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The ZEB Living Lab: a multi-purpose experimental facility

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Abstract

At the Research Centre on Zero Emission Buildings of NTNU, a new test facility is currently in the final stage of design process and its construction is expected to be finished later during 2014.

The aim of the new test facility, called Living Lab, is 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 the ways users interact with buildings characterized by high indoor comfort conditions and low energy demand is analyzed.

The 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. It is realized with state-of-the-art technologies for energy conservation measurements and renewable energy source exploitation. Moreover, the Living Lab has been designed with the aim of reaching the Zero Emission target, with care on the selection of materials and systems so that embodied emissions are limited to a great extent.

In this paper, the test facility is described and its architectural features and technological aspects highlighted. The focus is then placed on the detail description of the proposed measurement systems and measurement procedures.

The monitoring system is primarily designed to record the most relevant environmental quantities, to measure energy demand for heating, ventilation, lighting and appliances, as well as renewable energy harvesting by means of a roof-integrated PV system and of façade-integrated solar thermal panels. The main scope of the system is to assess the energy and environmental balance of the building as a whole and the interaction of the users with it, but further upgrade/extensions of the data acquisition system and probes are planned to improve the capability of more detailed analysis on single sub-components.

Keywords: Experimental, large-scale, measruements, test facility, zero emission

1. Introduction

The Living Lab at the Norwegian University of Science and Technology (NTNU) represents the result of a complex multidisciplinary effort that involved students, researchers and, industry partners. During a twelve-month integrated design process within the MSc in Sustainable Architecture at NTNU, students and researchers conceived and developed a prototype of an *energy positive hytte*. A *hytte* – a Norwegian word that can be roughly translated in English as *mountain cabin* – represent for many Norwegians the necessary tool for conducting a life close to pristine nature, outside modernity and is historically characterized by a high degree of austerity. The task of the design process was thus to develop a mountain cabin independent from the grid, thanks to the passive and active use of natural resources, which would not only strengthen the desired feelings of distance from modern society and symbiosis with nature, but also lower the environmental impact of the second house sector.

The original concept has been since then developed, with the name of Living Lab, in cooperation with industrial partners inside the Research Centre on Zero Emission Buildings (ZEB), in order to provide the research centre and the NTNU with a multipurpose experimental facility. This facility 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 the ways users interact with buildings characterized by high indoor comfort conditions and low energy demand is analyzed.

The Living Lab is representative of the Norwegian residential building stock for typology (detached, single family house) and surface, while it integrates state-of-the-art technologies for energy conservation and solar

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2. The Living Lab

2.1. Architecture

The test facility (Fig. 1 and 2) 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. It is realized with state-of-the-art technologies for energy conservation measurements and renewable energy source exploitation. Flexibility of the plan was particularly addressed towards the possibility of allocating many different programs within the building surface (young couple, old couple or even a student housing). The construction system was also chosen so that, if necessary, building equipment and components can be easily changed in case new technologies are to be tested.

The design of an advanced but versatile building construction system made of three independent but interrelated components: the functional cells, the transversal partitions and the roof.

The functional cells (three parallel rows) integrate technical equipment, external envelope and internal furnishing in the extremely compact section of 340 x 135 cm. Their construction has been organized in two layers: a primary, more constant and characterized by a high degree of abstraction and a secondary one, related to users' and programme's needs and thus adjustable. In the primary layer, structural frame and technical equipment have been integrated in order to ensure flexibility of the plan: vertical connections have been realized in correspondence of the pillars; horizontal ducts distributed along the beams. The secondary layer is intended to give to an otherwise aseptic box an architectural meaning with spatial and sensitive values, including a wide range of components that can be adjusted according to users' needs and desires, functional program distribution and climatic context (envelope, furnishing, and technical system).

Figure 1 - Exterior view of the Living Lab from south-east

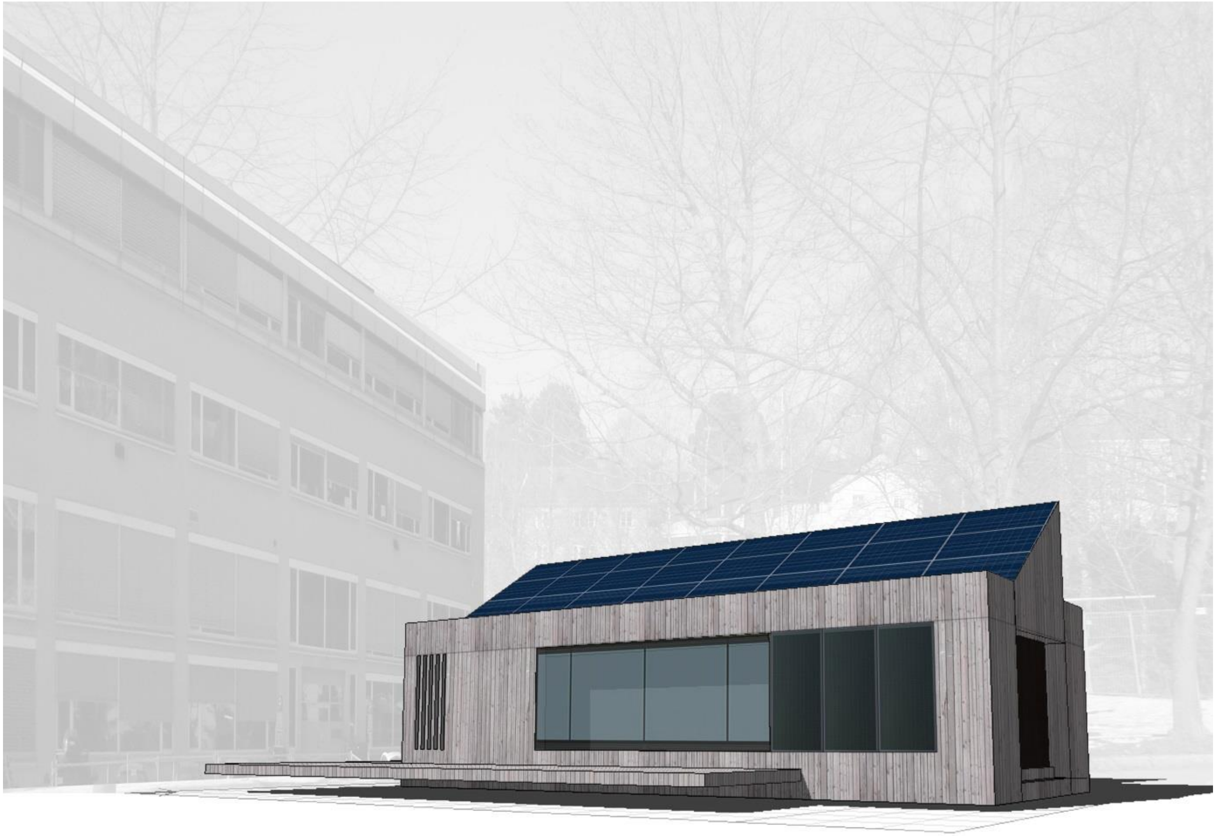

Figure 2 - View of the Living Lab and of its surrounding

Transversal partitions are meant to regulate visual, thermal and acoustic comfort among the different spaces within the program.

The roof components are characterized by a hermetic and insulating construction with a very high thermal resistance. The angle of these roof elements could be adjusted according to different climatic contexts and locations becoming a key component for landscaping. Renewable energy production coming from integrated PV was assumed as criteria for optimizing their construction and geometry.

All these three components were optimized in the Living Lab, within the climatic context of Trondheim, by running different sets of simulations. SIMIEN was used as tool for quantifying the thermal demand of the building. The lighting analysis were performed in RADIANCE, and PV-SYST and have been used to estimate the PV energy output. The preliminary calculations were performed assuming the use of an air-to-water heat pump with a (constant) COP factor of 2.8, a ventilation air-handling unit with a heat recovery efficiency of 85% (running in the heating season only, with a SFP of 1 kJ/m^3).

In Table 1 the thermo-physical properties of the building envelope components are summarized.

Table 1 - Thermo-physical properties of building envelope components

U-value wall	W/m^{2}K	0.11
U-value floor	W/m^{2}K	0.10
U-value roof	W/m^{2}K	0.10
U-value windows (south façade)	W/m^{2}K	0.65 / 0.69 (when ventilated)
U-value windows (north façade)	W/m^{2}K	0.97
U-value windows (east-west façade)	W/m^{2}K	0.80
U-value skylight	W/m^{2}K	1.0
g-value	-	0.5
Air tightness	ach	0.5
Thermal bridges (normalized)	W/m^{2}K	0.03

2.2. Building equipment and devices for solar energy exploitation

The Living Lab has been designed to have a low energy demand during its operation. Different solutions and building equipment are planned to be installed, so that several options can be tested within the same building.

Heating, ventilation and domestic hot water demands are primarily planned to be satisfied by a water-to-water heat pump, which is coupled with a ground heat-exchanger, situated in the north-side ground of the Living Lab.

The output of the heat pump is connected with a two-stage heat storage tank, where hot water for both DHW and space heating is stored. The storage tank has two auxiliary electric coils that can be activated when the storage temperature falls under the set-point. Solar thermal panels are also connected to this storage.

The balanced mechanical ventilation plan has a nominal air flow 120 m^3/h, with variable air volume supply. It integrates a heat recovery unit with an efficiency of 85% at the nominal value, and an additional electric coil capable of warming up the inlet air up to 40 °C (for ventilative heating purpose). Supply jets are located in the living room and in the bedrooms, exhausts in the bathroom and kitchen.

Two different terminal units have been designed for the heating system, so that it can be operated in different modes and efficiency of the two systems assessed: floor heating and low-temperature radiator. When the first mode is operated, the underfloor heating panels in the living room, bedrooms and bathroom are used; when the second mode is chosen, the sole radiator installed in the living room is used to heat up the main areas of the building, in combination with the floor heating in the bathroom. As mentioned above, ventilative heating is also planned as a possible solution for covering heating demand in combination with fresh air supply need.

Shut-off valves are widely installed in the plant so that each hydronic circuit can be isolated and equipment changed without affecting the whole system to a great extent.

Four building-integrated solar thermal panels are installed on the south-facing façade, at the two sides of a ventilated façade. They are directly connected to the centralized water-based heat storage.

Finally, a building-integrated PV system is also installed on the two slopes of the roof. The total installed power is 12.5 kW_P and the efficiency of the polycrystalline silicone cells are approximately 16%. Energy converted by the PV system is expected to cover the energy need of the building and to balance energy embedded in the materials and components used to realize the Living Lab.

3. The experimental facility

3.1. Aims and experiments

The primary aim of the Living Lab is to realize a building that is representative, as a typology, of the most common Norwegian dwelling – the single family house – and to demonstrate how CO_2-neutral construction can be realized in the Norwegian climate. Moreover, considering the features of this facility, research on how users interact with state-of-the-art technologies and low-energy buildings are planned to be carried out in the Living Lab. People are thus expected to live (for shorter or longer periods) in the Living Lab.

Given this premise, the development of the monitoring system in the Living Lab has been based on the following considerations:

- considering the main aim of the test facility (evaluate the total energy behavior of the building) a compromise between accuracy in the measurement of each physical quantity and quality of the sensors should be found – i.e. to reach a measurement accuracy similar to that of a laboratory test facility might be out of the scope of the Living Lab.
- 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 real-world application – i.e. on-purpose-made or very expensive sensors should be avoided as much as possible;
- 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-world application.
- the measurement system should be very flexible and allow a following upgrade to be easily realized, should some specific technologies (such as windows, or other building envelope technologies, or different HVAC equipment) be the object of dedicated investigation – where accuracy similar to that of a laboratory facility can be achieved;
- 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).

Figure 3 - Plan of the Living Lab

3.2. The monitoring system

In Figure 3 the plan of the Living Lab is shown. Sensors for the assessment of the different energy demands are all located in the technical room where HVAC equipment and electric switchboard are installed (to the south of the west bedroom). Sensors for indoor and outdoor environmental physical quantities are distributed in the entire test facility.

3.2.1. Outdoor environmental physical quantities

Outdoor air temperature and humidity are measure by means of *S+S Regeltechnik AFTF-U PT100* multisensor. The temperature probe is a Pt100 with accuracy of ± 0.1 K, while humidity ratio is recorded with an accuracy of ± 3%. Two *AFTF-U PT100* sensors are planned to be used: one is installed on the south-façade of the building and protected by the influence of direct solar radiation by means of a specific sunshade protector, while the other is installed on the north-facing façade.

Sensors *ALD-U* and *ACO2*, both by *S+S Regeltechnik,* are used to measure outdoor air pressure (accuracy ± 2%) and outdoor air CO_2 concentration (accuracy ± (70 ppm + 5%)), respectively. The two sensors are installed on the north-facing façade.

Figure 5 – Longitudinal section of the Living Lab

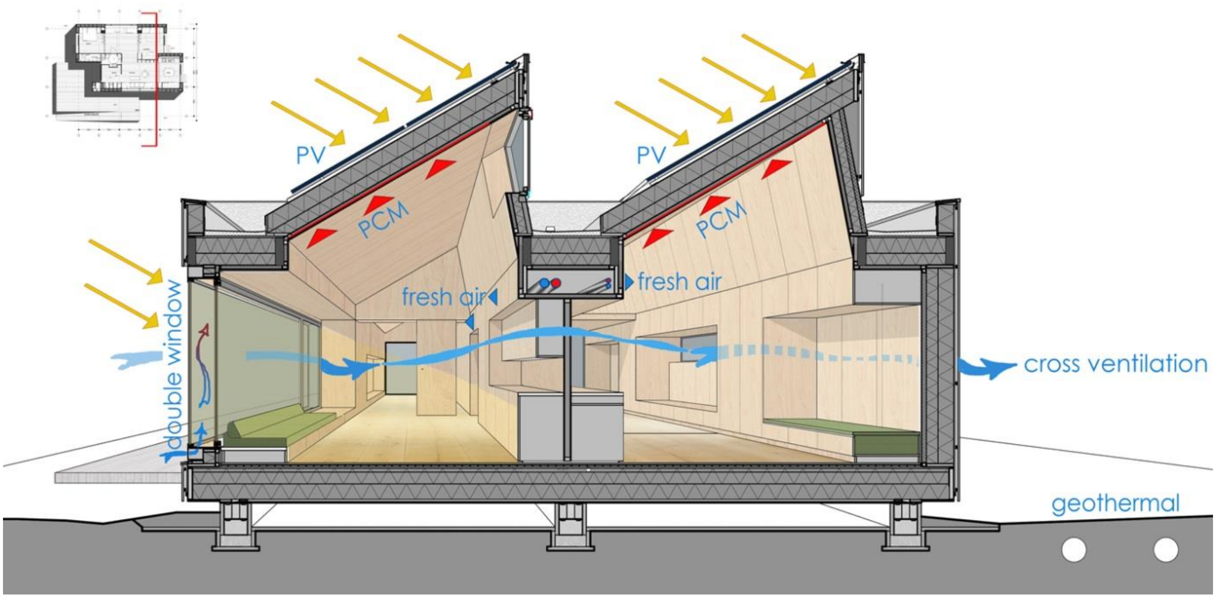

Figure 4 - Cross section of the Living Lab

Solar irradiance on the horizontal (on the roof top) and vertical (south-exposed façade) plane is measured by means of two pyranometers by *Hukseflux* (model *LP02*). Accuracy of these sensors are ± 3%. Diffuse outdoor illuminance level, measured on the north-facing façade (on the vertical plane), is recorded by *S+S Regeltechnik AHKF-U*, with an accuracy of ± 5%.

Finally, wind speed and direction are measured by means of the weather station *HD52.3D* by *Delta Ohm*. Both the physical quantities are recorded with an accuracy of ± 3%. The exact location of the weather station (on the roof top) will be decided during the installation of the monitoring system with a particular care to avoid shades on the building integrated PV.

3.2.2. Indoor environmental physical quantities

Indoor air temperatures are measured in every room of the Living Lab, at the height of 1.6 m from the floor. In two locations (in the living room and in the studio room, i.e. the room between the two bedrooms) temperature stratification is also measured (in 5 levels: 0.1, 0.8, 1.6, 2.4, 3.2 m from the floor). Temperature (Pt100 probe) is measured by means of the multisensory *RFTF-U PT100* by *S+S Regeltechnik*, which also records humidity ratio (accuracy is ± 0.1 K and ± 3%, for temperature and humidity ratio, respectively).

CO_2 concentration is also measured in every room. For this purpose, the *S+S Regeltechnik RCO2* sensor is used. As for the CO_2 sensor located outside, the accuracy is ± (70 ppm + 5%).

Diffuse illuminance level is also recorded in all the living areas of the building by means of *S+S Regeltechnik RHKF-U*, whose accuracy is ± 10%. Furthermore, a motion sensor is also installed in every room. The selected device is *RBWF-W* by *S+S Regeltechnik,* which monitors people's presence by means of a change-over contact.

The position (open/closed) of all the windows will be continuously recorded by means of magnetic alarm switches, which give a potential free changeover contact signal when the window is open.

3.2.3. Building envelope (roof) and integrated building components (PCM panels and BIPV)

Although the measurement system of the Living Lab is not specifically developed for investigating the behavior of the building envelope and of each building component, some additional sensors are planned in the roof in order to verify the performance of this component, which is characterized by an innovative vapor barrier, the use of PCM panels in the ceiling and by building-integrated PV panels (Figure 5).

For this purpose, several T/J thermocouples are installed at the indoor surface of the ceiling, and at different locations in the PV layer (on the external surface of the PV, in the cavity between the PV panels and the outer skin of the roof). Furthermore, temperature and moisture content is also measured in different points within the roof structure, at three different levels. The multisensor *EE0606 by E+E Elektronik Ges.m.b.H* is used, with anaccuracy of ± 0.3 K and ± 3%, for temperature and relative humidity, respectively.

3.2.4. Energy demand for HVAC and DHW

Thermal energy delivered by means of a hydronic circuits is measured by means of *Kamstrup Multicanal 602* in combination with *Kamstrup Ultraflow 54*. The first device is a calculator which, based on the information regarding the water volume flow and the supply and return water temperature measured by the second device, computes the energy delivered by the hydronic circuit. Declared accuracy for the energy measurement device is 1%.

Together with energy records, temperatures and water volume flows will be also montitored. Connection between the *Kamstrup Multicanal 602* and the data acquisition system will be done by means of RS485 ports.

A total of six *Kamstrup Multicanal 602 and Ultraflow 54* are planned to be installed in order to measure the following delivered energies: 1) heat pump heating output; 2) energy delivered by the floor heating in the living area; 3) energy delivered by the floor heating in the bathroom; 4) energy delivered by the radiator installed in the living room; 5) energy for domestic hot water; 6) energy for the water-based coil of the ventilation plant. One additional *Kamstrup Multicanal 602* and *Ultraflow 54* will probably be installed to measure the heat extraction from the ground thanks to the ground-coupled heat exchanger. The final decision on the measurement system for the assessment of this component has not yet been taken.

As far as the mechanical ventilation and heat recovery system is concerned, the enthalpy flux will be calculated during the acquisition, based on the measurement of the air temperature, of the humidity ratio and of the air speed in the ventilation ducts. *KFTF-U Pt100* (temperature and humidity ratio) and *KLGF-1* (airflow speed) sensors by *S+S Regeltechnik* are planned to be installed. Accuracy of the devices is ± 0.1 K (temperature) and ± 3 % (humidity ratio) for the *KFTF-U Pt100,* and 10 % for the *KLGF-1.* Four *KFTF-U Pt100* will be installed (supply and extract ducts in the inside, inlet and exhaust ducts in the outside, before the heat recovery system), while two *KLGF-1* are planned to be mounted in the inside ducts (supply and extract).

Finally, temperature of the water in the heat storage tank will also be recorded by means of T/J thermocouples located at different levels in the tank.

3.2.5. Energy supply from PV and solar thermal panels

The energy output from the two technologies for solar energy exploitation (PV and solar thermal panels) will be continuously measured as well. A coupled *Kamstrup Multicanal 602* and *Ultraflow 54* is installed in the hydronic circuit of the solar thermal panels so that solar energy converted by this technology can be computed. As for the other hydronic circuit, temperatures and water flow are also recorded.

Electric energy output from the photovoltaic roof will be monitored by means of the *SMA* monitoring system, which is supplied together with the PV plant. Presently, the challenge related to this measurement concerns the communication between the SMA monitoring system and the data acquisition system that collects all the other measurement in the Living Lab. Communication between the two devices is planned to be carried out through the RS485 port, but the full compatibility is still under investigation. The accuracy of the SMA monitoring system is also under evaluation, but given the purpose of the test facility and the decision to use to the largest extent real-world measurement systems, it is foreseen that no additional sensors need to be installed as far as the PV roof is concerned.

3.2.6. Electrical energy demand

Electrical energy demand is planned to be measured in almost every power line within the Living Lab. The reason for this requirement lies in the need of recording the different use of electrical energy from the users, as well as the desire to monitor, with a sufficient degree of precision, energy demand of the different auxiliary systems – which is often neglected, but has a relevant role in very low or zero energy buildings.

So far, 22 power lines have been planned, including a power line dedicated to the measurement system. Every room will have a line for power transmission and one for artificial light. Heat pump electric input and tank coils power input will be measured. Power to all the auxiliaries (e.g. fans, pumps) of the HVAC and solar thermal panel will be measured by grouping the auxiliary devices according to the system they belong to (e.g. all the auxiliaries in the ventilation plant and all the auxiliaries in the solar thermal panels). Powering of windows' motors will also be separately accounted.

Power metering is carried out by means of commercially available power meters to be installed on the main electrical switchboard. The *C18WS* by *FRER* has been selected for this purpose. It allows a resolution of 1 W h to be achieved and communication with the central data acquisition system is realized by means of pulses (1 pulse every 1 W h). Accuracy of the power meter is ± 1%.

3.3. Data acquisition and analysis

The data acquisition system will be based on the National Instrument compactRIO platform. This system is based on a modular structure, where controllers, chassis, devices/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 of the measurement layout can be relatively easily implemented.

The chosen starting configuration for the Living Lab includes one cRIO-9068 8-Slot Integrated Controller and Chassis System, two expansion chassis with 8 slots each and a series of different modules for signal acquisition, ranging from RS422/RS485 serial modules to 100 Ohm RTD 24-bit analog input modules, from different voltage analog input modules to TC analog input modules.

The data acquisition system will be controlled by means of the National Instrument LabVIEW programming code. This is a graphical programming environment specifically developed for sophisticated measurement and tests. Moreover, it is important to underline that this programming environment also allows control systems actions, which will be used in the Living Lab for controlling windows' opening in combination with the hybrid ventilation mode.

3.4. Stand-alone and integrated control systems

Due to the design of the Living Lab, the control over the heating and mechanical ventilation is designed to be performed by means of conventional, stand-alone devices supplied together with the HVAC equipment.

However, a dedicated investigation on the potentials of hybrid ventilation is instead planned since the beginning of the Living Lab operation. In fact, due to the increasing impact of cooling energy demand in buildings even in the Nordic climate, hybrid (combined mechanical and natural) ventilation will be tested and assessed. For this purpose, the acquired signals related to the indoor air temperature, CO_2 concentration, and solar irradiance will be used to control the opening of the windows (the ventilated window in the south façade, the skylight windows and the window in the north façade).

In order to do so, the data acquisition system will also perform as output source for controlling the windows motors. Therefore, sourcing digital output modules will also be installed together with the input modules and controlled by means of the LabVIEW interface.

4. Conclusion

The Living Lab at the Norwegian University of Science and Technology (NTNU) is a test facility, currently under construction, that is representative of a solar-powered single family house in the Nordic climate. Though it was designed with the aim of assessing the whole-building performance of a Zero Emission Building, its configuration (a flexible assembly of building envelope components, technologies for solar energy exploitation and HVAC systems) allows tests on different building elements and equipment to be carried out.

In this paper, the test facility is presented and the measurement aims are illustrated. A focus is then placed on the proposed measurement layout, which is currently in the last stage of development. The monitoring system has been designed in order to be flexible, expandable and easily reconfigurable. Furthermore, care has been paid to select sensors that could be also used in a real-world application without giving away a high degree of precision that allows advanced energy and thermo-physical analysis to be carried out.