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A roadmap towards intelligent net zero- and positive-energy buildings

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Abstract

Buildings nowadays are increasingly expected to meet higher and more complex performance requirements: they should be sustainable; use zero-net energy; foster a healthy and comfortable environment for the occupants; be grid-friendly, yet economical to build and maintain. The essential ingredients for the successful development and operation of net zero- and positive-energy buildings (NZEB/PEB) are: thermal simulation models, that are accurate representations of the building and its subsystems; sensors, actuators, and user interfaces to facilitate communication between the physical and simulation layers; and finally, integrated control and optimization tools of sufficient generality that using the sensor inputs and the thermal models can take intelligent decisions, in almost real-time, regarding the operation of the building and its subsystems. To this end the aim of the present paper is to present a review on the technological developments in each of the essential ingredients that may support the future integration of successful NZEB/PEB, i.e. accurate simulation models, sensors and actuators and last but not least the building optimization and control. The integration of the user is an integral part in the dynamic behavior of the system, and this role has to be taken into account. Future prospects and research trends are discussed.

Keywords: Net zero-energy buildings; Positive-energy buildings; Thermal simulation models; Monitoring systems; Optimization and control

1. Introduction

Energy consumed in-buildings accounts for 40% of the energy used worldwide, and it has become a widely accepted fact that measures and changes in the building *modus operandi* can yield substantial savings in energy. Moreover buildings nowadays are increasingly expected to meet higher and potentially more complex levels of performance. They should be sustainable, use zero-net energy, be healthy and comfortable, grid-friendly, yet economical to build and maintain.

Zero-energy or even positive-energy buildings are becoming a high priority for multi-disciplinary researchers related to building engineering and physics and have been recently discussed by energy policy experts: as on April 23, 2009 the EU Parliament has requested that by 2019 all new buildings to conform to zero-energy and emission standards (European Parliament, 2009).

A NZEB/PEB refers to a building with a zero or negative net energy consumption over a typical year (Wang et al., 2009). It implies that the energy demand for heating

Abbreviations: AC, Air conditioning; BIPV, Building Integrated PhotoVoltaic; BMS, Building Management System; BO&C, Building Optimization & Control; CEN, European Committee for Standardization; DS, Decision Strategy; EER, Energy Efficiency Ratio; ENEP, Estimated Net Energy Produced; FDD, Fault Detection and Diagnosis; GCEI, Generation–Consumption Effectiveness Index; HVAC, Heating, Ventilation and Air-Conditioning; MPPT, Maximum Power Point Tracking; NEB, Net Expected Benefit; NEC, Net Energy Consumed; NEP, Net Energy Produced; NER, Net Energy Ratio; PDA, Personal Digital Assistant; PEB, Positive-Energy Building; PP, Payback Period; REGS, Renewable Energy-Generation Systems; RFID, Radio Frequency IDentification; TC, Thermal comfort; NZEB, Net Zero-Energy Buildings; VAV, Variable Air Volume.

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and electrical power is reduced, and this reduced demand is met on an annual basis from a renewable-energy supply. The renewable-energy supply can either be integrated into the building footprint or it can be provided to building, for example, as part of a community renewable-energy supply system. It also normally implies that the grid is used to supply electrical power when there is no renewable power available, and the building will export power back to the grid when it has excess power generation. This 'two-way' flow should result in a net-positive or zero export of power from the building to the grid.

The NZEB/PEB design concept is a progression from passive sustainable design. Various innovative energy efficient technologies are mature and can be considered for the improvement of the energy efficiency and indoor comfort improvement in buildings:

- Improvement of the building fabric, i.e. improvement of insulation, increase of thermal mass, cools materials, phase change materials, etc.
- Innovative shading devices.
- Incorporation of high efficiency heating and cooling equipment, e.g. AC equipment with higher EER, heat pumps combined with geothermal energy or solar collectors, solar air-conditioning, etc.
- Use of renewables (solar thermal systems, buildings' integrated photovolatics, hybrid systems, etc.).
- Use of "intelligent" energy management, i.e., advanced sensors, energy control (zone heating and cooling) and monitoring systems.

The objective of a NZEB is not only to minimize the energy consumption of the building with passive design methods, but also to design a building that balances energy requirements with active energy production techniques and renewable technologies (for example, BIPV, solar thermal or wind turbines). The management on the supply side involves optimization techniques of the energy produced, e.g. use of maximum power point tracking system for photovoltaics and wind generators (Koutroulis and Kalaitzakis, 2006), energy storage management or feeding the extra energy produced to the grid.

Some application examples around the world are summarized by Hamada et al. (2003)—the database is continuously expanding (Crawley et al., 2009).

NZEB/PEB performance is measured and evaluated using various indicators, i.e. net primary energy consumption, net energy costs, carbon emissions (Torcellini and Crawley, 2006; Tsoutsos et al., 2010). A relevant indicator in PEB/NZEB studies is the computation of the Estimated Net Energy Produced (ENEP) (Iqbal, 2004; Parker, 2009) which is the energy available from renewable sources over a period of time after subtraction of the energy required for the building operation over the same period. Other indicators found in the literature is the Net Energy Ratio (NER) (Hernandez and Kenny, 2010) which is used to aid the decision-making mechanisms during the building design process towards life cycle NZEBs or zero-carbon dioxide emissions (Tsoutsos et al., 2010). Calculation and maximization of the NEP is almost exclusively used in the design and pre-implementation phases of current PEB/NZEB projects. Nevertheless, there are a number of parameters that cannot be *a priori* ascertained and differ during operational conditions: unpredictable user actions that adversely affect energy efficiency such as unnecessary operation of the lighting or the HVAC systems, opening and closing of windows, setting of the setback temperature too high or too low; influence of prevailing weather conditions on the thermal behavior of the building; the complex interplay of the NZEB/PEBs active and passive climate-control and energy-generation systems installed and their effect to energy efficiency and building thermal response; and, atypical availability of energy on a "weather-basis" rather than a "need-basis" through renewable energy-generation sources (e.g. wind, solar). For the calculation of the previously mentioned indicators, the energy-production (positive energy) calculations are usually performed uncoupled from the energy-requirement (negative energy) calculations, for typical winter and summer design days or weeks, without any regard to the uncertainties mentioned above, and make these indices useful from a feasibility viewpoint, but not very relevant regarding actual performance during real-time operation. In real-time operation of a NZEB, a coupling mechanism of the energy production and energy requirements can yield significant benefits since:

- The energy production installation may not be extremely oversized to cover the building's energy and indoor environmental quality requirements and therefore the initial investment costs may be decreased.
- The energy production can be maximized by suitable decisions, i.e. MPPT.
- The extra energy produced in a specific period may either be used for storage and coverage of the peak demand in the proceeding period or can be injected into the grid under specific conditions discussed in Section 4.
- Extreme weather conditions can be met on a yearly basis with suitable control actions.

Therefore the existing performance indicators such as ENEP and NER, and the calculations used to obtain them reflect a "static" view of the building and these shortcomings suggest that a more "dynamic" view is required especially during the operational phase. The building when viewed as a dynamic system responds to internal and external perturbations with the goal of fostering comfort conditions for the building users and also, in the case of PEBs, produces surplus energy. A performance measure for a NZEB/PEB may be the real time performance indicator (NEP, NER, etc.) that could be measured using a smart metering solution inside the building. This dynamic measurement can be integrated on seasonal or yearly basis to show the NZEB/PEB performance. In that case unpredictable user-behavior, changing weather conditions, generation–consumption matching, operation of active and passive climate-control systems, are some of the topics that affect the building's behavior and demand intelligent decisions in real-time. These decisions have direct consequences to energy efficiency, occupant thermal comfort and, ultimately, to the relevant real time indicator selected. The complex interplay between the many parameters precludes a simple set of rules or guidelines and necessitates the development of generic decision tools.

Therefore the road towards PEB/NZEB in real-time operation involves groundbreaking innovations and progress beyond the state-of-the-art in various fields. This may include the PEB/NZEB modeling, building automation components (i.e. infrastructure and networking) real-time optimization and control of PEB/NZEB operations and user-interaction as depicted in Fig. 1.

To this end the aim of the present paper is to present a review on the technological developments in each of the ingredients to support the future dynamic development of NZEB/PEB: accurate simulation models, sensors and actuators and, last but not least, the building optimization and control methodologies. The role of user as a dynamic part of the system is revealed. Future prospects and research trends are discussed.

The present paper is structured in three more sections. Section 2 provides the information regarding the role of modeling in NZEB/PEB processing. Section 3 analyses the role of sensors actuators, networking and infrastructure while Section 4 includes the buildings' optimization and control state of the art. Finally, Section 5 summarizes the conclusions and discusses issues for future consideration, research and development.

2. Modeling for NZEB/PEB

Buildings are complex systems and detailed simulation is needed to take into account the actual climate data, geometries, building physics, HVAC-systems, energy-generation systems, natural ventilation, user behavior (occupancy, internal gains, manual shading), etc. towards a zero or positive energy approach.

Moving from regular to high-performance buildings requires a departure from perceived notions on building design and operation and necessitates the inclusion of more sophisticated methods and tools in the design and implementation phases. In current practice, buildings and their energy performance are estimated based on calculations using simplified physical models and taking a largely static view of the building and its operation. This oftentimes leads to significant deviations regarding performance between the design calculations and the actual building operations (Degelman, 1999; Crawley, 2003). Energy efficiency measures (e.g. insulation, low-emissivity windows, active and passive cooling systems, thermal mass, etc.) are extensively studied in the

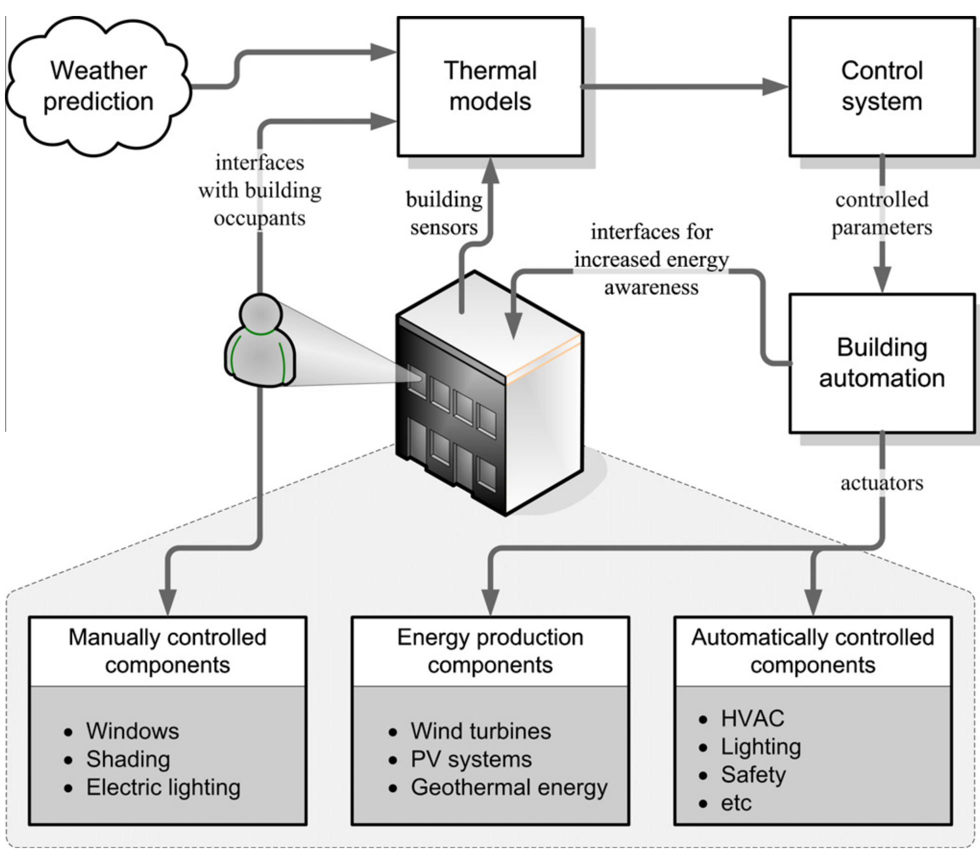

Fig. 1. The components of a ZEB/PEB architecture during real-time operation.

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literature and the effects of their usage are relatively well understood. Their use is encouraged by codes, certification and best-practice recommendations and the application of such measures yield tangible benefits in improving energy requirements while maintaining end-user comfort at acceptable levels. Still the complex interplay between the various design parameters precludes empiricism or simplistic models as the parameters neglected in such approaches are important with respect to the application of the efficiency measures. For example, the inclusion of a thermal mass combined with a natural ventilation strategy can yield significant and undisputable energy savings. A misuse though of such a practice, e.g. neglecting to open windows at night during hot summer days can have catastrophic results both with respect to thermal comfort and energy efficiency yielding exactly the opposite compared to the intended results, i.e. increased discomfort and cooling load. It is therefore necessary to be able to *a priori* ascertain performance characteristics and achieving this requires detailed modeling and simulation tools that yield meaningful representations of the building and all its subsystems, and are capable of predicting with sufficient accuracy energy requirements and system response.

In order to obtain an accurate simulation model, detailed representation of the building structure and the subsystems is required, but it is the integration of all the systems that requires significant effort. A number of simulation tools are available with varying capabilities (see Hong et al., 2000; Al-Homoud, 2001; Crawley et al., 2008) for a comprehensive comparative review of existing simulation tools. While an exhaustive list is out of the scope of this paper—for such an attempt the reader is referred to Crawley et al. (2001))—we mention below the ones most commonly encountered in the literature: TRNSYS (TRNSYS, 2004; Klein et al. 1976), ESP-r (Clarke et al., 2002, DOE (DOE, 2003)) and Energy Plus (Fig. 2) (Crawley et al., 2000; Crawley, 2001).

A basic modeling assumption used by most building-simulation software is the multi-zonal paradigm: dividing the building into regions (zones), each with a temperature and humidity variable, assumed to be spatially constant. The evolution in time of the zonal parameters is evaluated from the solution of a system of algebraic and ordinary differential equations (essentially the energy conservation equation on each zone is used to compute the temperature variation, and mass conservation is used to determine the humidity variables). Open and noncommercial modeling languages for the description of physical systems, like Modelica, can also be used for building simulation (Fritzson, 2004; Tiller, 2001; Haase et al., 2006). The open and noncommercial character of the language with capabilities of equation-based, acausal modeling, object-orientation, multiple inheritances and multi-physics modeling, guarantee a transparent simulation standard for the development of such models. A component library for building-simulation purposes containing models for thermal room performance, occupants' behavior, and weather model has been developed and used for building-simulation purposes (Matthes, 2006; Haase, 2007).

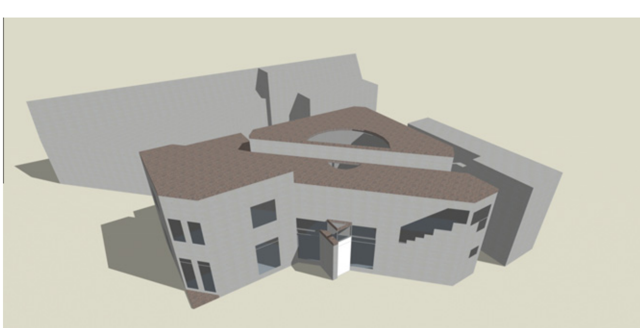

Fig. 2. A simulated building of the Technical University of Crete Campus using EnergyPlus (Stroponiati, 2009).

There are significant differences between the aforementioned simulation tools both with regards to implementation and usability as well to the actual thermal models that are employed yielding different model-level representations of the physical system. Each of the options above can be viewed as thermal simulation toolboxes that provide the necessary "building blocks" and the "mortar" to interconnect them in developing holistic building simulation models. This software have been validated in many synthetic and real-world benchmarks—e.g. using the BESTEST suite (Henninger et al., 2004; Neymark et al., 2002; Haddad et al., 2001). Simulation-based building design tools are nowadays mature and yield improved accuracy and detailed information especially in the design phases. Today they are an integral part of the design process especially for larger buildings, but still there is a need of significant expert knowledge to set up correctly simulation models that, at the simulation level, yield a realistic representations of the actual building. Usually simulation happens at an annual basis, with time-steps that can be as low as a few minutes, using weather data for a "typical year" in the building site, and yield information on building performance both with regards to energy performance and occupant's thermal comfort.

In the domain of zero-energy or zero-emission buildings, application examples include the use of both EnergyPlus and TRNSYS (Wang et al., 2009) to perform a feasibility analysis of zero-energy houses with renewable electricity, solar hot-water system and energy-efficient heating systems. Also, Visual DOE is used by Tavares and Martins (2007) to perform a sensitivity analysis that results to energy efficient design solutions for a specific case study where a significant number of pre-defined solutions are modeled and evaluated. The use of simulation models is expected to gain more ground as we move towards high-performance buildings. At present, most of these studies are limited to annual simulation for the evaluation of performance – we see below that simulation can play a larger role in the design *and* operation of NZEBs.

One significant ingredient for NZEB/PEB is the presence of renewable-energy sources to produce the energy needed by the buildings. Simulation capabilities for each of these sources are a prerequisite for the study of NZEBs. It has been observed in design studies that design teams were overly optimistic as they overestimated the energy produced through RES and also they underestimated the operational energy requirements (Crawley et al., 2009). This discrepancy is due, in part, to the inaccuracy of the weather data which are obtained from meteorological stations, usually near airports, and sufficiently far from the building location. Also, the urban microclimate (e.g. the presence of heat islands) can lead to significant discrepancies in the local weather data and this can have significant effect on the actual energy requirements (Oxizidis et al., 2007; Santamouris et al., 2001). It is therefore important that accurate weather measurements or modeling exist to yield pragmatic weather data at the site location so that they can be used to properly estimate building loads and energy availability through RES.

A second important aspect is the users' actions and the effect they have on the building performance. It has been observed that users are slow in adapting to new technologies. Also there is criticism on the models used to estimate thermal comfort (Humphreys and Hancock, 2007; Freire et al. 2008; Becker and Paciuk, 2009). In actual practice, users' behavior, governed by their subjective comfort feeling and their actions have significant impact in the buildings' performance. It is advocated that improvement on the effect of users' behavior can be obtained through enhanced energy awareness. There are significant efforts at the European level for the development of technologies that can help enhance users' energy awareness. BeAware (BeAware, 2010), strives to conceptualize the concept of energy and with the development of user interfaces aims at turning users into proactive players in the effort of rational use of energy and improvement of energy consumption.

In the effort towards, zero- and positive-energy buildings one final aspect, little considered in the current literature is that of generation–consumption matching. Most studies consider separately the generation part (through RES) from the consumption. In labeling a building as Net Zero the generation over a period (usually a year) has to match or surpass the consumption. This reflects a rather static view of the building. One aspect that has found relatively little attention in the current literature is the concept of generation–consumption matching, i.e. shaping demand by actively controlling the building subsystems to match the energy available through renewable energy systems. The control decisions need to be taken in (almost) real-time using environmental and fiscal performance criteria. The concept of *generation–consumption matching* as a NZEB/PEB performance indicator is described and analyzed in Section 4.

3. Infrastructure and networking

3.1. State of the art for buildings' applications

Sensors, actuators and interfaces are essential components for the successful implementation and real-time operation of NZEBs or PEBs. The evolution of the specific components was quite rapid the last decades leading to the intelligent buildings' concept derived from artificial intelligence and information technology. So far the intelligent building systems are supported by either building automation technologies such as Profibus (www.Profibus.org) (Yao et al., 1999), BACNET™ www.bacnet.org (Rodenhiser, 2008; Bushby, 1997) or home automation protocols like X10™, EIB™, and LonWorks or wireless networks such as ZigBee. The main features of the above protocols are tabulated in Table 1.

Although the transducers' industry was for quite a long time dominated by analogue signal communication, the situation is changed and traditional analogue connectivity is being currently challenged by the introduction of low-cost devices supported by object oriented programming and varying embedded communication media.

There are several key drivers for advanced networked sensors and actuators using various communication media:

- Demand for open systems with true interoperability and interchangeability of products from different vendors, enabling users to select the best product for the application.
- Decentralized intelligence in the control and measurement field and peer-to-peer communication between devices.
- Global explosion of information networking.
- Proliferation of make-to-order flexible manufacturing systems, demanding rapid production line configuration change.

In the building sector, sensors, actuators, networking and infrastructure are mainly used for the following applications:

- Measurement and validation of specific energy-efficiency technologies, i.e. innovative insulation, cool materials, etc. (Synnefa et al., 2006; Tian et al., 2009). In these cases, short term monitoring is applied focusing on the evaluation of the technologies applied.
- In-situ measurement and validation of the indoor environmental quality and energy efficiency of the overall building by the installation of a network of sensors for a specific period (Rosta et al., 2008; Toftum, 2010). This case also involves short term monitoring of indoor environmental quality and energy efficiency.
- Installation of a Building Management System (BMS) (Kolokotsa et al., 2005; Guillemin and Morel, 2002) which is a long term monitoring.

Examples below serve to better illustrate the concepts of short and long term monitoring of indoor environmental quality and BMS applications.

- The thermal characteristics, indoor conditions and energy efficiency of a bioclimatic Auditorium at the National University of La Pampa are monitored by

Table 1
Protocols used in-building automation.

	BACnet	ZIGBEE	Konnex (EIB)	Profibus	LonWorks
Application Target	Building automation	Process, discrete control, building automation	Building automation, electronics installation	Process, discrete control and building automation	Building automation, discr
Bus or Net	Net	Net	Bus	Bus	Net
Communication method	Master–slave	Peer to peer	Peer-to-peer	Master–slave and token pass	Peer-to-peer
Media access algorithm	CSMA/CD, Token bus	CSMA/CA	CSMA/CS	Master–slave, peer-to-peer	CSMA/CA
Media supported	Coax, Fiber,TP	Wireless	TP, Powerline, RF	TP, Fiber	TP, Fiber, Powerline, Coax, IR, RF
Addressing Schemes Uni-multi-broadcast	All	Multi-, broadcast	Multi-, broadcast	Multi-, broadcast	All
Network management tools?	No	Yes	Yes	Yes	Yes

Larsen et al., 2008. Climatic conditions such as wind velocity and direction, outdoor air temperature, and solar irradiance on horizontal surface plus indoor air temperatures are monitored. A data-acquisition system is used, consisting of two data acquisition and monitoring modules connected to a laptop PC for the assessment of the energy efficiency and support model development. A 70% reduction in conventional energy requirements is justified by the monitoring procedure.

- The design, implementation and validation of alternative new technologies to monitor occupancy and control of indoor environment are performed by Dodier et al., 2006. The scope was to design a methodology where the control decisions will be based on a network of low cost passive infrared occupancy sensors plus analysis tools where Bayesian probability theory is used to improve the overall system's reliability. This layout could offer significant advantages on management, security and environmental quality by mapping effectively buildings' occupancy in space and time.
- Liu et al., 2009 proposed a sensor network for the assessment of the indoor air quality. The design criteria proposed are the sensor network sensitivity, the response time and the acceptable indoor contaminants' concentration level. Alarm sensors, portable and continuous reading sensors are proposed for the network infrastructure. The sensor network proposes a methodology for optimizing the sensors' outputs. The sensor network is checked for a real contamination source's position. The position of the contamination source that the sensor network indicated was very close to the actual one.
- Kolokotsa et al., 2005 developed and tested a fuzzy controller for a BMS. The testing procedure took place in two buildings in Athens and Crete, Greece respectively. The reduction of energy consumption is estimated to be up to 20% for heating and cooling, and 50–70% for lighting.
- A measurements' network is developed to study the performance of a NZEB by the use of two identical constructions (Rosta et al., 2008). One is used as a reference conventional building and the other is a zero-energy building that incorporates various technologies such as energy efficiency features, solar power generation, and supplemental solar water heating. Both houses are monitored via a network of sensors that measure indoor environmental parameters and the energy use. The zero building used 83.27% less peak energy than the conventional building. When the energy consumed by gas is included in the overall energy balance, the building becomes a NZEB.
- A web-based RFID (Radio-Frequency Identification) maintenance system is proposed in (Ko et al., 2009) to support buildings' maintenance. The system is employed using tablet PCs and portable reader/writers. The RFID automatically identifies the equipment and facility read and saves operational time while the information stored on the tags can be easily changed. Moreover RFID can be interconnected with other systems or technologies.

Another critical issue is sensors' reliability. Malfunctioning sensors may misrepresent the operating conditions and mislead the BO&C systems resulting in false alarms due to false sensors' performance. Therefore reliable sensors operation is very critical for the overall performance. Some examples in performing sensors' fault detection and diagnosis include:

- The development of an on-line diagnostic tool for sensors' fault detection and diagnosis of sensor faults in air handling units, which adopts a robust sensor FDD strategy based on Principal Component Analysis (Xiao et al., 2006).
- A fault detection and diagnosis as well as evaluation strategy is developed by Wang et al. (2004). The overall strategy is based on the mass and energy conservation balance relationships. The sensor bias is calculated by minimizing the weighted sum of the squares for the corrected residuals for each conservation balance. The overall strategy is tested by Building Management Systems' sensors.
- Kolokotsa et al. (2006) proposed a methodology for sensors fault detection in BMS. The fault diagnosis decision criterion used is the average absolute prediction error

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between the actual and the predicted values of the sensor. The predicted value was calculated by a model based on faultless operation data collected using fuzzy control. Three experiments are presented with simulated biases in the temperature, illuminance and CO_2 sensors.

3.2. Potential role of wireless communication in NZEB/PEB

The wireless communication technology has progressed very rapidly the last decade. In the building sector wireless applications include building automation, indoor environmental monitoring and emerging technologies (Wu and Clements-Croome, 2007). Wireless technology has already deeply penetrated the HVAC systems' controls and measurements market. This is attributed to the fact that so far, installation of conventional wire-based monitoring and control systems for buildings requires significant time and labor. Apart from the significant labor costs that sometimes may be surprisingly high, wiring may be difficult or even impossible to be applied in specific buildings due to occupants' disturbance. Moreover wireless sensors are suitable for short-term site where the conventional wired monitoring systems may not be feasible. Some indicative applications of wireless communications' technology in buildings are:

- The benefits of the wireless sensors for buildings and especially for VAV systems are analyzed by Jeong et al. (2008). These include portability, flexibility, fast equipment setup, time synchronized data collection, negligible occupant disruption during the measurement, and wiring time and cost savings. The major drawback are high equipment costs which equalize any benefits and hinder the wider use of wireless sensors in the field measurements, except in those cases where accurate model tuning for a building is of high value for occupant risk reduction.
- A Kilavi approach is proposed by Oksa et al. (2008) as an open standard communication platform to enable wireless device control and monitoring in buildings. The proposed platform allows the interconnection of various open standard sensors such as temperature, brightness and motion detection sensors that can be used to provide environmental information for the application's control decisions.
- Home networking supported by wireless sensors that monitor a wide range of indoor environmental parameters is proposed by Chung and Oh (2006). The proposed module integrates humidity, temperature, CO_2 sensor, flying dust sensor, etc. The overall cost is reduced by using one RF transmission block for sensors signal transmission in time sharing. Indoor vision was transferred to client PC or Personal Digital Assistant (PDA) from surveillance camera installed indoor or desired site. A web server using Oracle DB was used for saving the visions from web-camera and various data from wireless sensor module.
- A hybrid sensors' network that integrates wireless sensors into an existing wired BMS is presented by Menzel et al. (2008). This configuration can be used for future expansion of existing BMS to integrate intelligent techniques.

In summary, wireless media in the building sector have the following benefits compared to previous wiring communication techniques:

- Ease of installation.
- Reduction of labor costs.
- Mobility and portability.
- Minimum interference with occupants.

3.3. Discussion on networking and infrastructure

Although there is significant progress in monitoring, networking and infrastructure for buildings that may allow the future deployment of NZEB/PEB, still there are some difficulties in the system integration. One considerable difficulty is pinpointed to the integration and communication between the building automation components and the existing building services (e.g. HVAC, lighting control or emergency systems). The second difficulty refers to the integration of different communication protocols mentioned in the previous paragraphs (Jianbo et al., 2009).

Based on the above, during retrofitting in most cases, the sensors, actuators and user-interfaces are introduced after the building is constructed, as an add-on, and in very few cases they are delivered as an integrated part of the building. This usually implies their connection to a central system through cables that are either integrated during the construction or added later, which is a very heavy task. Moreover, the typical case is that all the elements of the sensor, actuator and user-interfaces system deployed within the building have to "obey" to a pre-defined communication protocol; elements that do not obey to such a protocol are difficult to be connected and integrated to the system.

NZEB operation in a coupling production and consumption approach requires communication between many systems and elements that are of different type, serve different purposes, have been developed by different vendors and based on different design philosophies. This is clearly depicted in Fig. 3. Moreover, the operation of an efficient NZEB/PEB may require that new monitoring or control elements should be added after the initial system deployment (e.g. the addition of a renewable-energy generation system that is different than the already installed ones) or the existing elements should be interconnected with other elements and systems (e.g. for providing energy to neighboring buildings in case there is significant energy surplus in the PEB). In other words, such dynamic operation of PEBs requires solutions that allow for easy-to-deploy (and to-program and to-re-program), interoperable, expandable and scalable installation, integration and deployment of sensors, actuators and user-interfaces systems.

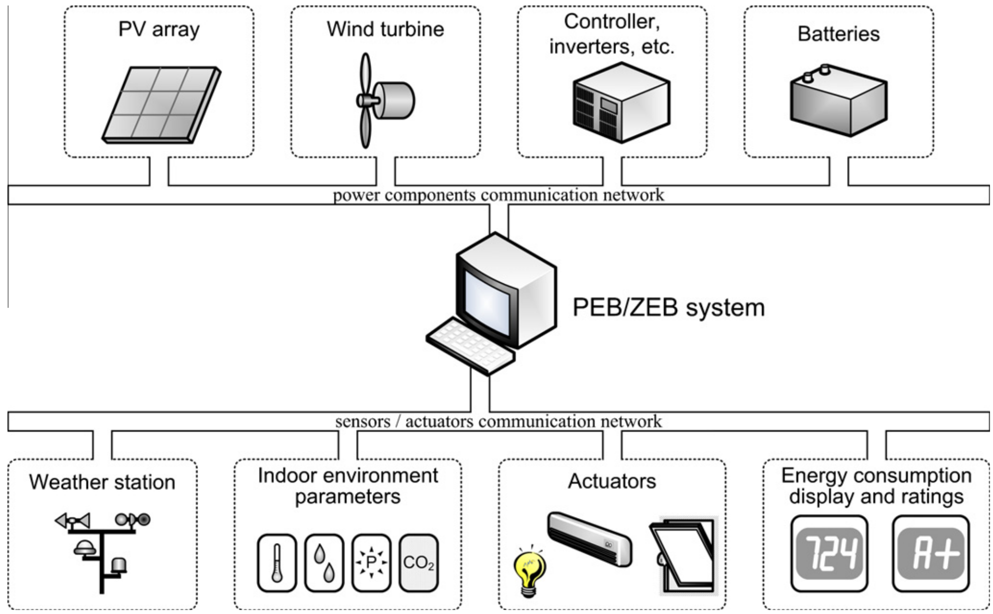

Fig. 3. The monitoring and infrastructure of a ZEB/PEB system.

To meet future requirements for PEB/NZEB sector, interoperable and low-cost wireless communication systems that will be able to operate to generic PEBs should be developed and deployed. Such systems may be based on a low power solution to wireless robust real-time connection for reaching long distances in a building by using mesh networking.

Moreover possible combination of wireless devices (for sensing and actuation through dedicated interfaces), of synchronized (or non-synchronized) coordination of these devices and cabled ones may improve the usability, comfort and eventually effectiveness either in the process monitoring and control procedure or in the user interaction procedure. The other benefit of possible combinations is the flexibility, durability and ease of deployment of wireless sensing and actuation networks allowing for fast installation and transparent operation at lower cost, even for long time if the devices have a very low-power consumption.

Therefore in the road towards use of wireless communications in NZEB/PEB design the following benefits could be achieved:

- Cost reduction in wiring, installation and debugging.
- Reduction in size and weight of the wiring.
- Significantly shortened process design cycle time.
- Reduction in commissioning time.
- Reduction of downtime.
- Improved system performance and reliability due to digital communication.
- Improved modularity and configurability due to the software and not hardware dependability.
- Rich bi-directional messaging that will enable enhanced product functionality, e.g.:
  - Multivariable devices.
  - Diagnostics.
  - Remote programmability.
- Ability to share information, while many devices are connected to a single communication system.
- Flexibility. No wires solution provides the advantage to move the sensor board in any place as long as we are inside the coverage area of another node of the network. The node doesn't have to be in the coverage area of the central node. Routing protocol can create communication paths between nodes that are not in the same coverage area.
- Small size factor. The size of a wireless sensor node is usually small. A typical size of a node with indoor housing protection is 5.7 × 3.17 × 4 cm.
- Low energy consumption.
- Easy to program via specialized software programming tools.
- Adaptable protocols. The protocols to be used for communication between the nodes and between the nodes and the central node should be flexible and adaptable, allowing communication between elements of different vendors and of different design methodologies.

4. Building optimization and control methodologies for NZEB/PEB

The third element that may contribute to the efficient operation of a PEB/NZEB is competent and robust Building Optimization and Control (BO&C) tools that use building networking inputs and thermal models to evaluate potential scenarios, and take (almost) in real-time decisions for the operation of the building subsystems with the goal of maximization of the selected performance indicators (e.g. NEP or NER) while retaining building conditions at user-acceptable comfort levels. It has to be emphasized that building occupants have a dual sensor–actuator role within the BO&C NZEB/PEB framework: through user-interfaces humans act as sensors communicating their thermal comfort preferences to the BO&C system, and in return the BO&C system returns recommendations or even commands (e.g. "open window X at room Y", "lower shades at window X at room Z", etc.) with the goal of engaging them in the effort of taking proper decisions.

To illustrate the challenge BO&C systems for NZEBs are facing, consider for example a 24-h period for an office building with installed renewable-energy-generation sources (e.g. solar, wind) and two possible scenarios:

- *Scenario 1*: electricity can be purchased but cannot be sold to the grid. Please note that in this case it is impossible for the building to achieve a NZEB performance; the reason we consider such a scenario is in order to illustrate the differences between the logic of a conventional BO&C system and that of a BO&C system that employs the logic required in the "NZEB framework".
- *Scenario 2*: electricity can be purchased and sold at the same price.

In Fig. 4 (top) the generation and consumption curves are shown for a typical day. The generation curve in both cases depends on the type of installed renewable-energy sources as well as the weather conditions on the specific day. The consumption curve is the energy required for the operation of the building and obviously decisions taken and building-user actions have an effect on the shape of this curve. The area under the generation or consumption curve is the energy generated or consumed respectively during that day.

If conventional BO&C systems were employed in the scenarios shown in Fig. 4, the best they could do would be to attempt – at each time-instant, i.e. myopically – to minimize the current energy consumed (by e.g. controlling the building's HVACs). On the contrary, a BO&C system designed to operate in an "NZEB framework" must be able not only to minimize the current energy consumed but also to "reshape" it, for instance, by having the HVACs operating during the night when demand is low but renewable generation surplus is available (e.g. from midnight to 6 h in the scenarios of Fig. 4), in order to keep the building at the desired temperature. Please note that a myopic conventional BO&C system would make no attempt to control consumption at that period, which may have the result of high power consumption when the offices are open.

For scenario 1 the shaded area is the energy that has to be purchased from the utility company and a monetary value can be directly assigned as it is proportional (in a flat pricing structure) to the amount of energy that will be purchased. The decisions taken for the operation of the building subsystems modify the consumption curve but not the generation curve – "good" decisions make the shaded area

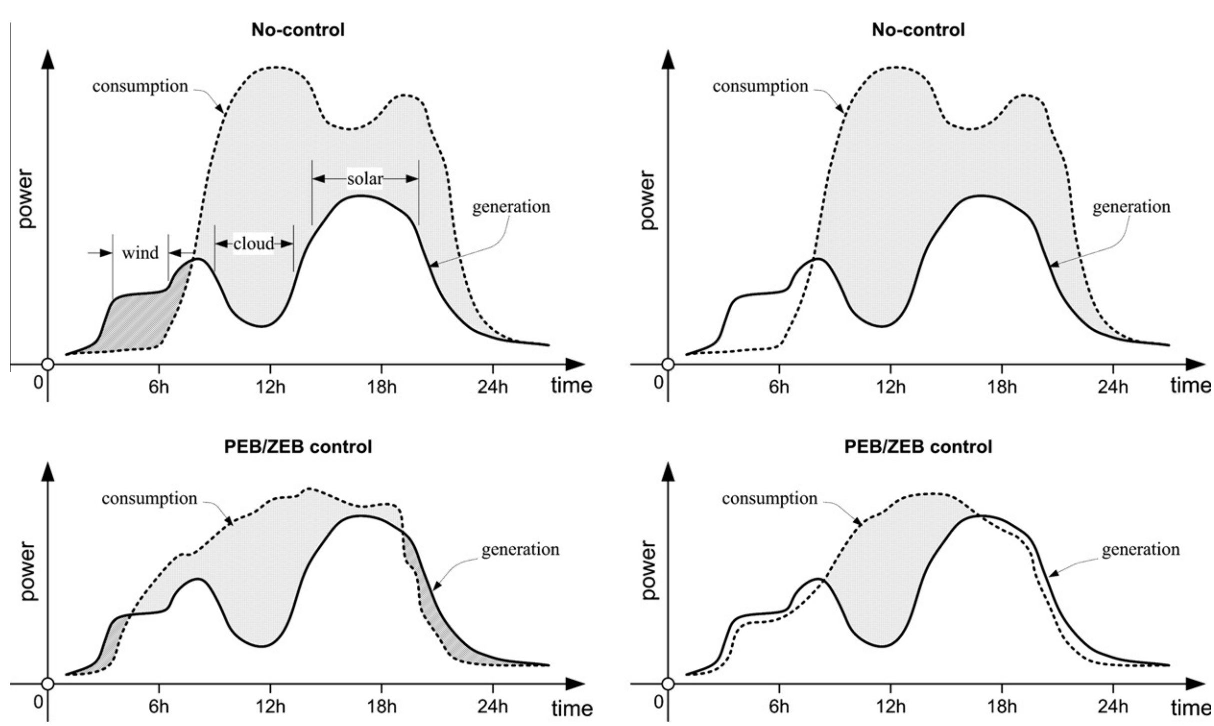

Fig. 4. Generation–consumption without (upper sub-plots) and with (lower sub-plots) ZEB/PEB's BO&C system. The left sub-plots refer to a scenario where electricity can be purchased but cannot be sold to the grid and the right ones to a scenario where electricity can be purchased and sold at the same price.

smaller, whereas "bad" decisions make it larger. In an efficient BO&C strategy the available building systems should be used in the most effective manner and the consumption curve should move so that the area is minimized (bottom figure).

In the case of scenario 2 the situation is similar: the generation curve is fixed but the shape of the consumption curve is affected by the BO&C system's decisions. The area between the consumption and generation curve represents an indicator that may be called 'Net Energy Consumed' (NEC) which is the amount of energy that needs to be purchased from the utility company. Moreover NEC is equal to the negative of the NEP and the aim of the optimum BO&C strategy is to minimize NEC or maximize NEP respectively.

In both scenarios the generation curve acts as a baseline and the consumption curve is adapted by proper control decisions to minimize or maximize an appropriate metric which may be the respective shaded areas for the two scenarios described above. Obviously in the two scenarios the different metrics used to evaluate performance, imply that the optimal decisions are different, and consequently the optimal consumption curves will be different.

Addressing in an efficient manner the generation–consumption matching problem (or, equivalently, the problem of optimizing NEP, NEC or NER) is not a trivial issue. Certain advances beyond the state-of-the-art both with regards to control and optimization systems for BO&C systems for large-scale systems in general, are required to achieve an efficient and practicable solution to this problem. Moreover, clearly defined and straightforward methods to calculate evaluation criteria are required for assessing the efficiency of different BO&C methodologies that are currently under development or will be developed in the future.

4.1. Performance Indicators of BO&C systems for NZEBs

A set of clear and straightforward performance indicators to calculate and assess targeted measurable objectives and quantifiable operations goals should be defined in order to evaluate the efficiency and applicability of BO&C systems for NZEBs. These objectives and goals – which should be calculated based, mainly, on real-life data to be gathered from NZEBs – are described next. It has to be emphasized that setting as a goal that a NZEB produces a strictly positive or an averagely-positive NEP can be misleading since a positive NEP can be the result of simply installing a sufficiently large renewable-energy generation capacity and not of efficiently handling and harmonizing the generation–consumption balance. Other indices like the percentage of the total energy used in the building generated from renewable sources can also be defined, but this definition fails to account for the transient, intermittent character of renewable energy availability, as well as the dynamic behavior of a PEB/NZEB system. The indices defined below can be used to assess energy performance, thermal comfort, and cost efficiency.

4.1.1. The Generation–Consumption Effectiveness Index

In reality there is never a symmetric pricing structure with the utility companies as they usually purchase energy in wholesale and sell in retail. In such a situation a relevant metric would probably be the Net Expected Benefit (NEB) which is the generation–consumption mismatch weighted appropriately by the buy or sell prices offered, and equals the expected monetary gain. A number of comments are in place:

- Maximization of the NEB is not equivalent to maximization of the NEP, the first being the target set by the building operator (essentially to minimize operational costs or, equivalently, maximize return on the energy-efficiency measures investment), while maximization of the NEP is the most environmentally-friendly approach since it maximizes the energy produced from the building.
- The NEB-maximization policy is also a good policy in terms of environmental considerations since the two performance metrics defined above are in mathematical lingo "equivalent".
- Improved efficiencies from the use of BO&C-like systems imply faster returns on renewable-energy/energy-efficiency investments, making them more attractive and, helping attain global environmental targets.

In the case when no energy-generating components are installed, the baseline generation curve is at zero and the NEC, NEP, and NEB are all proportional to the area under the consumption curve, making their distinction no longer necessary. Proper decisions lower the consumption curve to reduce the area below or, synonymously, attain better energy efficiency.

In real-world applications, the irregular character of renewable-energy generation implies that when we are taking the decisions the shape of the generation curve is not known. It is therefore impossible to *a priori* compute the optimal decision strategy that would maximize the performance index. In reality, following any decision strategy (DS) we will obtain a NEB_{DS} which is smaller than the NEB_{OPTIMAL}. The building with the no-control strategy has a performance which we denote as $NEB_{\mathrm{NO\text{-}CONTROL}}$. User comfort and satisfaction is particularly important consideration and maintaining it within reasonable levels (e.g. as per CEN recommendations (CEN, 2006a,b)), is a constraint that has to be satisfied by all acceptable decision strategies. For a feasible decision strategy (like, for example, one obtained through the BO&C approach) the Generation–Consumption Effectiveness Index (GCEI), defined as follows:

$$\mathrm{GCEI_{DS}} = \frac{\mathrm{NEB_{DS}} - \mathrm{NEB_{NO\text{-}CONTROL}}}{\mathrm{NEB_{OPTIMAL}} - \mathrm{NEB_{NO\text{-}CONTROL}}}$$

is an index to measure the quality of the decision strategy compared to the optimal strategy. The GCEI takes values that are less or equal to 1: a value of the GCEI from 0 to 1, implies that the DS improves the NEB with respect to the no-control strategy, whereas a negative value means that the DS makes things worse. The GCEI is an index that can be used to objectively compare different decision strategies, for relevant metrics and allows quantifying the effectiveness of a decision strategy to perform generation–consumption matching. Based on the discussion above, this index is applicable for buildings with and without energy-generation elements.

The GCEI is not only of theoretical value but can be computed (or, at least, comprehensibly approximated) for different decision strategies, using the following procedure:

- For a preselected demonstration period, the no-control strategy and the (BO&C's) decision strategy are alternatively (e.g. every week) applied and sensor measurements, weather data, the generation curve (using, for example, smart metering) and the $NEB_{NO\text{-}CONTROL}$ and NEB_{DS} are recorded. If the demonstration period runs for a relatively long time, then we can make sure that we obtain $NEB_{NO\text{-}CONTROL}$ and NEB_{DS} at many different sets of comparable weather and occupancy conditions.
- The demonstration period is "replayed" at the simulation-level using the building thermal models (this step can be used to validate the thermal-models for the BO&C demonstration buildings).
- Once the models are validated, we can test (at the simulation level) for varying decision strategies. With the generation curve known, the proactive optimizer can then be used to *a posteriori* compute the optimal strategy and obtain the $NEB_{OPTIMAL}$.
- Once this known, we can easily compute the GCEI for various decision strategies. Please note however that there will be *a priori* no guarantee that the above-described no-control and BO&C system experiments will be performed under comparable weather and occupancy conditions (unless the experiments are performed over very long periods of time). As a result, there is always the possibility the above described procedure for calculating the GCEI to end up with a non-reliable approximation.

4.1.2. Indoor environmental quality and comfort

Energy efficiency cannot be implemented without taking into account the occupants' thermal and visual comfort as well as the indoor air quality. A successful energy management system for buildings, apart from reducing the energy demand, should be able:

- To maintain indoor environmental quality within limits as defined by international standards (EN 15251, 2007; ASHRAE 62, 2004; ASHRAE 55, 2004).
- To be flexible, i.e. to have the ability to satisfy the users' comfort requirements.
- To achieve a transient response towards the required set point overshoots and oscillations that can cause energy waste.

Regarding *thermal comfort*, the following control variables are used in real time optimization and control systems for buildings:

- Predicted Mean Vote (PMV) and Percentage of People Dissatisfied (PPD) based on ISO7730 standard (Moujalled et al., 2008; Dalamagkidis et al., 2007).
- Effective temperature based on ASHRAE standards (Moujalled et al., 2008).

For visual comfort, the most widely used control variable is the indoor illuminance (Guillemin and Molteni, 2002; Kolokotsa et al., 2005) while indoor air quality can be accessed via the CO_2 concentration index (Kolokotsa et al., 2005; Doukas et al., 2007; Dalamagkidis et al., 2007) or ventilation rate (Blondeau et al., 2002).

To ensure indoor environmental quality for all buildings, including NZEB/PEB, comfort objectives should be defined.

An example of indoor air quality performance indicators may be a vector called Comfort $\text{Index}_1(CI1)$ (see Table 2):

$$CI1 = [IAQ_{in}(t)\ TC_{in}(t)\ VC(t)];$$

which includes thermal comfort (TC), visual comfort (VC) and indoor air quality (IAQ) measured by specific sensors in the building. For all of these values, minimum and maximum allowable values should be defined in cooperation with the buildings' operators and end-users following e.g. CEN's standard EN 15251 (CEN, 2006a). The index *CI1* takes the value "Pass" when the respective sensor measurements do not violate any of the requirements enforced by the standards throughout PEB/NZEB operational period except for the time-intervals where buildings are not occupied.

The communication of the users' preferences to the overall energy management system is of a major importance. Using user web interfaces the occupants can communicate their comfort preferences to the system (Kolokotsa et al., 2005). The occupants' preferences should be recorded on a daily basis via for example electronic datasheets available on the building's intranet. The end-users will be asked to rate their subjective feeling of e.g. thermal comfort on a 7-point scale (−3: too cold ... 0: satisfactory ... 3: too warm) and if the average value of responses is between −1 and 1, then the index *CI2*, takes the value "Pass" (Table 2).

4.1.3. Cost efficiency

Regarding cost efficiency a series of performance indicators are included in the literature for both low energy as well as zero-energy dwellings (Parker, 2009; Kolokotsa et al., 2009b) including direct costs and initial investment

Table 2
Performance indicators NZEB/PEB-BO&C.

Performance indicator	Description
GCEI	The Generation–Consumption Effectiveness Index (GCEI) is an objective and quantitative indicator to compare the effect different decision strategies have on system performance. To measure system performance a relevant metric is selected like, for example, the Net Expected Benefit, which is a monetary equivalent on the effects of a particular decision strategy. The BO&C system takes decisions with the goal of maximizing the selected metric and, as would be expected, different metrics can yield different decisions. For the computation of the GCEI index the "no-control" case can used as the base, and is effectively the decision-strategies used before the implementation of a decision-system like BO&C. Since the renewable-energy generation pattern is not *a priori* known, it is hard for a system to take optimal decisions. The optimal decision strategy can be computed *a posteriori* for the calculation of the GCEI. The GCEI takes values less than one, and for a particular decision strategy a value of 0.8 (80%) indicates that we are getting a performance improvement (as measured in the selected metric) that is 80% of the performance that would be obtained had we taken all the correct decisions
CI1	Thermal comfort objectives that are related to quantities measured directly from the installed sensors. These quantities include temperature, humidity, illuminance and CO2 levels. For all of these quantities, minimum and maximum allowable values should be defined in cooperation with the buildings' operators and end-users following, e.g. CEN's standard EN 15251 (CEN, 2006a). This standard specifies how design criteria can be established and used for dimensioning of systems and how to establish and define the main parameters to be used as input for building energy calculation and long term evaluation of the indoor environment. The index CI1 takes the value "Pass" when the respective sensor measurements do not violate any of these minimum and maximum values throughout the overall demonstration period (except for the time-intervals where buildings are not occupied)
CI2	Using user interfaces the end-users can communicate their thermal comfort preferences to the system. The answers should be recorded on a daily basis via electronic questionnaires available on the building's intranet. The end-users will be asked to rate their subjective feeling of e.g. thermal comfort on a 7-point scale (−3: too cold ... 0: satisfactory ... 3: too warm) and if the average value of responses is between −1 and 1, then the index CI2, takes the value "Pass"
PP:	BO&C Payback Period: The period required to amortize BO&C implementation and operational costs (for all energy-generation elements, sensors, control devices) from cost-savings due to reduced energy consumption

costs, annual ongoing charges, Net Present Value (NPV), Internal Rate of Return (IRR), Life Cycle Cost, etc. The role of Payback Period (PP) in the cost efficiency is tabulated in Table 2.

4.2. State of the art of BO&C methodologies for NZEBs

A large variety of BO&C methodologies, systems and designs have been developed, deployed and evaluated the last decades towards providing energy efficient building operations; these BO&C systems cover a wide range of different buildings designs and uses as well as a variety of automatically and manually-control energy-influencing elements and components (e.g. HVAC, ventilation and shading, fan cooling, floor heating, etc.). The vast majority of these systems employ specific optimization & control strategies: based on current – or, in the best case, short-term future predictions (Kolokotsa et al., 2009a) of – in-building and external weather conditions, they modify the settings of energy-influencing elements in an attempt to minimize the current total energy consumed in the building. The majority of existing BO&C systems suffers from three additional drawbacks:

- In their large majority they are based on either heuristic or data-driven approaches (see e.g. Holter and Streicher, 2003; Kafetzis et al. 2006; Kolokotsa et al., 2002; Rieberer et al. 2007; Armstrong et al. 2006; Braun et al., 2001; Bruant et al., 2001; Clarke, 2001; Clarke and Kelly, 2001; Conceição et al., 2009; Curtiss et al., 1994; Donaisky et al. 2007; Doukas et al., 2007; Dounis et al., 1996; Gouda et al., 2006; Mahdavi, 2001; Raja et al. 2001). This is largely due to the fact that the – alternative, more theoretically sound – model-based approaches typically require accurate knowledge/prediction of the building's dynamical model and implementation of "computationally expensive" control and optimization systems.
- The vast majority of BO&C methodologies concentrate on single-mode BO&C (e.g. of HVAC without taking into account self-power-generation components, fan cooling, natural ventilation, etc.).

No matter whether they are employing heuristic, data-driven, model-based approaches (Diakaki et al., 2008; Braun, 1990; Freire et al., 2008; Henze et al., 2004; Keeney and Braun, 1996; Kummert et al. 2000; Lee and Braun, 2008; Mahdavi and Pröglhöf, 2008; Spindler and Norford, 2009a,b; Xu et al., 2009), or they are used for single- or multi-mode BO&C (Kolokotsa et al., 2005; LeBreux et al. 2009; Spindler and Norford, 2009a,b), all existing BO&C systems and methodologies require a tedious and sometimes prolonged calibration (fine-tuning) procedure after the initial deployment of the BO&C system (see e.g. Dalamagkidis et al., 2007; Kolokotsa et al., 2002, 2001; Bruant et al., 2001; Curtiss et al., 1994; Dounis and Caraiscos, 2009; Gouda et al., 2006; Kalogirou, 2000; Kreider et al., 1992; Wright et al., 2002). Such a calibration procedure, which is typically performed by experienced engineers—apart from being cost- and time-consuming—provides no guarantee that the system will reach an efficient performance after the completion of the fine-tuning. There are several reported cases, where even after a prolonged calibration procedure, the overall BO&C system failed to produce significant energy savings as compared to the no-control case (see e.g. Bi et al., 2000; Li et al., 2005 and the references therein). Most importantly, the dependence of the BO&C system performance on seasonal variations and the human factor (occupants' behavior) renders the overall calibration procedure pretty much useless, unless it is performed on an everyday basis: typically, after the completion of the calibration procedure, the BO&C system performance deteriorates as a result of the weather seasonal variations, changes in the occupants' influence to BO&C system performance (due to e.g. the number of occupants has increased or decreased as compared to the one during calibration, etc.) as well as—even small—modifications in the building infrastructure. Attempts that have been made to incorporate adaptive, neural or other intelligent techniques (Dalamagkidis et al., 2007; Kolokotsa et al., 2002; Kolokotsa et al., 2001; Bruant et al., 2001; Curtiss et al., 1994; Doukas et al. 2007; Dounis et al., 1996; Dounis and Caraiscos, 2009; Kalogirou, 2000; Kreider et al., 1992; Krarti, 2003) within the BO&C system to automatically calibrate it and adaptively respond to weather, human-behavior, etc., variations have not succeeded so far to provide with significant improvements of BO&C system performance as compared to conventional BO&C systems: adaptive, neural network, fuzzy systems, etc., are known to suffer from very poor transient performance, in case of abrupt changes in e.g. weather conditions or human-behavior. This is due to the so-called "loss-of-controllability" problem that is inherent in all these approaches, which can be roughly described as follows: whenever there are abrupt changes in the building dynamics then adaptive, neural, etc. techniques need to directly or indirectly come up with a new estimate of the building dynamics. However, there is no guarantee that that this "new" estimate is controllable (although the actual building dynamics are controllable). If the process of constructing the new estimate of the building dynamics is non-controllable then the resulted BO&C scheme is non-efficient or, even, unstable—in which case, such a process has to be repeated until a controllable estimate is produced. While the procedure of repeatedly constructing estimates until a controllable estimate is produced, the BO&C decisions (which they will have to rely on uncontrollable estimates of the building dynamics) may lead to a very poor performance over long periods of time (sometimes days). The interested reader is referred to Ioannou and Sun (1995) and Kosmatopoulos (2010) for more details on the issue of "loss-of-controllability". In contrast to existing BO&C systems, efficient NZEB BO&C systems should be able to address a significantly more complicated and hard-to-attain objective than just myopically minimizing the current energy consumed within the building: based on long-term (e.g. >10 h) weather and human-relating predictions, efficient NZEBs' BO&C systems should be able to optimally schedule the operation of all available energy-generation and energy-consumption elements over a long period of time (typically >10 h) in order to neglect the building's energy requirements from external (non-renewable) sources and, most importantly, optimize the building's NEP (or NEB). Such an optimal scheduling requires that the operation of all available energy-generation and automatically- and manually-controlled building elements is intelligently combined so that not only energy consumption is minimized but, most importantly that energy is stored" within the building for immediate future use.

For instance, efficient NZEB BO&C systems may decide to operate their HVAC systems, even when the occupants are not present or the current in-building conditions do not require HVAC operation, in order to take advantage of the energy surplus that is currently available (and may not be available later, when demand reaches its maximum) either at the building renewable generation elements or other renewable sources available to the building through the grid.

The decision on the utilization of the energy surplus, available through energy-generating elements like renewable-energy sources, depends on a plethora of exogenous and endogenous parameters. If there are any notions of optimality in the building operation – and (near-) optimal energy utilization is a prerequisite for achieving the net-zero building ideal – decisions taken by the operators or the BMS should strive for maximization of the Net Expected Benefit. In a pricing policy where the selling price is higher than the buying-off-the-grid price then the optimal strategy is always to sell to the grid and buy back any energy needed at the lower prices – in such cases, the decision problem degenerates to the (comparatively easier) case of achieving the best possible energy efficiency. A limiting but quite interesting from the decision point of view, is the symmetric pricing structure (where the buy price equals the sell price) in which case the building operator (operating system) should try to minimize overall energy consumption – covering as much as possible of the energy requirements from the renewables and selling the excessive surplus only to be bought later if, and when, the need arises. A concomitant effect to such pricing policies is that operator strives to minimize energy requirements for the building operation achieving obvious environmental benefits (reduced energy intensity, CO_2 emissions, etc.). The ultimately more interesting case – and, in the future, the more realistic from a practical perspective – is the case where the buy price is lower than the sell price. In such cases, it might be beneficial to use the excess energy even though it might not be needed (based on building energy-requirements forecasting models) and even "controlled storage" of the energy (e.g. using the building's thermal mass) for later use. In all cases, the availability of automatic decision systems is relevant and especially, for the "harder," last case a necessity. More to this, demand- and peak-shaping requirements from the grid operators, enforced using a dynamic pricing structure, strengthens the conviction that such decision systems will be even more relevant and play a prominent role in the not so distant future.

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Apparently, the intelligent combination of all available energy-generation, automatically- and manually-controlled building elements cannot be achieved if simple heuristic or data-driven BO&C strategies are employed. The complex interplay of all these elements with the building's dynamical behavior, and its complex dependence on weather and other environmental variations and the occupants' behavior call for the development and deployment of BO&C systems that take into account all these interactions and dependencies, accurately predict the overall NZEB performance subject to different control and human actions and—based on these predictions—compute the optimal control actions each time. In other words, model-based BO&C systems, i.e. systems that compute their control and optimization decisions based on efficient and accurate NZEB models are required in order to obtain efficient and nearly-optimal operation of NZEBs.

Unfortunately, model-based optimization and control systems for complex, highly-varying systems such as NZEBs – which, moreover, involve the use of many different control elements – face the so-called curse-of-dimensionality problem that renders them practically infeasible even for small-scale NZEB implementations: model-based BO&C systems require searching over the space of all possible optimization & control actions which cannot be practically accomplished in real-time even for NZEBs involving a small number of energy-generating and controlled elements. The curse-of-dimensionality problem in combination with the fact that the efficiency of model-based optimization & control systems crucially depends on the accuracy of NZEB models and weather forecasts, renders the use of model-based BO&C systems not only practically infeasible but also non-robust: the inevitable inaccuracy on NZEB models and weather forecast, may lead model-based BO&C systems to quite poor performance that may not only be far from its optimal level, but also not significantly better than the no-control case.

Addressing in an efficient manner the generation–consumption matching problem (or, equivalently, the problem of optimizing NEP and NEB) is not a trivial issue. Certain advances beyond the state-of-the-art both with regards to control and optimization systems for buildings and control and optimization systems for large-scale systems in general, are required to achieve an efficient and practicable solution to this problem. Moreover, clearly defined and straightforward to calculate evaluation criteria are required for assessing the efficiency of different BO&C methodologies that are currently under development or will be developed in the future.

Proactive BO&C systems are required that are capable of efficiently harmonizing generation–consumption elements by (a) performing multi-mode optimization and control of all energy-influencing elements, (b) optimally scheduling NZEB operations in long-term (e.g. by "storing" heat or cold for future "use" when self-generating energy surplus is available) and (c) interacting and communicating with the operators and the end-users to guarantee user comfort, satisfaction and safety.

Fully-automated, efficient BO&C system calibration approaches are needed which guarantee rapid optimization of the system operations.

Based on the concise analysis presented above, a prerequisite for the deployment of efficient NZEB BO&C systems is the development of a new BO&C methodology that meets the following two objectives:

- On the one hand, it is model-based, i.e. involves and it is based on accurate models of the overall NZEB operations but, on the other hand, it is computationally efficient and scalable, i.e. it is applicable to NZEBs of arbitrary size and scale containing a large number and variety of energy-influencing control and optimization elements.
- It is able to efficiently and robustly take care of the inaccuracies involved in the NZEB models and, most importantly, to robustly and rapidly optimize the overall NZEB system performance whenever changes – due to e.g. weather changes or changes in the user behavior patterns – affect its operations. In other words, an automated and adaptive system is required which will continuously – and efficiently – optimize the performance of the BO&C system in order to compensate for the inevitable inaccuracies of the NZEB models and forecasts and their deterioration due to medium- and long-term weather variations and changes in the user behavior patterns, NZEB infrastructure, etc.

The fully-automated adaptive fine-tuning methodology of Kosmatopoulos (2009) and Kosmatopoulos and Kouvelas (2009) can be used towards such a purpose. The functioning of such methodology – as applied to fine-tuning of BO&C systems for NZEBs – may be summarized as follows:

(a) At the end of each day, the automated fine-tuning methodology receives the value of the real (measured) performance indices (e.g. daily NEP as well as daily aggregated user-comfort) as well as the values of the most significant external factors (e.g. power generation and demand, weather conditions, user constraints and requirements).
(b) Using the measured quantities, it calculates new tunable parameter values of the BO&C system to be applied at the next day in an attempt to improve the system performance while maintaining user-comfort as well as meeting the user-imposed constraints and requirements.
(c) This (iterative) procedure is continued over many days until a maximum in performance is reached; then, the on-line fine-tuning procedure remains active for continuous adaptation in order to account for the medium and long-term changes in weather conditions and occupants' behavior.

It is worth noticing that the above-mentioned adaptive fine-tuning methodology will be implemented and evaluated in real-life in three large-scale NZEBs (two in Germany and one in Greece) as part of the European Commission funded project PEBBLE (Rovas et al., 2010).

We close this section by noticing that BO&C systems that meet the above-mentioned objectives will have a very significant impact if deployed in non-NZEB buildings as scenario 1 of Fig. 4 illustrates (see beginning of Section 4).

5. Conclusion and future prospects

Based on the above analysis, to address future PEB/NZEB objectives, a number of advances beyond the state of the art are required.

Thermal simulation models that incorporate all components of a building, and capable of efficiently and accurately predicting the dynamic response of the system are essential for the effective implementation of control strategies, decision on sensor and actuator placement, as well as, identification of energy-efficiency measures. In the effort of realizing increased efficiencies and improved operational performance in general—as required for operation in net-zero energy realm—the availability of such models will be crucial. Especially for models that are integrated for the development of control systems efficient response, accuracy and especially the trade-off between the two has to be carefully investigated. In future NZEB/PEB the need for both accuracy and efficiency (for real-time response of the BO&C system) suggest that further modeling simplifications might be required (e.g. in usage of a simplified model for the calculation of the shape factors in radiation calculations). Each such simplification requires extensive testing and validation with respect to the real building.

In terms of buildings' infrastructure the potential easiness to install sensors and monitoring equipment presents an opportunity to further improve the existing thermal models. The presence of human detection and comfort sensors that communicate thermal comfort preferences via appropriately constructed interfaces along with sensors that record physical parameters and models that can compute comfort indices provide also an opportunity for improvement of thermal comfort models. Moreover the monitoring evolution will allow the integration of weather forecasting models to be used in the simulation which is especially important for PEB/NZEB buildings, since to a large extend weather variations can affect the availability of energy generation via renewable-energy sources.

The understanding that control decisions are important with regards to energy efficiency has led to a significant number of efforts (see references for a number of research papers in the area). An important aspect of BO&C for NZEB/PEB will be the model-based predictive control. When physical models are utilized, the expert has the opportunity to understand the cause-and-effect relationship between the various building components, the control strategies and the climatic conditions.

Therefore in the road towards NZEB/PEB, intelligent predictive control schemes based on just enough accurate models and supported by easy to install and commission monitoring and networking schemes are useful in order to perform the necessary generation–consumption matching under real time dynamic conditions.

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