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A zero energy concept building for the Mediterranean climate

Francesco Causone[a]*, Salvatore Carlucci[b], Lorenzo Pagliano[a], Marco Pietrobon[a]

[a]Politecnico di Milano, Energy Department, via Lambruschini 4 – 20156 Milano, Italy
[b]NTNU Norwegian University of Science and Technology, Department of Civil and Transport Engineering, Høgskoleringen 7A, NO-7491 Trondheim, Norway

Abstract

The Mediterranean climate distinguishes for a mild heating season and a hot (and usually dry) cooling season. All along the year solar radiation is plentiful and the daily range of temperature during the summer is large, due to dry and clear conditions. This environment allowed to design and build a zero energy concept building (a detached single family house) on the basis of passive heating and cooling technologies, supported, when required, by short time active conditioning. The design process was optimized by extensive energy simulations, resulting in an optimal energy balance and favorable thermal comfort conditions along the year. The building is instrumented with an accurate building automation control system, and a number of sensors for a detailed energy and environmental monitoring. The monitoring equipment and framework, have been devised to support further detailed studies to improve the design concept and to provide accurate and comprehensive data to the scientific community.

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Keywords: zero energy building, Mediterranean climate, passive building, energy simulation, energy monitoring, energy balance

1. Introduction

The Mediterranean climate (*Csa/Csb* - under the Köppen climate classification [1-3]) is a particular variety of subtropical climate. The lands around the Mediterranean Sea form the largest area where this climate type is found [4]. The majority of the regions with Mediterranean climates have relatively mild winters and very warm summers. Because most regions with a Mediterranean climate are near large bodies of water, temperatures are generally moderate with a comparatively small range of temperatures between the winter low and summer high (although the daily range of temperature during the summer is large due to dry and clear conditions, except along the immediate

* Corresponding author. Tel.: +39-02-2399-8621; fax: +39-02-2399-3913.
E-mail address: Francesco.causone@polimi.it

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coasts) [4]. Under the Köppen-Geiger system, "*C*" zones have an average temperature above 10 °C in their warmest months, and an average in the coldest between 18 to −3 °C. Areas with this climate receive almost all of their precipitation during their winter season, and may go anywhere from 4 to 6 months during the summer without having any significant precipitation [4].

Building cooling is the most challenging issue in the Mediterranean climate, due to the strong solar radiation and to the high ambient temperature. The large daily range of temperature during the summer, provides, nevertheless, a considerable potential for nigh-time ventilative cooling [5].

The mild temperatures and the plentiful solar radiation during winter, help reducing heating requirements for buildings, which can easily be contrasted by means of passive strategies [5].

On the basis of this climate features, a concept for the design of a zero energy building (a detached single family house) has been developed, supported by literature review. Energy simulations were used to optimize and correct the design process, that resulted in an optimal energy balance and favorable thermal comfort conditions, as described in the following sections. The concept is nevertheless based on an accurate control of building systems and components. The building automation control system (BACS) was therefore complemented with several sensors which will provide a detailed monitoring of energy flows and comfort conditions, useful for the management of the building and to further improve the design concept for future constructions.

Nomenclature

BACS	building automation and control system
EAHE	earth to air heat exchanger
HDPE	high density hygienic polyethylene

2. Introduction

2.1. Possibilities and limitation

The Mediterranean climate, as described under the Köppen-Geiger system [4], provides a high potential to exploit passive strategies for building design [5].

The use of thermal mass inside the building (mostly the floor slab) has been shown effective to reduce heating demand, when coupled with thermally insulated walls, because it helps providing a useful storage and delay of internal and solar heat gains along the day [6]. This strategy showed to be mostly effective when thermal insulation is on the outer face of the wall [6]. Even from the thermal comfort point of view, internal thermal mass may provide a more homogeneous and acceptable surface temperature distribution along the day [7].

During the cooling season, the use of thermal mass inside the building may prove effective, if coupled with night-time ventilation, to reduce cooling loads and to enhance thermal comfort [6]. Due to the high daily range of temperature (Figure1), night-time ventilation may be easily exploited in the Mediterranean climate, especially if vegetation is growing in the surroundings of the building. An accurate control of solar gains is nevertheless required, because sufficiently ample charge/discharge loops of building thermal mass may not be provided by means of night-time ventilative cooling, for extreme heat gains. The orientation and size of the windows become therefore fundamental parameters to reduce heat gains, together with building shape [6], solar shading devices and glazing g-value [8].

An effective way to exploit thermal mass in low rise buildings, is an exposed floor slab, with some thermal contact with the ground. In this case the heating demand may slowly increase, but cooling loads may substantially decrease due to some coupling with the large thermal inertia of the ground. Night ventilative cooling also makes use of the interaction with thermal mass and particularly with the floor that has been partly exposed to solar radiation during the day [6]. The cooling effect of ventilation may be further extended during the day if ground thermal mass is exploited by means of an earth to air heat exchanger (EAHE) [4, 9]. An accurate management of the mechanical or mixed-mode ventilation system is nevertheless required, and it may be guaranteed only by a BACS.

The use of thermal insulation layers in walls and roof has been proved useful also in the Mediterranean climate by several authors [6, 8]. During the heating season, the position of the thermal insulation layer is not substantial, although it was shown that heading demand may be lower when thermal insulation is on the outside face of the wall [6]. This is true for passive buildings with no heating system, while in building with heating systems, performance substantially changes on the basis of the building system and its control. The position of the thermal insulation layer on the outdoor face is nevertheless suggested to decrease condensation risk.

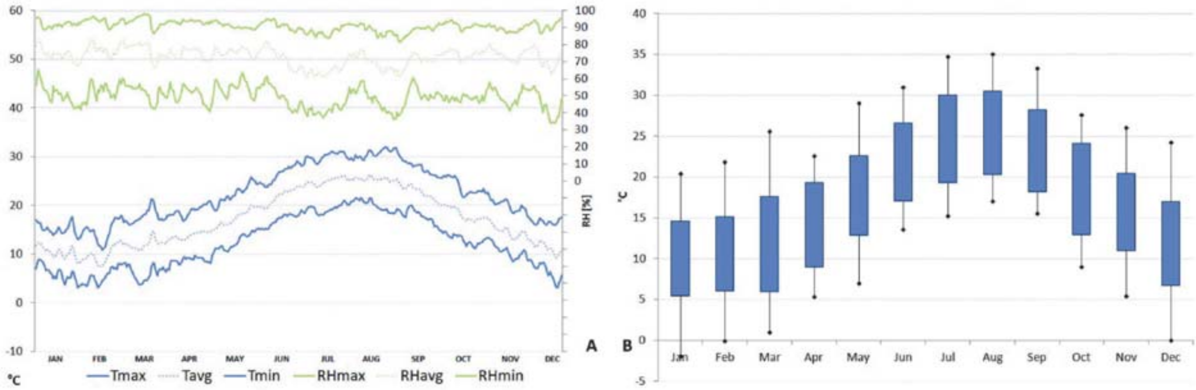

Fig. 1. Catania (Italy) weather data: (a) ambient running mean temperature and relative humidity (max, min, average); (b) monthly maximum, minimum and average range (blue bar) of ambient temperature

During the cooling season the position of the thermal insulation layer is, instead, very important, and external insulation provides better performance [6, 10]. According to standard EN ISO 13786 [11] the dynamic thermal characteristics of the building envelope which mostly affect cooling load are:

- the decrement factor: ratio of the modulus of the periodic thermal transmittance to the steady-state thermal transmittance (U-value)
- the time shift: period of time between the maximum amplitude of a cause (ambient temperature) and the maximum amplitude of its effect (internal heat flux)
- the periodic thermal transmittance: complex quantity defined as the complex amplitude of the density of heat flow rate through the surface of the component adjacent to zone m, divided by the complex amplitude of the temperature in zone n when the temperature in zone m is held constant
- the thermal admittance: complex quantity defined as the complex amplitude of the density of heat flow rate through the surface of the component adjacent to zone m, divided by the complex amplitude of the temperature in the same zone when the temperature on the other side is held constant.

When the thermal insulation layer is moved to the external face of the wall, the periodic thermal transmittance decreases, and so it does the decrement factor, while the thermal admittance increases. Since the periodic heat flux due to the temperature difference between indoor and outdoor increases when the decrement factor increases and the thermal admittance decreases, if the thermal insulation layer is moved to the external face of the wall, the heat flux decreases its value. It can also be calculated that the time shift lengthen.

The use of thermal insulation on the external face of the wall is therefore suggested in the Mediterranean climate, especially if coupled with highly reflective finishing materials, which reduce solar radiation absorption by the wall.

Following the concept described so far, and adopting a detailed energy simulation and optimization approach [12], it is possible to design a passive building according to the Passivhaus standard (originally developed to substantially decrease heating loads), characterized also by a very low cooling demand. Due to the very low total energy demand along the year, and to the large amount of available solar radiation, it is possible to reach a zero energy balance, on yearly basis, by means of reasonably sized on site photovoltaic and solar thermal systems.

The zero energy concept building, whose energy simulation will be further illustrated in the following sections together with a detailed description of the construction, consists therefore of:

- U-shaped plan,
- External vegetation and pervious paving materials,
- Solar shading and high performance glazing,
- High reflectance external wall and roof finishing ('cool roof' and 'cool walls').
- High thermal insulation on the external face of walls and roof,
- Indoor thermal mass exposed, floor mostly, and internal face of walls,
- Coupling of the building with the ground: low thermal insulation of the ground floor and EAHE,
- Cross-ventilation + nigh-time ventilative cooling,
- BACS for building systems optimization and monitoring,
- Photovoltaic and solar thermal panels – on site renewable energy conversion and exportation.

2.2. The concept building

The considered building is a single family detached house, located in the municipality of Mascalucia (Catania) in the Italian region of Sicily (Figure 2). It follows the requirements of Passivhaus certification method in terms of thermal performance: energy need for space heating lower than 15 kWh/(m^2y), energy need for cooling and dehumidification lower than 15 kWh/(m^2y), primary energy for all domestic applications (heating, hot water and domestic electricity) lower than 120 kWh/(m^2y), and air tightness (n_{50}) lower than 0.6 ach. The high envelope performance is complemented by the local production of renewable energy by means of photovoltaic modules, a solar thermal system and by an EAHE in the mechanical ventilation system. A thick external mineral wool continuous layer, triple glazing windows and great care in construction details, guarantee high thermal insulation and airtightness levels. Thermal mass is given mainly by concrete floor and roof slabs directly in contact with indoor air, and by masonry walls with external insulation. Natural cross ventilation is enhanced by windows disposition and by the external patio (Figure 3).

In particular, the EAHE provides pre-heating or pre-cooling to the air supplied by the ventilation system. The supply-air temperature can be further adjusted by means of a heat recovery unit, with automatic bypass when temperatures allow it, and by a heating/cooling coil before entering the indoor environment. The solar thermal system is integrated with a heat pump generator. The complex system is automatically regulated by a BACS supported by Konnex (KNX) protocol. The dwelling also benefits from natural ventilation (cross ventilation), especially for night cooling.

Fig. 2. Zero energy concept building (a) in different construction phases: completion of (b) mineral wool thermal insulation and (c) structural concrete and masonry elements.

The EAHE consists of 3 circular ducts, 10 m long each, installed at 3 m depth in the ground. The air ducts are made of flexible high density hygienic polyethylene (HDPE), with an internal diameter of 142 mm, and they allows a maximum total air flow rate of 350 m^3/h. Design parameters [13], layout and installation details were chosen to maximize its energy performances [14] in cooling and heating periods, and to allow easy maintenance activities. Duct diameters, linear layout and curves minimization were optimized with the aim to reduce pressure losses and ventilation fans energy consumption. The geometric features and the horizontal tubes slope (2.5%), have been designed to allow effective simple cleaning operations and an adequate condensation drainage.

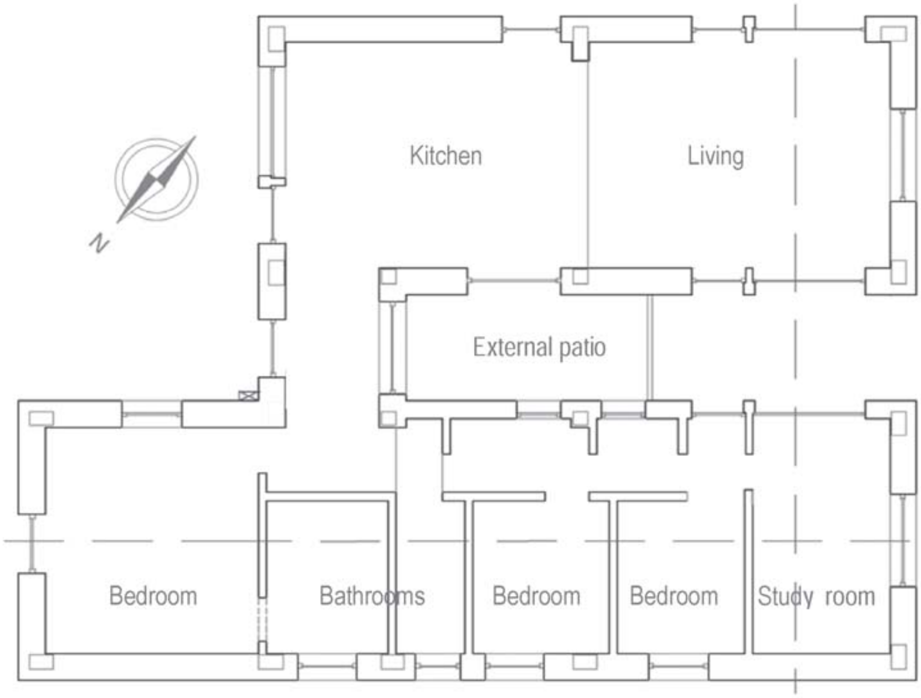

Fig. 3. Plan view of building with orientation.

Table 2. Building main features

Building main features	
Project name and location:	*Progetto Botticelli* in Mascalucia (Sicily)
Building type:	Detached single family house
Conditioned floor area:	144 m^2
External walls thermal transmittance:	0,13 W/(m^2K)
Roof thermal transmittance:	0,13 W/(m^2K
Basement thermal transmittance:	0,23 W/(m^2K
Windows thermal transmittance:	0,90 – 1,10 W/(m^2K)
Envelope air tightness (n_{50}):	Lower than 0,60 ach
Construction type:	Structural concrete and masonry, with mineral wool thermal insulation

3. Energy simulation and design methodology

The energy simulation of the building was performed using the building performance simulation tool EnergyPlus [15], version 6.0.0.23. EnergyPlus is validated against the ANSI/ASHRAE 140 [16] and IEA SHC Task34/Annex43 BESTest method. Within the capability of EnergyPlus, the physical models and algorithms for calculating heat exchanges have been selected with a trade-off between precision and computation time. The update frequency for calculating sun paths is set to 20 days. The heat conduction through the opaque envelope is calculated via the conduction transfer function method with four time steps per hour. The natural convection heat exchange near external and internal surfaces was calculated via the adaptive convection algorithm [17] to better meet the local conditions of each surface of the model. The initialization period of simulation is set at 25 days, instead of the default value of 7 days to reduce the uncertainties connected to the thermal initialization of the numerical model. The voluntary ventilation and involuntary air infiltration are calculated with the *AirflowNetwork* module, instead of the simpler scheduled approach, to better calculate the contribution of natural ventilation and infiltration.

By following the principles of integrated design [18], a large number of passive strategies and concepts, on which inspiring the construction of building variants, were analyzed and simulated during the concept design phase. The selection of the best features of the building envelope elements such as roof, external walls, floor, glazing units on the several orientations, and strategies and/or set-points for controlling solar shading devices, and the night opening of windows to foster natural ventilation was driven by a particle swarm optimization algorithm via the optimization engine GenOpt [19, 20].

When a mechanical heating and cooling system (a reversible heat pump) is included in the numerical model of the building (besides the EAHE), requirements about thermal comfort in indoor spaces have been set referring to the Fanger comfort model [21] as implemented in the International standards ISO 7730 [22]. The seasonal optimal comfort temperatures is calculated assuming a metabolic activity of 1.2 met, a fixed summer clothing resistance of 0.5 clo, a fixed winter clothing resistance of 1.0 clo, an air velocity of 0.1 m/s, a target relative humidity of 50% and an external work set at zero met. According to these assumptions the optimal summer operative temperature is 26.5 °C and the optimal winter operative temperature is 21.2 °C. The duration of summer and winter has been defined using the method proposed in [23] and, for this specific case study, summer lasts from June 1st to October 15th and winter from November 15th to April 30th. The boundary temperatures of the comfort range are calculated in compliance with the Category II of the European standard EN 15251 [24], suitable for new buildings.

In Figure 4 (a), the annual fluctuation of indoor operative temperature inside the dining room is drawn, contrasted to the outdoor (dry bulb) air temperature and the optimal comfort temperature and the Category II comfort ranges.

According to this scenario, the building is all-electric and delivered energy can be used equally well as primary energy to express the breakdown of energy uses (Figure 4 (b)).

Annual delivered electric energy for space heating amounts to 7.3 kWh/(m^2 y) and annual delivered electric energy for space cooling (sensible plus latent) is 9.5 kWh/(m^2 y). The overall electricity demand, which includes all energy uses such as space heating and cooling, dehumidification, production of hot water, ventilation, lighting, plug loads, is 7 253 kWh per year, i.e. 48.8 kWh/(m^2 y).

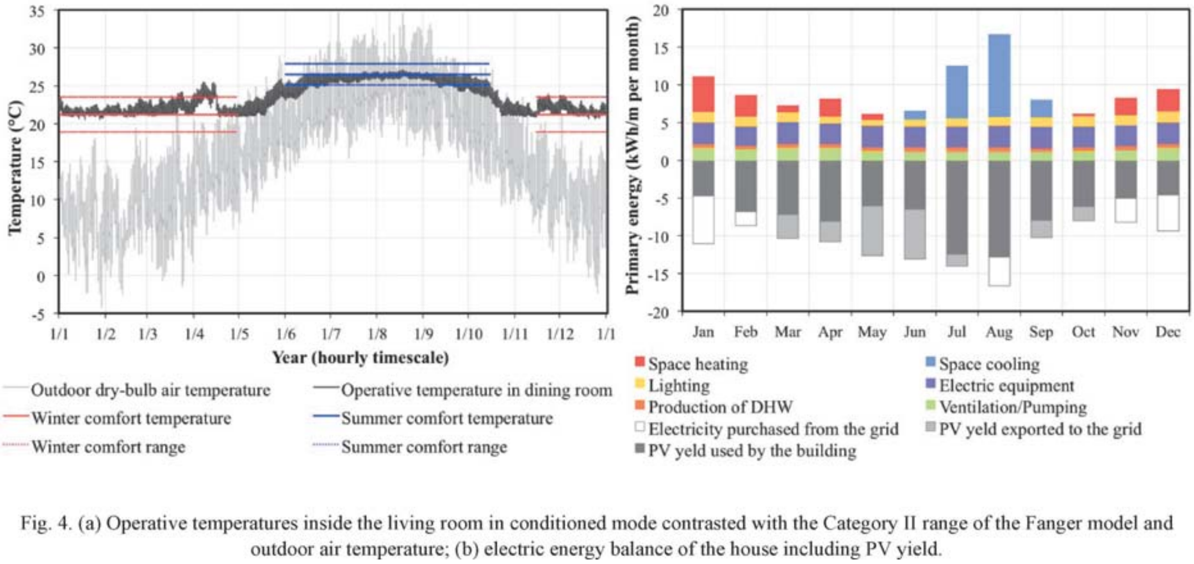

Fig. 4. (a) Operative temperatures inside the living room in conditioned mode contrasted with the Category II range of the Fanger model and outdoor air temperature; (b) electric energy balance of the house including PV yield.

Since the slope of the roof is 22° and assuming to install southwest facing mono-crystalline cells with a nominal efficiency of 18.4% and a peak power of 300 W per panel, and an overall DC to AC derate factor of 0.77, 20 PV panels are sufficient to balance (over one year) the whole electricity demand of the building. The PV field is characterized by a nominal peak power of 6.0 kW_p and a covered area of 32.6 m^2. The expected annual PV yield is 7 580 kWh per year, hence, the building is expected to produce more electricity than it requires (Figure 4 (b)).

Results show a good potential of the proposed concept (high insulated building coupled to an EAHE and internal thermal mass exploitation) in the selected climate, since the building is expected to produce on site slightly more energy than all energy requirements, and to deliver thermal comfort defined according to the Fanger comfort model.

4. Experimental set-up

Building energy performance and thermal comfort conditions will be monitored by a detailed control and monitoring system. The zero energy concept house is intended as a full-scale-test building, operating under real conditions in the Mediterranean climate. The building automatic control system will allow to monitor and evaluate different strategies for solar protection and mechanical ventilation operation, including the EAHE, and considering the real dynamic effects of heat storage in building components.

Monitoring will include: air and operative temperatures, thermal energy demand for heating, cooling, and domestic hot water, electrical energy use for lighting and electrical equipment, the energy production by solar thermal and photovoltaic systems. The total primary energy demand will furthermore be calculated. Temperatures, water flow rates and thermal energy are measured in supply and return pipes via ultrasonic heat and cooling energy meters mounted in each hydronic loop of the system, with proper setting path upstream and downstream from the meters, to reach their best accuracy. Also electric energy demand for reversible air to water heat pump and auxiliary systems is monitored via electric energy meters. The state and opening position of automatic mixing valves and of ventilation dampers is logged too.

A detailed monitoring layout [13] was designed for the EAHE (Figure 5 (a) (b)) with several sensors for temperatures (PT100, class A accuracy, 4 wires connection) and moist water content in the ground.

The monitoring of the air to air heat recovery system will be performed with the installation of temperature, relative humidity and mass flow rate sensors, together with electrical meters for the fans.

Electric energy demand is separately monitored for lighting, domestic electrical equipment (oven, induction hob, refrigerator, dishwasher, washing and dryer machine, coffee machine), and plug loads. For more detailed analysis, the actuators, and all the auxiliaries such as circulators and fans will be separately monitored. The measurements will give detailed information also on internal heat gains related to lighting and electrical uses, which are estimated to be relevant in the energy balance of a passive building like this.

Important information on solar thermal gains and daylighting conditions will be given by monitoring of vertical position and slats angles of external blinds devices (Figure 5 (c)), which are automatically controlled for each windows.

Windows opening will be logged to monitor where, when and how natural ventilation is adopted for free cooling. These kind of measures will allow to elaborate a long term monitoring of the occupants behaviour and of the BACS.

Thermal and visual comfort and indoor air quality will be monitored by globe-thermometers, relative humidity, CO_2 and lux sensors in the main rooms. Calculation of long term comfort indexes will be performed and different methods will be tested and analysed. The use of globe-thermometers will allow to control thermal comfort on the basis of operative temperature in contrast to air temperature.

In order to correlate building performance with external conditions, a weather station was installed on the roof of the building, measuring outdoor air temperature, wind velocity, external illuminance level, solar radiation and sun position. External temperatures are further monitored by two sensors close to the supply ducts of the EAHE, and three sensors placed at different heights in the patio (Figure 5 (d)), with the aim to study the cooling effect of the patio, due to cool air falling from the sloped roof during clear summer nights. Also outdoor relative humidity is measured in the patio and close to supply ducts of the EAHE.

Eventually all of the measured data will be useful to finalize the whole building commissioning phase, reaching optimal regulation of all system components.

Different control strategies for natural and mechanical ventilation will be tested and monitored, particularly focusing on thermal comfort effect due to free cooling, when possible.
The model developed for dynamic energy simulations will be calibrated based on measurements output.

Fig. 5. (a) EAHE with sensors in installation phase and (b) after completion; (c) automatic external blinds and (d) external patio.

5. Conclusions

A concept building was conceived, designed and constructed in the south of Italy, targeting, on yearly basis, net zero primary energy balance and high comfort conditions for the peculiar Mediterranean climate.

Passive strategies were extensively adopted, and active technologies were limited as support to guarantee high comfort standards under extreme weather conditions. The low energy consumption resulted, in energy simulations, to be easily contrasted by renewable energy conversion on site (photovoltaic and solar thermal).

Although passive strategies prevail, the concept building is not an outdated construction: 'smartness' have been shifted from active conditioning to building automation and control, and beforehand to the design process, where advanced energy simulation and optimization techniques were adopted.

To check if the concept building is operating as designed, and to fine-tuning and manage the whole building-system, an advanced monitoring framework was installed, enhancing the BACS capabilities.

Many outcomes are expected from the operation of the building: management and fine-tuning, energy simulation model and process validation, design feedbacks, occupant behavior monitoring and modeling, detailed energy breakdown, energy demand/production curves layout for management of zero energy building networks, energy and comfort combined analysis for the development of new indicators.

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