Journal of Building Engineering 16 (2018) 57–71

Contents lists available at ScienceDirect

Journal of Building Engineering

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

Multi-objective optimization methodology for net zero energy buildings

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ARTICLE INFO

Keywords:
Net zero energy building
Optimization
Decision making
Climate
Passive measures
Life cycle cost
Renewable energy systems

ABSTRACT

The challenge in Net Zero Energy Building (NZEB) design is to find the best combination of design strategies that will face the energy performance problems of a particular building. This paper presents a methodology for the simulation-based multi-criteria optimization of NZEBs. Its main features include four steps: building simulation, optimization process, multi-criteria decision making (MCDM) and testing solution's robustness. The methodology is applied to investigate the cost-effectiveness potential for optimizing the design of NZEBs in different case studies taken as diverse climatic zones in Lebanon and France. The investigated design parameters include: external walls and roof insulation thickness, windows glazing type, cooling and heating set points, and window to wall ratio. Furthermore, the inspected RE systems include: solar domestic hot water (SDHW) and photovoltaic (PV) array. The proposed methodology is a useful tool to enhance NZEBs design and to facilitate decision making in early phases of building design. Specifically, the non-dominated sorting genetic algorithm (NSGA-II) is chosen in order to minimize thermal, electrical demands and life cycle cost (LCC) while reaching the net zero energy balance; thus getting the Pareto-front. A ranking decision making technique Elimination and Choice Expressing the Reality (ELECTRE III) is applied to the Pareto-front so as to obtain one optimal solution.

1. Introduction

Economic growth and social development nowadays push governments to focus on providing population with necessary energy requirements. Concerns about energy security arise from increasing energy demand, rising oil prices, and doubts from oil and fossil fuel depletion. Currently, the concept of energy security includes challenges to provide secure, unabated, reasonably priced, and sustainable energy sources for electricity supplies and other energetic applications. While taking into consideration reducing greenhouse gases emissions and exploiting renewable energy resources.

Globally, buildings' energy demand is estimated to keep increasing in the next decades. Buildings (residential, commercial and public) have consumed around 30.6% of worlds' total primary energy supply (TPES) in 2014. The residential sector represents approximately 66.5% of TPES final consumption in buildings, and is ranked as the third-largest main energy consumer in the world (22.7% of world TPES) after industrial and transportation sectors [1]. If no action is taken to develop energy efficiency in buildings' sector, energy demand is expected to augment by 50% in 2050 [2]. By the end of 2014, buildings represented about 49% of the world's electricity consumption, where the residential sector accounts for 27% of the total electrical use, and is ranked as the second-largest electricity consumer in the world [1].

Nowadays, a new approach is suggested to limit energy consumption and pollution emissions in buildings (since buildings have a real potential to ameliorate energy efficiency), Net Zero Energy Building (NZEB). Many researches in the world are trying to find a particular definition for NZEB in order to facilitate their application, by easily specifying and finding their target. There is no common definition. Each one defines NZEB depending on his/her needs, interests, and goals to achieve. The adopted definition in this study is the following: a Zero Energy Building (ZEB) is a building with significantly low energy demands and the balance of energy needs can be supplied by renewable energy (RE) systems. A NZEB is a ZEB connected to the utility grid (electricity grid, district hot water, or other central energy distribution system) to offset its energy needs. NZEBs might employ utility's energy when the on-site RE generation doesn't meet its needs. However, it has to return back to the grid the equivalent of the energy drawn as a RE form in a yearly basis, in order to maintain the zero energy status of the building. Once the on-site energy production surpasses the building's needs, the surplus energy is exported to the utility grid, or stored in the building for later use during non-favorable weather conditions [3,4].

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https://doi.org/10.1016/j.jobe.2017.12.003
Received 10 August 2017; Received in revised form 28 October 2017; Accepted 9 December 2017

Nomenclature

AC	Alternating current
AHP	Analytical Hierarchy Process
CI	Consistency index
COP	Coefficient of performance
DC	Direct current
DM	Decision maker
EP	Expanded polystyrene
ELECTRE	Elimination and Choice Expressing the Reality
LC	Life cycle cost
MOO	Multi-objective optimization
MCDM	Multi-criterion decision-making
NSGA-II	Non-dominated sorting genetic algorithm
NZEB	Net Zero Energy Building
PV	Photovoltaic
PMV	Predicted mean vote
RC	Reinforced concrete
RE	Renewable energy
SPF	Spray Polyurethane Foam
SDHW	Solar domestic hot water
T_w	Temperature of water supply, °C
Ta	Monthly mean air temperature, °C
TPES	Total primary energy supply,
TCF	Temperature correction factor
UNDP	United Nations Development Program
WSM	Weighted sum method
WPM	Weighted product method
WWR	Window to wall ratio
ZEB	Zero Energy Building

Innovative concepts, reviews, calculation methodologies and feasibility of achieving NZEBs have been inspected deeply all over the world. Fig. 1 represents the essential elements in defining NZEB in this study according to Sartori et al. scheme [5].

Besides, building optimization is an effective technique to evaluate design choices (building envelop, internal set points conditions, energy efficient appliance and lights, and type and size of installed renewable systems) and to get the perfect solution for a specific intention (i.e. economy, environment, energy, or exergy) expressed as objective functions (minimize greenhouse gases emissions, minimize energy consumption, minimize capital cost, maximize energy and exergy efficiencies) under several constraints (thermal comfort, area availability, investment costs limits, thermal regulations in benchmarks) [6]. Multi-objective optimization (MOO) is the optimization of conflicting objective functions that require to be satisfied simultaneously [7]. MOO results are sets of non-dominated solutions called Pareto optimal solutions represented as a Pareto frontier [8,9]. The Pareto frontier is a curve in case of two dimensional problems (bi-objective optimization) and a surface in case of three dimensional problems. Each point of the Pareto frontier is a possible best solution. An extensive variety of researches are reported to evaluate the impact of optimization application on improving buildings zero energy performance, and the implementation and testing of recent MOO algorithms and techniques [10–57].

Once the Pareto frontier is obtained, here comes the importance of the multi-criterion decision-making (MCDM) process in order to select the final optimal solution among all available possibilities [10]. MCDM is a well-established research technique with a comprehensive combination of solution concepts and methodologies. It has been extensively used to evaluate sustainable energy solutions in buildings domain. Noting that the decision regarding the use of NZEB measures is complex, MCDM can efficiently review the problem in accordance with the significance of different criteria and the preferences of the decision maker (DM) (for an overview see, for example, [58–69]). MCDM approaches can be classified into [70–72]:

a) Aggregation methods: They are based on the principle that a disadvantage on a particular objective function might be compensated by outperforming with respect to another objective function, which creates a weakness in case of multi-dimensional MCDM problems. In addition, these methods masks the extreme non-comparable situations (actions with very strong differences, such that it is not reasonable to compare them). Among aggregation methods, there are:
   Weighted sum method (WSM)
   Weighted product method (WPM)
   Analytical Hierarchy Process (AHP)
b) Outranking methods: They are based on concordance and discordance tests. Among outranking methods, there are:
   Choice problematics, select the ideal variant from all feasible variants (e.g. ELECTRE I, ELECTRE Iv, and ELECTRE IS).
   Sorting problematics, assign variants to predefined real or fictive categories which serve as reference (e.g. ELECTRE TRI).
   Ranking problematics, rank variants from the best to the worst (e.g. ELECTRE II, ELECTRE III, ELECTRE IV, and PROMETHEE)
   Description problematics, understand the problem through actions, criteria and performances.

This paper presents a MCDM methodology for NZEB performance optimization. The aim of the proposed method is to get the best design solution from a set of Pareto-front solutions, a solution which reflects the DM preferences. The suggested simulation-based methodology is composed of four steps: building simulation, optimization, MCDM and finally a sensitivity study to test the robustness of the optimal result. Besides, it is applied to a prototypical residential NZEB in different climatic zones in Lebanon and France. First, the base case design conditions, RE systems, and simulation results are described. Then, a wide range of design and operating measures is optimized, including wall and roof insulation levels, windows glazing type, WWR in eastern and western facades, cooling and heating set points, photovoltaic (PV) and solar collector (SC) systems sizing. Besides, in order to obtain a unique solution, a MCDM technique is employed. Finally, a set of recommendations is outlined in order to improve the performance design of NZEBs.

2. Methodology

This section presents a methodology for NZEBs multi-objective optimization. The methodology consists of several sequential steps as presented in Fig. 2, and are described below.

2.1. Base case building simulation

The first step is to constitute the building to be optimized including

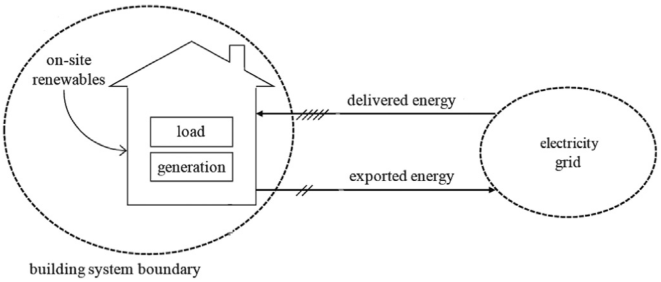

Fig. 1. Basic elements in definition of NZEB [5].