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The ZEB Living Laboratory at the Norwegian University of Science and Technology: a zero emission house for engineering and social science experiments

Francesco Goia[1,*], Luca Finocchiaro[2] and Arild Gustavsen[1,2]

[1]The Research Centre on Zero Emission Buildings, Faculty of Architecture and Fine Arts, Norwegian University of Science and Technology, Trondheim - Norway
[2]Department of Architectural Design, History and Technology, Faculty of Architecture and Fine Arts, Norwegian University of Science and Technology, Trondheim - Norway
[*]*Corresponding email: francesco.goia@ntnu.no*

SUMMARY
At the Research Centre on Zero Emission Buildings of NTNU, a new test facility (Living Laboratory) is currently in the final stage of construction and will start its operation in summer 2015. The Living Laboratory 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 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. 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 and control system.

KEYWORDS
Experimental, large-scale, measurements, test facility, zero energy/emission buildings.

INTRODUCTION
The Living Lab at the Norwegian University of Science and Technology (NTNU) is the result of a complex multidisciplinary effort that involved a wide range of actors, including students, researchers and industry partners. It started as an integrated design process within the MSc in Sustainable Architecture at NTNU, where students and researchers developed a prototype of an *energy positive hytte*. A *hytte* – a Norwegian word that can be roughly translated into the English *mountain cabin* – represents for many Norwegians a necessary tool to get close to pristine nature, outside modernity, a weekend house 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 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 since then been developed, with the name of Living Laboratory, in cooperation with industrial partners inside the Research Centre on Zero Emission Buildings (ZEB), to realize 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 studied.

Moving from the original *energy positive hytte* configuration, the Living Laboratory has later been designed to be representative of the Norwegian residential building stock for typology (detached, single family house). However, it integrates state-of-the-art technologies for energy conservation and solar energy exploitation, representing a step forward in the development of a low-carbon built environment. The building has been design with the aims of lowering to the minimum extent energy demand for operation, harvesting to a great extent solar energy (both by means of passive and active technologies), and reaching the Zero Emission target – therefore, particular care was paid in order to select materials and systems that minimizes embodied emissions.

The primary aim of the Living Laboratory is thus 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 Laboratory.

In this paper, the test facility is described and its architectural features and technological aspects highlighted. The focus is then placed on the detailed description of the proposed measurement and control system. Specific reference to the manufactures and product names of building components, sensors, transducers and other equipment have been on-purpose avoided in the paper as much as possible to prevent from any possible perception of commercialism.

THE LIVING LABORATORY AS A SINGLE FAMILY HOUSE
Architecture and construction

The Living Laboratory (Figure 1) 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/old couples, families or housing for students).

The plan of the Living Lab (Figure 2) 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 south west 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 have been 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/working 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/m^2K, respectively).

Figure 1: The Living Laboratory during the last phase of the construction: *left)* view from south-west; *right)* view from north-west.

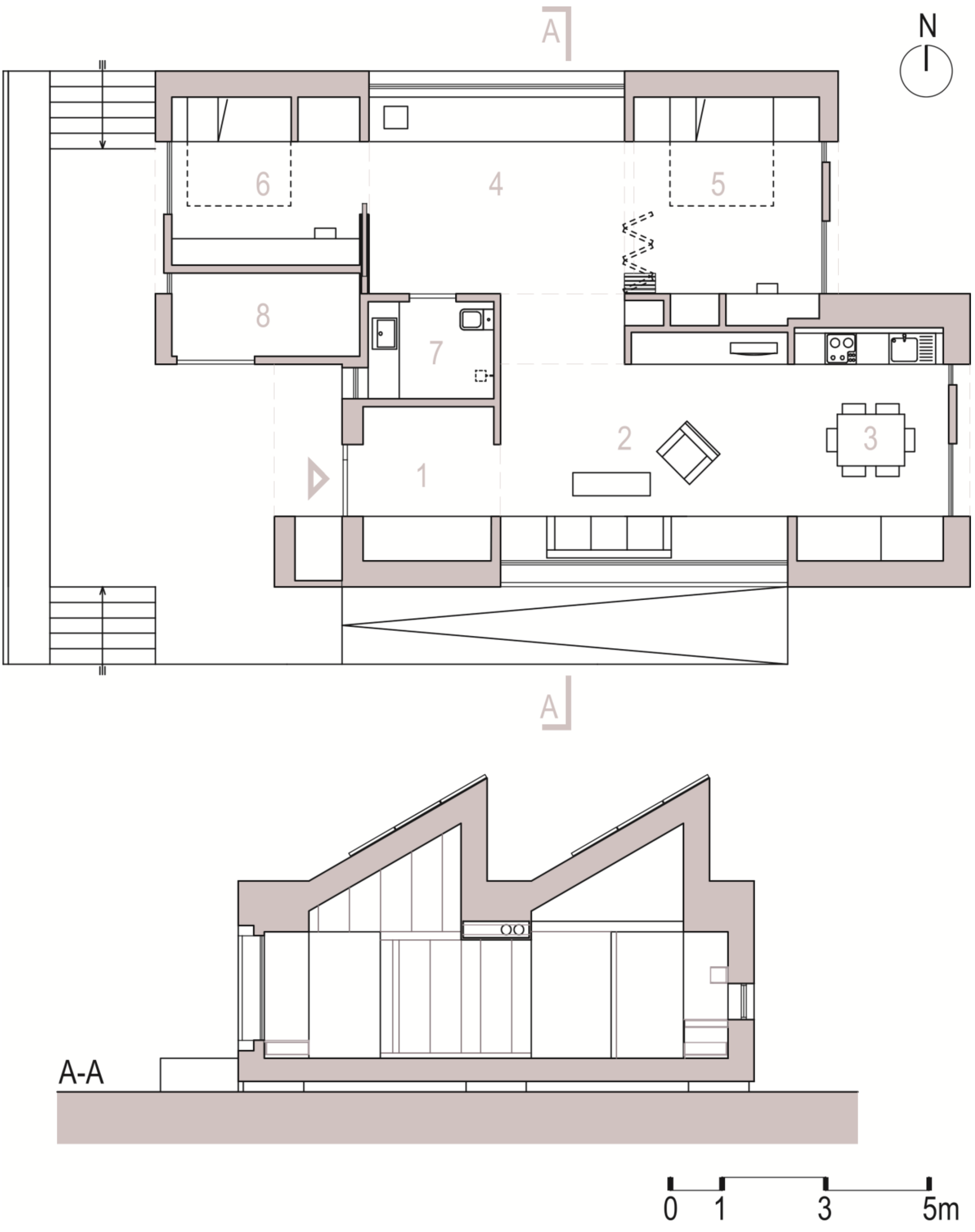

Figure 2: Plan and vertical section of the Living Laboratory (1: entrance; 2: living room; 3: kitchen; 4: studio room; 5,6: bedroom; 7: bathroom; 8: technical room)

Ninety squared meters of PCM-based boards have been installed at the indoor interface of the roof slopes (just behind the finishing, wooden cladding) to minimize the risk of overheating due to the light-weight construction feature of the building.

All the windows are characterized by low u-value (0.65 to 0.69 W/m^2K, depending on the ventilation feature, for the south-facing window; 0.97 for the north window; 0,80 W/m^2K for the windows of the kitchen and bedrooms; 1.00 W/m^2K for the roof windows). As mentioned, the double skin window facing south and the north-facing, single skin window are equipped with motor that can open them.

Two couples of roof windows are also installed above the kitchen and above the mezzanine (above one of the bedrooms); these are also equipped with electric motors for automated/manual operation.

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. The energy flow within the building plant, including on-site renewable energy supply, is schematically illustrated in Figure 3.

Technologies and components for heating, ventilation and air conditioning

Thermal energy necessary to cover heating, ventilation and domestic hot water demands is primarily planned to be obtained by a ground source heat pump (GSHP in Figure 3), 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 ground source heat pump has a fix speed scroll compressor and R134a heat transfer fluid. 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, which is described in a further paragraph.

The plant-side of the heat pump is connected to an integrated tank (IWT in Figure 3) that combines a buffer tank (BT in Figure 3) for the heating circuit (160 l) and a domestic hot water tank of 240 l (named DHTW in Figure 3). The lower, buffer tank, is equipped 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. Thermal output from the heat pump flows directly into the buffer tank (tank in the flow). After flowing in the coil of the lower tank, the domestic hot water is stored in the upper tank. This latter tank is 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.

The balanced mechanical ventilation plant has a nominal air flow 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 with the main heating circuit. A flow control valve is used to enable the heat carrier fluid to flow in the water coil. 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. The unit is connected to the (upper) building level control system by means of Modbus communication, which can therefore manage the unit. It is important to highlight that an hybrid ventilation system can be also realized, by coupling mechanical ventilation with natural ventilation. This latter ventilation strategy is achieved by means of a suitable control of automated windows, as described further in this chapter.

Two different terminal units have been installed for the heating system, so that it two different modes and efficiencies can be tested: floor heating and one high-temperature (55 °C) radiator. When the first mode is operated, the underfloor heating panels in the entrance, living room, kitchen, studio 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 previously mentioned, ventilative heating can be also exploited to cover heating demand in combination with fresh air supply need. In the latter case, underfloor heating in bathroom is expected to operate in combination with the overheated fresh air supply.

Technologies for artificial lighting

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.

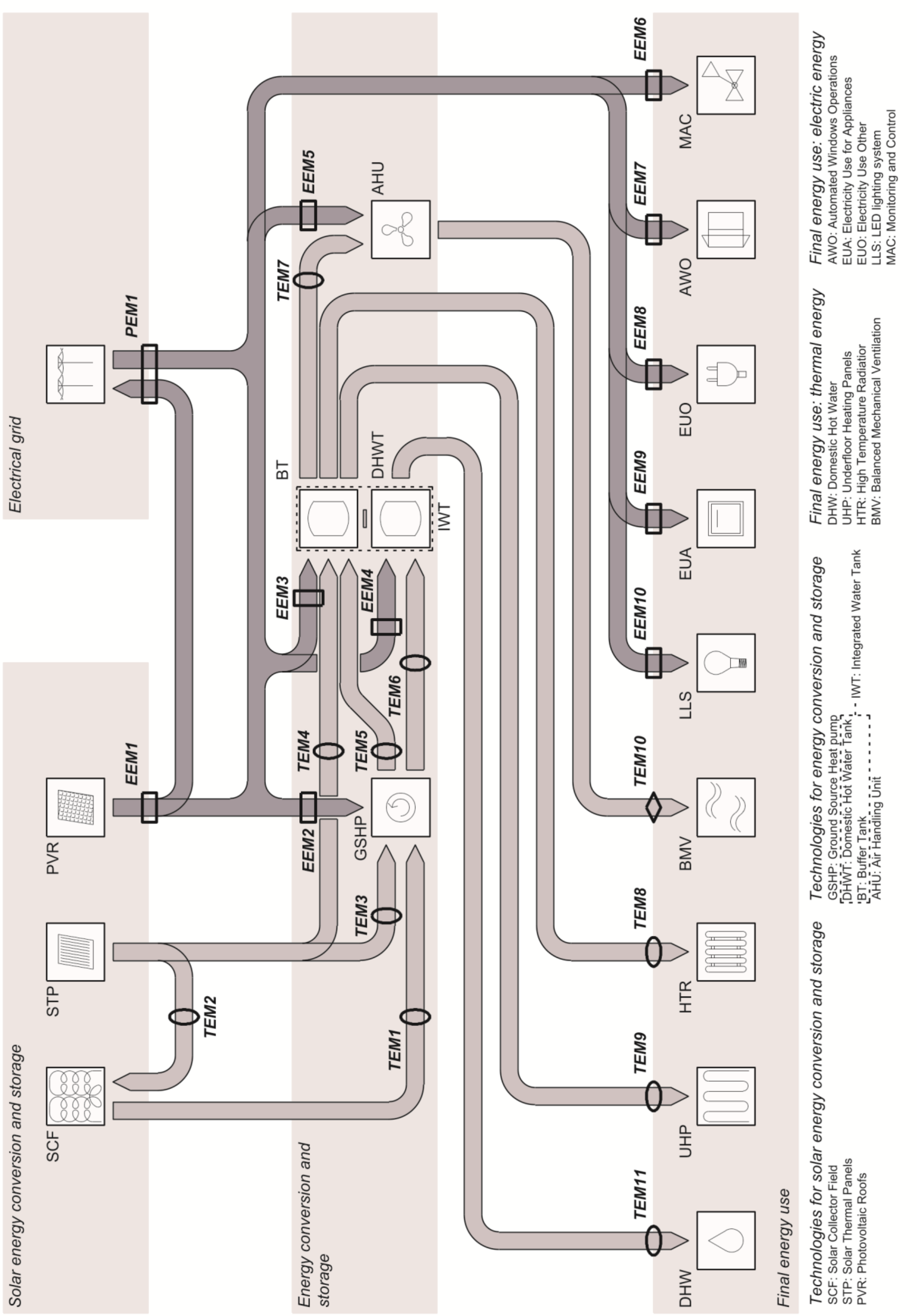

Figure 3: Thermal and electrical energy/power flow within the Living Laboratory; technologies and devices for energy conversion and storage; associated monitoring system.

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.

The building is equipped with both physical (pulse switches) and virtual (on touch screen) interfaces to turn on/off and dim the luminaires. 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 (each panel has a gross area of approx. 2.1 m^2 and a net active area of approx. 1.8 m^2) and have optical efficiency of 0.82.

A total of 48 PV modules (3 strings of 20 polycrystalline silicone cells with bypass diodes; dimensions: 1,67 x 0,99) are installed on the two roof slopes of the building, 24 modules for each slope. The PV module has a nominal power (values at STC: AM 1.5, irradiance 1000 W/m^2, cell temperature 25 °C) of 260 W (V_{mpp}: 30.7 V; I_{mpp}: 8.5 A) and the efficiency is just lower than 16%. It is worth mentioning that, at low irradiance of 200 W/m^2 (with AM 1.5 and cell temperature 25°C), at least 96% of the STC module efficiency should be achieved, according to technical documentation. 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). The European weighted efficiency of each inverter is 96.5%. The layout of the system (2 inverters, one each roof) was designed in order to optimize energy conversion, given the fact that shading over the two roof slopes is different (the northern slope being partially shaded by the southern slope).

Other building technologies

A group of windows in the Living Laboratory are equipped with motors to allow automated opening to be achieved. The aim of this configuration is to enable the natural ventilation potentials in the building. In detail, the windows that can be automatically operated are: the double skin window located in the living room and facing south; the window in the studio room facing north; two roof windows installed on vertical section of the roof above kitchen (north-facing wall); two roof windows installed on the vertical section of the roof above one bedroom (north-facing wall). The two windows in the living room and studio room are equipped with 24 V DC motors and are directly managed by the building level control system through power trimmer relays. The roof windows have 230 V AC motors that are radio controlled through dedicated devices. These devices are connected to the (upper) building level control system.

A shading system is also installed in the cavity of the double skin window of the living room. It can be operated by means of 230 V AC motors controlled by the central building management system. There is not a physical interface (switch) to rise/lower the venetian blinds, but this will be done through a virtual user interface (as explained in the following chapter).

THE LIVING LABORATORY AS AN EXPERIMENTAL FACILITY
Aim and requisites of the monitoring system

The monitoring system in the Living Laboratory has been developed starting from consideration on the experimental data that will be collected to fully characterize the energy and environmental performance of the building. In short, the following tasks are given to the Data Acquisition (DAQ) system:

- to monitor the most relevant environmental quantities, both indoor (air temperature, humidity ratio and pressure; CO_2 concentration; diffuse illuminance) and outdoor (air temperature, humidity ratio, and pressure; wind velocity; global solar irradiance on different planes and illuminance);
- to record users patterns and occupants' habits (rooms occupancy, windows/shading systems opening/displacement; use and control of appliances and lighting system);
- to measure energy use for heating, ventilation, domestic hot water, artificial lighting, appliances and other uses;

- to quantify solar energy exploitation (by PV roofs and façade-integrated solar thermal panels) and energy from the grid; and
- to assess efficiency in conversion and storage of energy for different uses.

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

- given the main scope of the test facility, 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 might be 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 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, occupied housing;
- 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 a 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).

Sensors and transducers

Outdoor environment physical quantities

The building is equipped with a weather station that integrates sensors for measurements of outdoor air temperature (Pt 100; range: -40…+60 °C; accuracy: ±0.3 °C), relative humidity (thin film capacitive sensor; range: 0…100%; accuracy: ±3%), barometric pressure (piezoresistive sensor, 600…1100 hPa; accuracy: 50 Pa), wind velocity (ultrasonic sensor, two axes; range speed: 0…60 m/s; range direction: 0…360 deg; accuracy speed: ±3%; accuracy direction: ±2 deg), global solar irradiance on the horizontal plane (thermopile; range: 0…2000 W/m^2; accuracy: II class pyranometer). Communication between weather station and controller is assured via Modbus protocol. 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 In the horizontal plane (thermopile, 0…150 klux; 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 (range: 0…2000 W/m^2; accuracy: 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; range: -50…+90 °C; accuracy: ±0.1 °C). Both sensors are suitable protected from the influence of direct solar irradiation thanks to a specific sunshade protector.

Indoor environment physical quantities and building occupancy

Indoor air temperatures 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 (i.e. the room between the two bedrooms) temperature stratification is also measured at 5 levels (0.1, 0.8, 1.6, 2.4, 3.2 m from the floor). Temperature is measured by means of a wall mounted sensor with PT100 probe (range: -30…70 °C; accuracy: ±0.1 °C).

Relative humidity is recorded too, thanks to a wall mounted capacitive probe (range: 0…100%; 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; range: 0…50 °C; accuracy: ±0.8 °C) which is used as temperature signal for the controller. This layout was chosen so that sensors for monitoring are decoupled from sensors for control of the heating/ventilation system.

Air temperature and relative humidity is 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 (range: 0…50 °C; accuracy: ±0.8 °C) and a capacitance probe for relative humidity measurement (range: 0…100%; accuracy: ±3%).

CO_2 concentration values are recorded by means of a non-dispersive infrared sensor (range: 0…2000 ppm; accuracy: ±70 ppm + 5% MV), one sensor in each room.

Diffuse illuminance level is recorded thanks to a combined ceiling mounted sensor. It contains a probe for light intensity (digital sensor for illuminance; range: multi-range, switchable, in use 0…1000 lux; accuracy: ±5%) and a sensing element for motion detection (infrared sensor). This solution allows people presence to be detected and recorded in order to obtain a detailed occupancy schedule for each of the room. For the time being, signal from people occupancy will not be used to control the lighting system, but this possibility can be later exploited.

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 – energy demand for lighting at luminaire level is calculated considering the control signals sent to each LED luminaire from the controller.

Energy use for heating, ventilation, and domestic hot water

When talking about energy for heating, ventilation and domestic hot water it is important to differentiate between energy demand (thermal energy delivered at the indoor environment) and energy use (the energy necessary to cover, through a series of energy conversions by means of the technical equipment of the building, the thermal energy demand).

Thermal energy demand for heating purpose is measured for two independent terminal configurations (high temperature radiator, TEM8 in Figure 3, and low temperature underfloor heating panel, TEM9 in Figure 3). 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% - when used in combination with pure water as heat transfer fluid. Monitoring of energy demand when underfloor heating panels are in use allows a more detailed picture to be achieved, since energy demand can be split in three different zones: living areas, i.e. entrance, living room, kitchen and studio; bedrooms; and bathroom. It is worth underlining that also in the heating installation sensors for monitoring are decoupled from sensors for controls.

Energy demand for domestic hot water (TEM11 in Figure 3) and waterborne energy demand for ventilation (when the water coil is activated, TEM7 Figure 3) are also monitored by means of similar configuration (i.e. energy meter calculator connected to PT500 temperature probes and ultrasonic flow meter). All the energy meter calculators are connected to the DAQ by means of RS485 with Modbus communication protocol.

Airborne thermal energy demand for ventilation (TEM10 Figure 3) 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 (range: -40…+150 °C; accuracy: ±0.3 °C) and a capacitive probe (range: 0…100%; 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. Both sensible and latent thermal energy demand can be calculated starting from the measured physical quantities – however, it is important to remember that the installed system only allows control of the sensible load.

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 these energy meters have a resolution of 1 Wh and an accuracy of 2%. The description of the calculation procedure for obtaining the exact subdivision for heating, ventilation and domestic hot water is rather complicated and cannot be here described due to the sake of brevity – complexity of the energy supply and conversion scheme can be seen in Figure 3. However, through data post-processing it is possible to precisely differentiate the energy need for each of the above mentioned functions

Energy use for lighting, appliances and other uses

Electrical energy use for lighting, appliances and other uses is detailed recorded in the building through several electrical energy meters as described in the previous paragraph.

A detailed list of power lines cannot be herewith given for the sake of brevity, but, in summary, 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 3), 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).

However, it is important to highlight that the monitoring system, based on a total of 25 power lines independently monitored (single-phase energy meter with 1 Wh resolution and 2% accuracy), 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. Of course, 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 (i.e. auxiliaries for hydronic circuits; auxiliary and control of Air Handling Unit; circulation pump for surface collector field; circulation pump for solar thermal system). 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.

Energy supply from renewable sources, storage (PV, solar thermal panels, surface collector field) and grid energy supply

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 inverter by means of RS485 communication with Modbus protocol. 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 (range: 0.5…10 A; accuracy: ±0.5%), voltage (range 10…277 V; 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 3.

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; range: 1…60 l/h; accuracy: ±5%) and temperature (of flow and return), the latter one by means of PT100 probes (range: -50…+180 °C; 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 3) 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 3) 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 (range: 2…120 l/h; accuracy: ±5%) and temperatures with PT100 probes (range: -50…+180 °C; accuracy: ± 0.1 °C).

Other monitored physical quantities

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%.

Among others, it is worth mentioning: temperature measurements on the rear side of the PV modules and in the air cavity between the PV modules and the roof structure; temperature measurements in the integrated water tank (IWT); temperature (and relative humidity) measurements in the exhaust and fresh air intake ducts from/to the air handling unit; temperature and relative humidity measurements in the technical room and in the switchboard cabinets.

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 features 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.

CONCLUSION

The Living Laboratory at the Norwegian University of Science and Technology (NTNU) is a test facility that is representative of a solar-powered single family house for the Nordic climate. It integrates state-of-the-art technologies for building envelope, building equipment and solar energy exploitation. Though it was designed with the aim of assessing the whole-building performance of a single family house and the way the users interact with advanced, low-energy buildings, its configuration (a flexible assembly of building envelope components, technologies for solar energy exploitation, HVAC systems, control interfaces) allows different tests to be carried out, ranging from building elements to equipment, from building occupancy to control strategies.

In the paper, the test facility was briefly detailed from an architectural and technological perspective. The measurement aims and requisite were outlined, leading to the definition of the data acquisition system (sensors and transducers, signal acquisition/sourcing hardware, control logics and interfaces). 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 up a suitable degree of precision that allows advanced energy and thermo-physical analysis to be carried out.

In total, more than 200 signals are continuously acquired to fully monitor energy and environmental performance of the building. Simultaneously, more than 70 signals are sent out from the building level controller (integrated with the data acquisition system) to manage the wide range of building features that can be controlled in the facility.

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