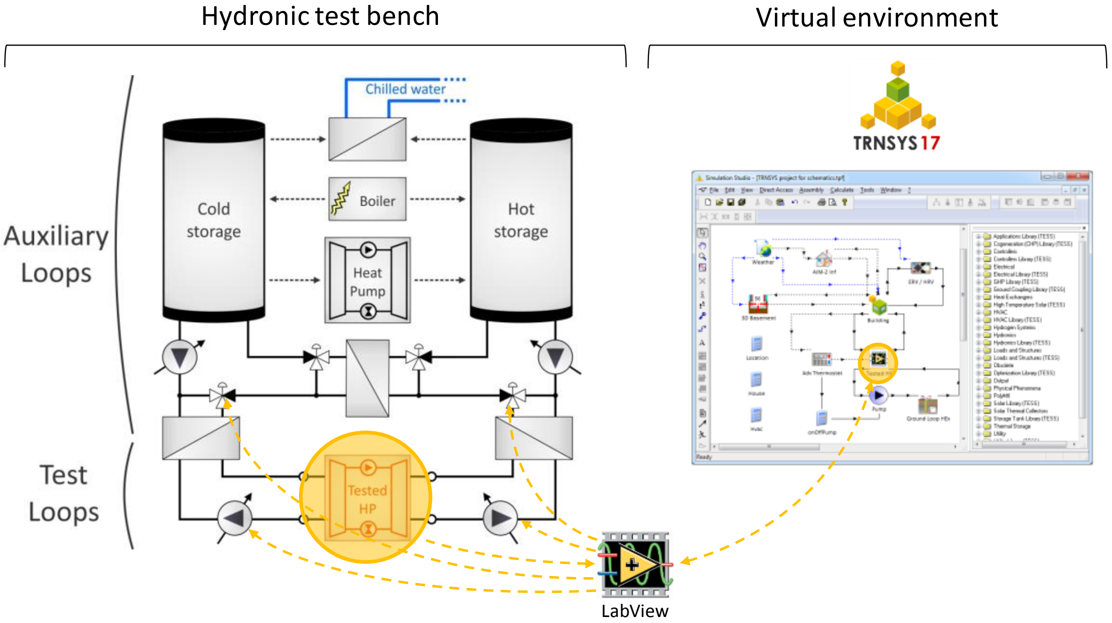

Figure 35. Semi-virtual testing at Polytechnique Montréal.

TRNSYS simulations predict system performance, calculating the flowrates and temperatures of the fluid streams entering HVAC equipment under test, which are used as actuator control signals in the Laboratory. The equipment's response to these operating conditions is sensed in the laboratory and imposed back on the building simulation.

Dynamic operating conditions are imposed on the tested equipment (e.g. a heat pump, as in the figure) based on a full system simulation. Measured outlet conditions (in this case temperature and flowrate on the source and load sides) at a given time step are sent to the simulation, which then calculates the inlet conditions for the next time step.

Testing possibilities

The flexibility of the Semi-Virtual Laboratory allows to perform different types of experimental tests:

- Standard tests imposing predefined (possibly highly dynamic) inlet conditions on HVAC equipment to assess its performance and to develop or validate numerical simulation models.
- Semi-Virtual tests where HVAC equipment is integrated within a full system simulation, therefore testing the equipment as if it was in a real system. This allows assessing the equipment performance in these conditions, and developing or validating models adapted to them.
- Semi-virtual tests also allow testing the response of the equipment's embedded controls to realistic operating conditions, therefore allowing to understand and model these controls realistically. This is especially important for recently introduced variable capacity devices (e.g. variable speed heat pumps, and Variable Refrigerant Flow devices) which often include proprietary and undocumented control strategies for which developing accurate models is a challenging task.
- Detailed testing and performance assessment for prototypes, in order to develop them and improve their performance for realistic operating conditions in addition to predefined standard tests.
- Assessment of the difference between the seasonal or yearly performance extrapolated from standard steady-state tests and the seasonal or yearly performance obtained from models validated in highly dynamic, realistic operating conditions. These studies can also inform standard certification bodies and help them develop new, more accurate standards methods of testing.

8.2.1. Equipment specifications

The 4 hydronic loops of the laboratory are shown in Figure 36. Two auxiliary loops (blue and red) can produce water at temperatures between -10 °C (with glycol solution) and +85 °C. Although the two loops are both connected to the heat production and heat rejection devices, for the sake of this explanation the blue loop will be considered as the cold loop and the red loop will be considered as the warm loop. These auxiliary loops are hydraulically isolated from the test loops (yellow and green) by plate heat exchangers equipped with 3-way valves. These heat exchangers and their control valves are used to impose the desired inlet conditions (optionally calculated from the full system TRNSYS simulation) on the tested equipment.

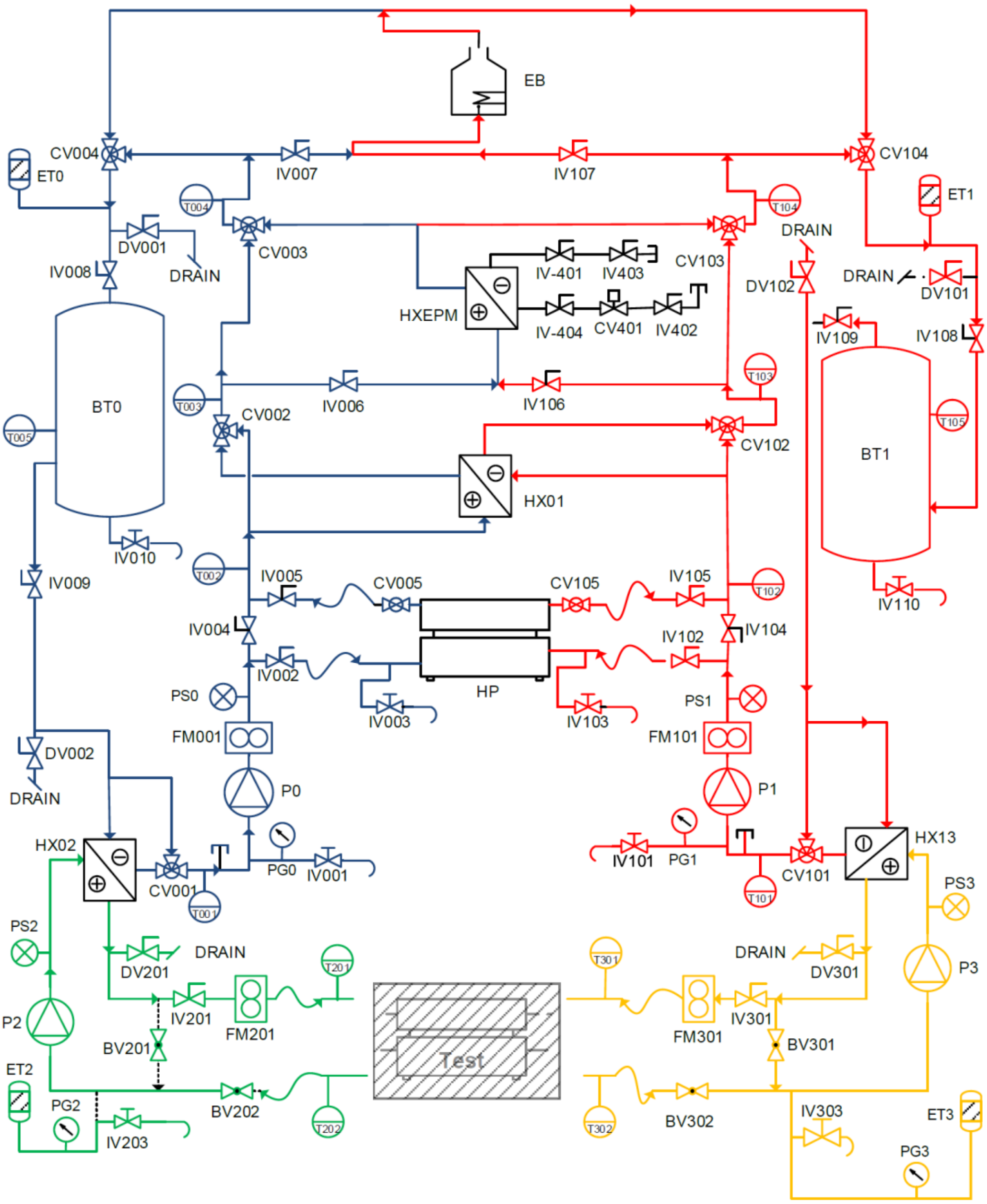

Figure 36. Hydronic loops of the Semi-Virtual Laboratory.

The hydronic loops piping has a diameter of 2.5” (62.5 mm) to allow relatively large flowrates, and adapters (with specific flowmeters) are available to reduce the test loops to a diameter better suited to smaller equipment (e.g. residential heat pumps). Operating temperature limits are between -10 °C and +85 °C depending on the fluid (up to 30 % glycol) and the equipment used.

The nomenclature in Figure 36 uses the first digit to represent the hydronic loop: “0” and “1” to denote the auxiliary loops, “2” and “3” to denote the testing loops. CV001 for example would be the first control valve (“01”) in the “cold” auxiliary loop (“0”).

The main components are described below:

- CVnnn: 3-way valves, centrally controlled. CV103 is a special constant-pressure control valve located in the university chilled water network, allowing to obtain a constant flowrate independently of the chilled water loop operation.

- EB: electric boiler (54 kW thermal, compatible with up to 30 % glycol)
- HxEPM: heat exchanger with the university (École Polytechnique de Montréal) chilled water network. The heat exchanger capacity is sized to reject 100 kW with a ΔT of 7 °C
- BT0 and BT1: storage tanks (974 L each)
- Hx01: heat exchanger between the two auxiliary loops ("0" and "1"). Standard tests imposing predefined (but possibly highly dynamic) inlet conditions on HVAC equipment to assess its performance and to develop or validate numerical simulation models. It is sized to exchange 100 kW with a ΔT of 4.5 °C.
- HP: variable capacity water-to-water heat pump (can be used as part of the auxiliary loops, or as the tested equipment). Operating limits: -10 °C on the evaporator side (with glycol), 55 °C on the condenser side (note that when bypassing the heat pump, the electric boiler can heat the auxiliary loops up to 85 °C).
- P0 and P1: Variable speed pumps for the auxiliary loops. The design maximum flowrate in the loops is 4.7 L/s (75 GPM). The actual maximum flowrate depends on operating conditions because of pressure limits (e.g. with the "HP" heat pump in service, the maximum flowrate is about 3.8 L/s (60 GPM).
- Hx02 and Hx13: heat exchangers between the auxiliary loops and the test loops. These exchangers are designed to transfer 100 kW with a ΔT of 3 °C.
- P2 and P3: Variable speed pumps for the test loops. The design maximum flowrate in the loops (depending on the configuration because of minimum and maximum pressure limits) is 4.7 L/s (75 GPM).

8.2.2. Sensors, data acquisition and control

The laboratory is equipped with high accuracy temperature sensors and flowmeters, as well as power transducers:

- Pt 100 with 1/10 DIN accuracy in the test loop and Pt100 with 1/3 DIN accuracy in the auxiliary loops. In addition, various thermopiles can be fitted to the test loops to measure temperature difference with a very high accuracy.
- Flowmeters with traceable calibration reports with an accuracy better than 1 % of reading in their full operating range. Standard range is 1 L/s to 11 L/s (15 to 180 GPM), optional smaller flowmeters for test loops have a range of 0.06 L/s to 0.6 L/s (1 to 10 GPM).
- Power transducers with an accuracy (for voltage, current and power) better than 0.5 % of full scale are available in 1-phase and 3-phase, for 120 V to 600 V and rated current between 5 A and 100 A. These transducers output voltage, current, VA, RMS power and power factor.

Data acquisition and control are performed by a modular high accuracy National Instrument CompactRIO system programmed in LabVIEW. As described above, the LabVIEW program can optionally communicate with TRNSYS for semi-virtual testing. Figure 37 shows a screenshot of the LabVIEW interface. In semi-virtual mode, T201_set, T301_set, FM201_set, and FM301_set come from the TRNSYS simulation through shared variables in LabVIEW.

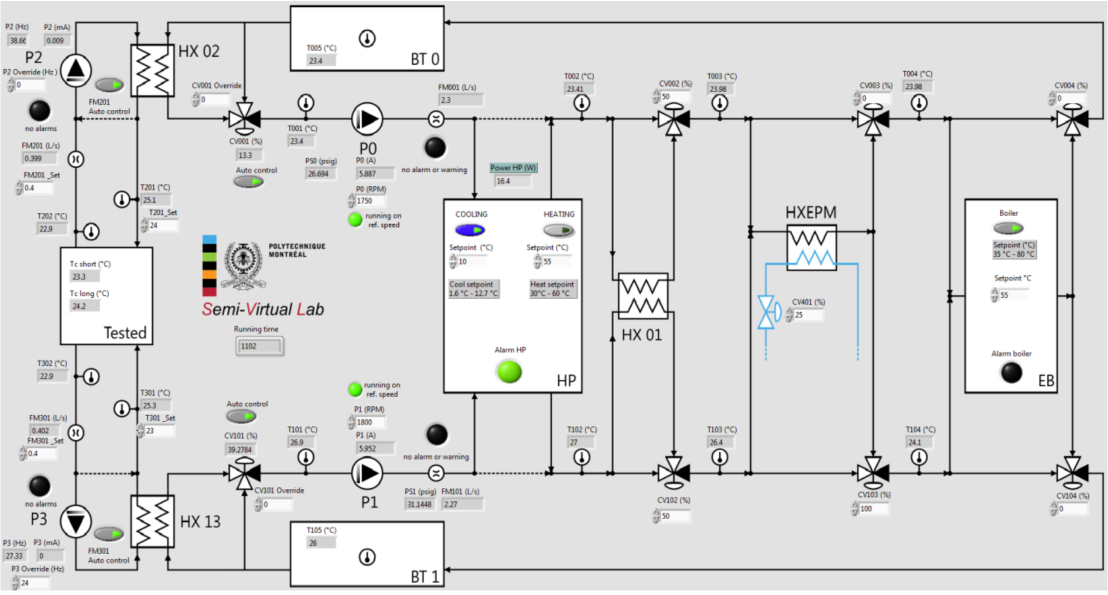
P2 (Hz) 38.66
P2 (mA) 0.009
P2 Override (Hz) 0
FM201 (L/s) 0.399
FM201 _Set 0.4
T202 (°C) 22.9
T201 (°C) 25.1
T201_Set 24
Tc short (°C) 23.3
Tc long (°C) 24.2
T302 (°C) 22.9
T301 (°C) 25.3
T301 _Set 23
FM301 (L/s) 0.402
FM301 _Set 0.4
P3 (Hz) 27.33
P3 (mA) 0
P3 Override (Hz) 24
T005 (°C) 23.4
CV001 Override 0
CV001 (%) 13.3
T001 (°C) 23.4
PS0 (psig) 26.694
P0 (A) 5.887
P0 (RPM) 1750
FM001 (L/s) 2.3
Power HP (W) 16.4
Running time 1102
CV101 (%) 39.2784
CV101 Override 0
T101 (°C) 26.9
P1 (RPM) 1800
P1 (A) 5.952
PS1 (psig) 31.1448
FM101 (L/s) 2.27
T105 (°C) 26
T002 (°C) 23.41
CV002 (%) 50
T003 (°C) 23.98
CV003 (%) 0
T004 (°C) 23.98
CV004 (%) 0
COOLING Setpoint (°C) 10
Cool setpoint 1.6 °C - 12.7 °C
HEATING Setpoint (°C) 55
Heat setpoint 30°C - 60 °C
CV401 (%) 25
Boiler Setpoint (°C) 35 °C - 80 °C
Setpoint °C 55
T102 (°C) 27
CV102 (%) 50
T103 (°C) 26.4
CV103 (%) 100
T104 (°C) 24.1
CV104 (%) 0

Figure 37. Screenshot of the Labview interface.

8.3. Examples of previous studies

8.3.1. Study 1: Development of a LabVIEW-TRNSYS bidirectional connection

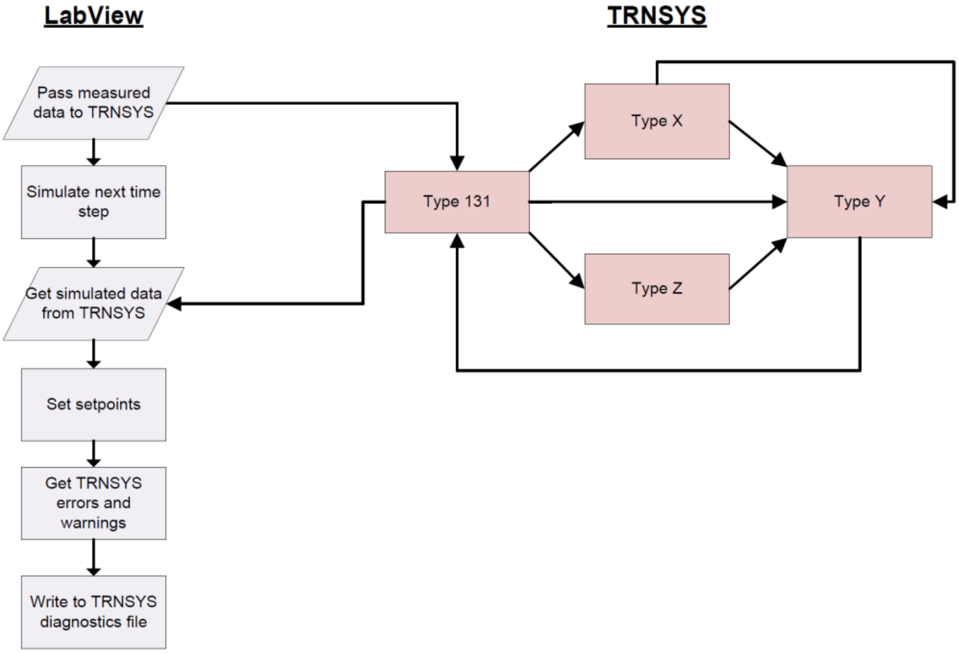

Figure 38. Principle of the LabVIEW interaction with TRNSYS.

In this project (Macdonald et al., 2014), a novel communication methodology was developed to allow rapid data exchange between the Data Acquisition software LabVIEW and the energy simulation program TRNSYS. The developed method uses data exchange through shared variables between the TRNSYS DLL and the LabVIEW executable, and does not require writing or reading data files. A procedure to properly initialize the simulation and the laboratory equipment was also developed and implemented. Changes to the TRNSYS code source are encapsulated in a newly developed component, named Type 131. The principle of the communication between the two programs is described in Figure 38.

8.3.2. Study 2: Experimental Study of a Phase-Change Material storage tank

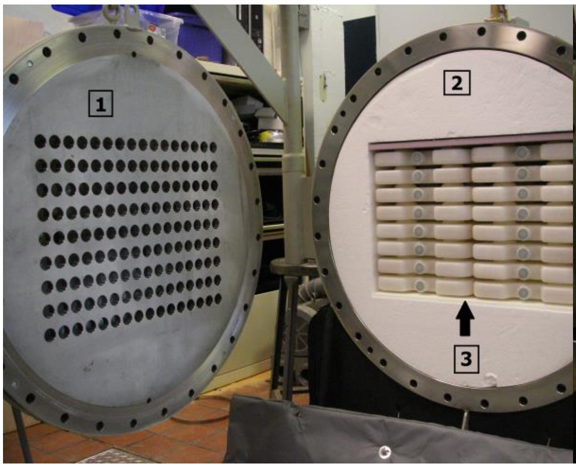

Figure 39. PCM tank viewed from the inlet, including 1) perforated plate, 2) capsule support and 3) PCM capsules.

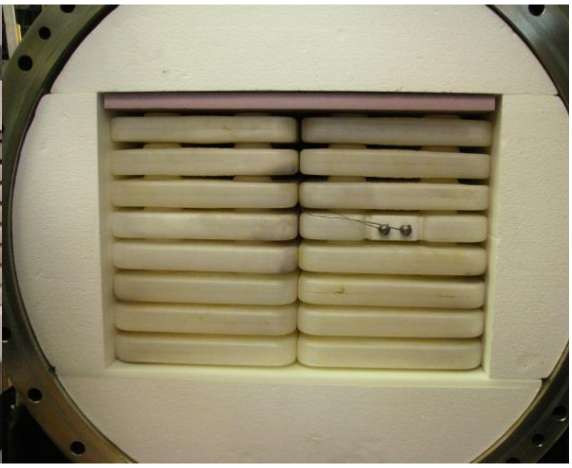

Figure 40. Position of the instrumented PCM capsule in the tank as viewed from the outlet.

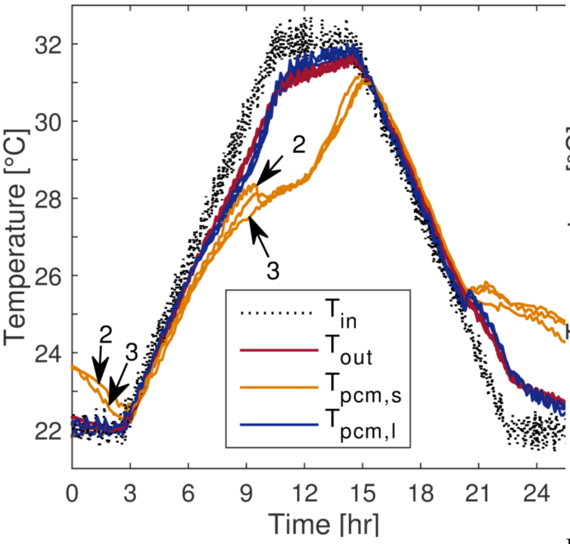

Figure 41. Example of results for a test with a fixed temperature change rate at the inlet of the tank.

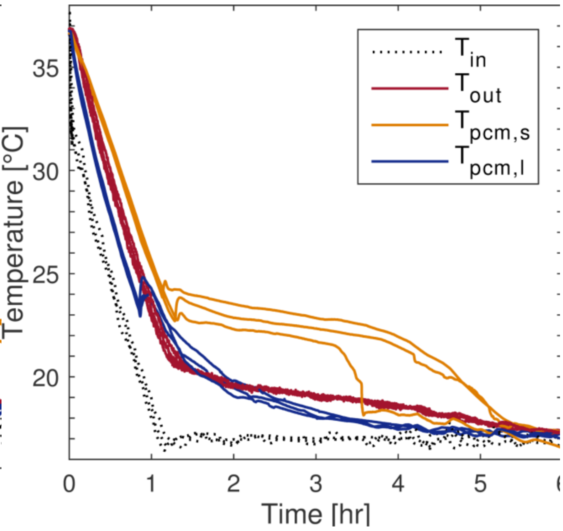

Figure 42. Example of results for a cooling step test.

This project aimed at designing a storage tank with Phase-Change Materials (PCM) and to test it in realistic operating conditions (D'Avignon and Kummert, 2013; D'Avignon and Kummert, 2016). The first objective was to integrate the newly designed PCM tank into the lab and adapt the data acquisition environment to allow its detailed monitoring. A first series of tests was performed using predefined procedures, therefore without using the communica-

tion with TRNSYS. But the dynamic capabilities of the Semi-Virtual Laboratory were used to impose changing conditions to the tank and fully validate its detailed model.
Figure 39 to Figure 42 show the PCM tanks and some examples of results (Tin and Tout are the inlet and outlet temperatures of the tank, Tpcm,l and Tpcm,s are the PCM mass temperature at 2 different locations).
In a second step, the PCM tank was tested in a semi-virtual environment. A TRNSYS simulation model was developed to represent a building with its heating system, and the PCM tank was used to reduce the building peak demand and operating costs by shifting demand from on-peak to off-peak periods.

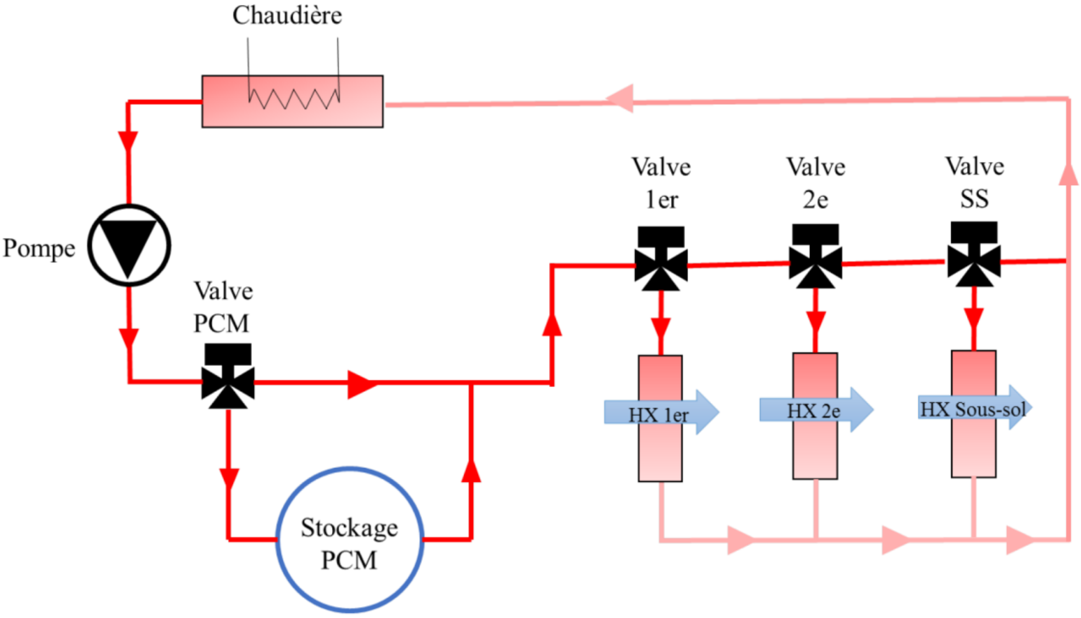

Figure 43. PCM tank in a hydronic heating loop for semi-virtual testing.

More details on the study are available in D'avignon (2015) and Lessard (2016). The Semi-Virtual environment allowed to further validate the developed model component in TRNSYS and demonstrate the usefulness of the laboratory to assess the storage tank behaviour in realistic operating conditions.

8.4. Maintenance and collaborations

The Semi-Virtual Laboratory at Polytechnique Montréal was funded through a partnership with the Canada Foundation for Innovation (CFI), and is now run by the graduate students and staff at Polytechnique Montréal. The CFI also provides a maintenance budget that can help adapting the laboratory to the different requirements of new research projects. The PCM tank is currently being replaced by water-to-water heat pumps (commercially available models and in-house developed prototypes). Projects can be performed in partnership with other research institutions, manufacturers, utilities, or government agencies interested in developing standard testing procedures.

8.5. Additional information

Research team website:
http://www.polymtl.ca

8.6. Relevant publications

K. D’Avignon and M. Kummert. 2013. ‘Comparison of system-level simulation and detailed models For storage tanks with phase change materials’, in Proceedings of Building Simulation 2013:13th Conference of International Building Performance Simulation Association, Chambéry, FRA, August 26-28, pp. 2940–2948.

K. D’Avignon and M. Kummert. 2016. ‘Experimental assessment of a phase change material storage tank’, Applied Thermal Engineering, 99, pp. 880–891. doi: 10.1016/j.applthermaleng.2016.01.083.

K. D’Avignon. 2015. ‘Modeling and experimental validation of the performance of phase change material storage tanks in buildings’. PhD thesis, Montréal, QC, CAN: Polytechnique Montréal, Dept. of Mechanical Engineering.

D. Lessard. 2016. ‘Essais du Laboratoire Semi-Virtuel d’Équipements CVAC’. MEng thesis, Montréal, QC, CAN: Polytechnique Montréal, Dept. of Mechanical Engineering.

F. Macdonald, K. D’Avignon, M. Kummert and A. Daoud. 2014. ‘A TRNSYS-LabVIEW bi-directional connection for HVAC equipment testing using hardware-in-the-loop simulation’, in Proceedings of SSB 2014: the 9th International Conference on System Simulation in Buildings, Dec 10-12. Liège, BEL, p. P65.1-P65.15.