Energy and Buildings 83 (2014) 140–148

Contents lists available at ScienceDirect

Energy and Buildings

journal homepage: www.elsevier.com/locate/enbuild

Proposal of a nearly zero energy building electrical power generator with an optimal temporary generation–consumption correlation

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ARTICLE INFO

Article history:
Available online 2 May 2014

Keywords:
Energy correlation
nZEB
Photovoltaic System
Self-sufficient PV system
SMLsystem
Solar Decathlon Europe 2012
ZEB

ABSTRACT

This study presents an electrical photovoltaic (PV) power generator system, which was designed, built, and tested during the Solar Decathlon Europe 2012 competition as part of the SMLsystem, i.e., the CEU Cardenal Herrera University prototype. One of the main aims of the contest was to evaluate the prototype's electrical energy balance capacity in terms of self-sufficiency, low energy consumption, and the temporary generation–consumption correlation demand. The design and evaluation were determined according to the competition rules and a framework was built for a type of nearly zero energy building (nZEB), where the specific criteria required that all the necessary energy was obtained from the sun. Various aspects were considered in the design of the PV system, including the energy demand and disposability, possibility of grid connection, power installation, appropriate battery capacity, electrical PV system configuration (AC coupling and/or DC coupling), and the temporary generation–consumption correlation demand. To achieve an optimal energy balance, the electrical PV power generator system design strategy focused on the energy correlation analysis behavior and the efficient management of the energy system, while maintaining the main load of the nZEB at a sufficiently low level using a timed controller.

1. Introduction

The republication of European Directive 2010/31/EU on May 19, 2010 [1] defines a nearly zero energy building (nZEB) as a building with a very high energy performance, which utilizes almost zero or a very low amount of energy that is derived mainly from renewable sources, including energy from renewable sources produced on-site or nearby.

The use of on-site or nearby energy resources is known as energy self-consumption. The term *on-site energy* is easy to understand because the energy is produced in the same building where it is produced. In addition, *nearby energy* is an extended term for the same concept, which implies higher control of the energy flow. Thus, the electrical power grid concept called Smart Grid [2] has to be employed for energy management.

In the medium term, the use of a small-scale Smart Grid as a neighborhood energy exchange system maximizes the local photovoltaic (PV) energy consumption [3] and minimizes the energy losses due to energy storage conversion. This situation can be facilitated by demand-side management (DSM), which is defined by the European Commission as a tool that affects the global energy market and the security of the energy supply in the medium and long term.

DSM has many benefits, such as reducing the generation margin capacity and improving the transmission grid investment and operational efficiency, but further challenges need to be addressed, including advanced metering and control technologies due to the lack of an ICT infrastructure, the use of real-time information, the higher complexity of operating the system, and the lack of understanding of the benefits and the difficulty of evaluating them, as shown by Strbac [4].

In the present study, we present an electrical PV power generator system, which was designed and implemented by participants from the Department of Building Engineering and Industrial Production of the University CEU Cardenal Herrera at the Solar Decathlon Europe 2012 (SDE12), as part of the SMLsystem project. This generator was designed according to the contest rules, but it also complied with European laws so it can be applied to real buildings in the future.

1.1. Competition and rules framework

The Solar Decathlon Europe (SDE) is an international competition where universities from all over the world meet to design,

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http://dx.doi.org/10.1016/j.enbuild.2014.03.083
0378-7788/

build, and operate an energetically self-sufficient house, which is grid-connected, using solar energy as the only energy source and it is equipped with numerous technologies that facilitate maximum energy efficiency.

During the final phase of the competition, the teams assembled their houses in Madrid and during September 2012 they participated in 10 different challenges related to renewable energy use and savings. The SDE organization specified the framework rules for the competition, which comprised the prototype evaluation criteria and the procedures for juries. The houses presented by the teams were monitored constantly and information related to the behavior of the houses was assessed and made openly available.

The winner of SDE12 was named after the evaluations of the 10 contests or challenges, which received different scores, as follows.

1. Architecture
2. Engineering and construction
3. Energy efficiency
4. Electrical energy balance
5. Comfort conditions
6. Functioning of the house
7. Communication and raising social awareness
8. Industrialization and market viability
9. Innovation
10. Sustainability

1.2. Electrical energy balance contest

Contest 4 had special significance for the present study. *Electrical energy balance* is one of the main objectives of the SDE, which aims to *"promote research in the development of efficient houses. [. . .]. Particular emphasis is put on reducing energy consumption and on obtaining* ***all the necessary energy from the sun****."* [5]

Thus, the objective was to evaluate the electrical energy self-sufficiency of the houses, which was provided by solar active technology, and the intensity of their electricity usage.

The energy production and energy consumption by each house were measured. The main aim was to evaluate three different concepts that comprised the idea of a self-sufficient house, as follows.

1. Autonomy
2. Temporary generation–consumption correlation
3. Consumption per measurable area

1.2.1. Autonomy

This sub-contest evaluated the self-supply of a house during the weeks of the competition.

$$E_{G-yearly} - E_{L-yearly} \geq 0 \quad (1)$$

$$E_G - E_L \geq 10kWh \quad (2)$$

For a positive annual electrical energy balance, a house had to satisfy Eq. (1), where $E_{G-yearly}$ represents the energy generated throughout a whole year and $E_{L-yearly}$ represents the consumption of the loads throughout a whole year.

During the competition, it was impossible to determine the yearly production and consumption, but Eq. (2) yielded a value of 10 kWh, which was considered sufficient in September (equivalent to the yearly electrical energy balance).

However, if the house did not exceed 10 kWh, it could achieve a reduced point between $-10\,\text{kWh} \leq E_G - E_L < 10\,\text{kWh}$.

The measurement period was determined as the free shadow period (generation frame), i.e., between 1000 h and 1700 h. The PV system had to be disconnected outside this generation period.

1.2.2. Temporary generation–consumption correlation

One of the main advantages of distributed electrical generation is that electricity is consumed in the same place where it is generated. This reduces the need for transmission lines and minimizes the losses that occur during electricity transport. The benefit is maximized if the electricity is consumed at the same time as it is generated (this concept is discussed in more detail in Section 2).

To evaluate the score in this sub-contest, Eq. (5) yields the score as a function of ξ, which is the correlation between the generated energy and the energy consumed simultaneously by the loads.

This score depended on whether batteries were available (Eq. (4)) or not (Eq. (3)). The value of ξ was integrated continuously during the measurement period of the competition, which was a longer period than the generation period. The value of ξ ranged between [0, 1].

$$\xi = \frac{\int E_{G-L}}{\int E_L} \quad (3)$$

$$\xi = \frac{\int (E_{G-L} + E_{Bat-L})}{\int E_L} \quad (4)$$

$$Points = \xi \cdot Points_{total-contest} \quad (5)$$

For the *autonomy* sub-contest, there was a measurement frame for the *correlation* sub-contest, where the measures were obtained between 800 h and 2300 h.

1.2.3. Consumption per measurable area

To reduce the CO_2 emissions and the external energy dependency of the countries, it is important to have a high level of renewable energy production to facilitate efficient energy consumption, as follows:

$$\frac{E_{L-average}}{A} \quad (6)$$

where $E_{L-average}$ is the average energy consumed by the daily loads during the weeks of the contest, i.e., a lower value resulted in a higher score.

1.3. SMLsystem: SDE 2012 prototype

The *SMLsystem* project (Fig. 1) is an ongoing research project, which was initiated by the *SMLhouse* (small, medium, and large) in the SDE 2010. The *SMLsystem* employs prefabrication as an architectural concept, where structural, composition, and functional values are introduced in a sustainable building approach. The *unit* or basic *module*, which is treated as a box, is formed completely from prefabricated materials and dry-assembled, where wood is the main material in the *SMLsystem* prototype. Each of these *units* is transported fully assembled.

A courtyard acts as a composition element. All of the construction *units* had a courtyard equipped with a louver, which divided the space and provided a special form of access to the house. It also provided natural lighting and ventilation control as part of a high value space. The effectiveness of the courtyard was increased by the use of horizontal and vertical louvers, which reduced excess radiation at specific times of the day, while they could also be adjusted to provide more privacy.

Reducing the demand for energy is the main objective of the *SMLsystem* as a nZEB [1], as well as the efficient management of the renewable energy produced on-site. Thus, passive systems were incorporated into the design, thereby minimizing the need for and the dependency on active systems for cooling and heating houses. In addition, efficient active systems optimized the use of energy and reduced the demand. In the HVAC system, a heat pump was combined with phase change materials as a thermal