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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

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Abbreviations: AC, Air conditioning; BIPV, Building Integrated Photo-Voltaic; 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