Energy and Buildings 127 (2016) 627–636

Contents lists available at ScienceDirect

Energy and Buildings

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

Genetic algorithm based optimization for photovoltaics integrated building envelope

Amr Mamdoh Ali Youssef [a,b], Zhiqiang John Zhai [a,*], Rabee Mohamed Reffat [b]

[a] Department of Civil, Environmental and Architectural Engineering (CEAE), University of Colorado, UCB 428, ECOT 441, Boulder, CO 80309, USA
[b] Department of Architectural Engineering, Assiut University, Assiut 71518, Egypt

ARTICLE INFO

Article history:
Received 22 April 2016
Accepted 6 June 2016
Available online 9 June 2016

Keywords:
Building integrated photovoltaics
Genetic algorithm
Building envelope
Energy consumption
Power generation

ABSTRACT

A growing attention has been paid to building integrated photovoltaics (BIPV) when designing net-zero-energy buildings. Envelope features of large commercial buildings can be properly designed to both enhance PV integration and reduce building energy use. Many studies have been focused on predicting PV performance of designed systems or optimizing building envelope properties to reduce energy consumption. This study introduces an optimization framework using genetic algorithm (GA) via the GenOpt program to determine the best options for building envelope designs to reduce net building energy cost and increase PV utilization capacity/efficiency. A set of envelope design features were tested in this study, such as, building dimensions, window-to-wall-ratio (WWR), orientation, and PV integration placement, upon which the associated PV and building energy cost are evaluated and compared. Cubic commercial buildings commonly found in Egypt were used to demonstrate the application of the proposed optimization process. The developed tool can help designers to determine the optimal envelopes with appropriate BIPV options from both energy and economic perspectives.

1. Introduction

Utilizing photovoltaic (PV) systems in electrifying buildings receives growing attentions in developing net-zero-energy buildings, especially in climate zones with rich solar resources. External façades of commercial buildings, in addition to the roof, are needed for the placement of PV, because roof-mounted PV cannot generate adequate power for single multi-story building demand. For instance, roof-mounted PV may generate 404 kWh/(m^2 yr) in hot climates under standard test conditions, while commercial buildings require 134 kWh/(m^2 yr) in this climate based on ASHRAE standard [1]; the roof thus can only supply three floors of electricity need. PV integration with external facades (rather than using supporting racks) is also appreciated by architects and users for enhanced architectural dynamics and esthetics.

High cost and low efficiency of PV modules are the main challenges in building integrated PV (BIPV) designs. The goal of this study is to explore how to determine the best combinations of envelope characteristics for better BIPV performance and the overall building energy performance. For example, changing the dimension ratios of a cubic building(as a feature) from 1:1:2 (width: length: height) to 1:2:1 with a fixed volume (e.g., 62,000 m^3) as well as other features can achieve 9.8% net energy saving in a hot climate zone (2A), predicted using eQuest [2]. This study proposes a framework of an optimization procedure – using genetic algorithm (GA) via the GenOpt program – that can determine the best options for various BIPV envelope features, using the energy net consumption and PV economic impact as two optimization criteria. Cubic commercial buildings in Egypt were used to demonstrate the developed optimization process.

Numerous studies were aiming to optimize building envelope features for better energy performance. Jin et al. [3] proposed an optimization algorithm to reach minimum building thermal load using "RHINO" tool. Tuhus-Dubrow and Krarti [4] developed an approach to selecting the optimal values among envelope parameters of residential buildings to minimize energy consumption. Znouda et al. [5] presented an optimization method to minimize thermal loads of Mediterranean buildings using pseudo-random. Ouarghi and Krarti [6] examined commercial building envelope shapes using GA and neural network to optimize energy and construction cost. Wang et al. [7] presented a multi-objective optimization model that assists in designing economic and environmental green buildings. Caldas and Norford [8] developed an optimization tool to determine building envelope properties that minimize HVAC, lighting energy and their costs.

* Corresponding author.
E-mail address: john.zhai@colorado.edu (Z.J. Zhai).

http://dx.doi.org/10.1016/j.enbuild.2016.06.018
0378-7788/

List of symbols

BIPV	Building integrated photovoltaics
SAM	System advisor model (a software tool)
eQUEST	The QUick energy simulation tool (a software tool)
WWR	Window-to-wall-ratio
GA	Genetic algorithm
GenOpt	Generic optimization program
So.i	*i* denotes to a solution number
So.i-i'	*i'* denotes to a developed case by applying a consecutive optimization on solution number *(i)*
Fa. n	*n* denotes to one of the model facades (as specified in Fig. 3)
L.1, L.2	The 2 lengths of the model edges (as specified in Fig. 3)
SA:V	Surface area to volume ratio

Few approaches and tools were developed to help in optimizing PV integrations. El-Arini et al. [9] proposed an optimization approach to maximizing the power of PV panels using GA with Lagrange multiplier algorithm, focusing on the PV technical variables (e.g., tilt angle, temperature and etc.).“RADIANCE”, a computational tool, optimizes urban geometric forms for receiving more solar irradiation [10]. Sui and Munemoto [11] developed a simulation program “GRIPVS” to optimize shapes of PV gable roofs towards lower CO_2 emission and higher investment value. Efforts to optimization envelope designs for combined focuses of reducing building energy consumption and increasing BIPV electricity generation were not found in the literature.

Youssef et al. [12] proposed an optimization method for BIPV envelope design with a focus on the best orientation (as a variable) for individual BIPV surfaces to maximize solar exposure using sensitive analyses. Building surfaces can then be varied towards those sensitive orientations to generate better alternatives in terms of the received solar exposure as shown in Fig. 1. This step is then followed by identifying the most matching PV modules for individual surfaces, upon which the PV power generation rate and the related economic impact are analyzed and compared. The study does not explore the detailed yet critical envelope variables such as dimensions, WWR, etc., which will largely increase the number of the variation cases to be studied. As a result, an optimization algorithm will be inevitable to find best combinations of the design options among numerous alternatives. This new study will also consider the net building energy performance (including both consumption and generation) as the evaluation criteria. The following sections detail the updated optimization framework, as well as its relation with the previous framework.

2. Proposed optimization framework

The proposed optimization framework consists of two essential steps as shown in Fig. 2, followed by an optional step of applying the previous optimization method.

2.1. Step 1: determining building envelope variables and options for generating possible solutions

An initial building design in a given location (for climate identification) is a starting point for the optimization. Designers can determine and fix any building envelope variables and their options that meet their design priorities/preferences, such as geometry dimensions, height, orientation, window-to-wall-ratio, potential PV integration placement locations, etc.; each variable contains different options that can be combined to create a comprehensive solution (with one option from each variable); each option has a different effect on PV integration performance and energy consumption. For instance, WWR can be varied among 9 options (10–90%) for each façade, and combining only these options in a simple cubic building can produce 6561 possible solutions (9^4) ($\text{options}^{\text{facades}}$) for evaluation. Evaluation criteria can be determined based on the design priorities, such as net energy consumption, PV generation cost, PV payback period, etc.

The step-1 achieves a numerical determination for the available variables, options and criteria for optimizing a given building envelope towards the best BIPV designs.

2.2. Step 2: applying GA algorithm to determine the best solutions and options of building envelope variables

An optimization algorithm is necessary to identify the best solutions among the generated vast number of potential solutions. GA was chosen as one of the best optimization algorithms for this application based on a detailed comparative analysis. Compared to other algorithms, GA uses a cycle of random exploration that leads to successive reproduction of global solutions, so it can avoid a local maximum or minimum if the population finds better values in other definition domain areas. Moreover, GA performs well in difficult types of functions, such as linear, non-linear, continuous, discontinuous functions and others, and it performs also with large ensembles, complex problems, and large number of probabilistic variables [13]. GA optimization starts with conducting a population of random individual solutions; each solution is a combination of

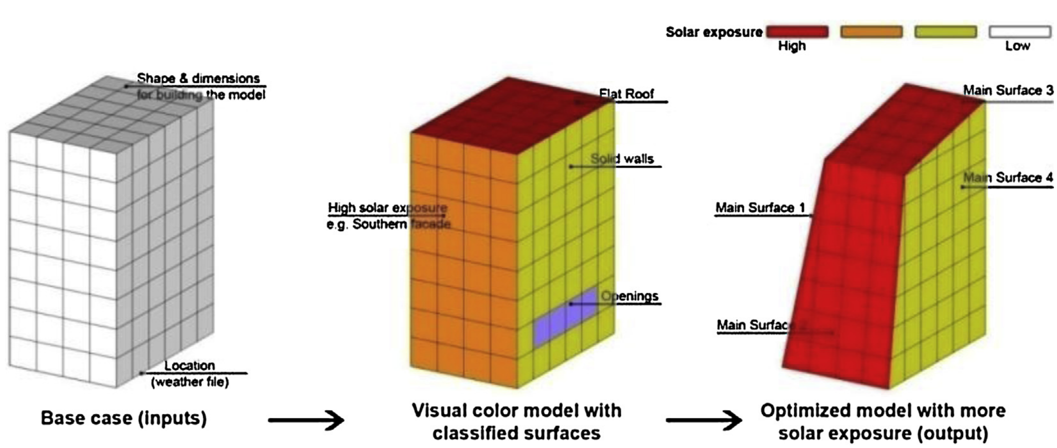

Fig. 1. An example of applying the best orientation variations based on the previous optimization method [12].