Applied Energy xxx (2016) xxx–xxx

Contents lists available at ScienceDirect

Applied Energy

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

Optimization of a residential district with special consideration on energy and water reliability

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HIGHLIGHTS

- A new optimization model for high sustainability standards in residential districts is proposed.
- The optimal capacity of hybrid renewables power system and water harvesting systems is pursued.
- The optimization minimizes the life cycle costs and maximize the reliability.
- The reliability of the hybrid renewables power system can vary between 40 and 95%.
- The maximum water harvesting system reliability varies between 30% and 100%.

ARTICLE INFO

Article history:
Received 26 March 2016
Received in revised form 16 September 2016
Accepted 1 October 2016
Available online xxxx

Keywords:
Optimization
Genetic algorithm
Renewable energy
Hybrid power systems
Water harvesting
Residential urban districts

ABSTRACT

Many cities around the world have reached a critical situation when it comes to energy and water supply, threatening the urban sustainable development. From an engineering and architecture perspective it is mandatory to design cities taking into account energy and water issues to achieve high living and sustainability standards. The aim of this paper is to develop an optimization model for the planning of residential urban districts with special consideration of renewables and water harvesting integration. The optimization model is multi-objective which uses a genetic algorithm to minimize the system life cycle costs, and maximize renewables and water harvesting reliability through dynamic simulations. The developed model can be used for spatial optimization design of new urban districts. It can also be employed for analyzing the performances of existing urban districts under an energy-water-economic viewpoint.

The optimization results show that the reliability of the hybrid renewables based power system can vary between 40 and 95% depending on the scenarios considered regarding the built environment area and on the cases concerning the overall electric load. The levelized cost of electricity vary between 0.096 and 0.212 $/kW h. The maximum water harvesting system reliability vary between 30% and 100% depending on the built environment area distribution. For reliabilities below 20% the levelized cost of water is kept below 1 $/m^3 making competitive with the network water tariff.

1. Introduction

According to the World Health Organization, more than half of the current world's population (53%) lives in urban areas [1], whereas the United Nations forecasts project that 6.3 billion people are going to live in cities by 2050 [2]. Thus, the sustainability of cities around the world is threatened by the growing demand for energy, water and food supplies. The urban water-energy-food nexus development requires an integrated design process that comprises not only policies but also technical solutions [3]. From an engineers and architects point of view, the above mentioned statistics put a lot of pressure on how to design our modern and future cities.

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http://dx.doi.org/10.1016/j.apenergy.2016.10.005
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The aim of this paper is to analyse the integration of renewable hybrid power systems and water harvesting technology into the urban environment as sustainable solutions for high urban water and energy self-sufficiency. In particular, this study aim at analyse the reliability of renewables and water harvester compared to electricity and water loads in a residential district.

Hybrid power systems have been studied thoroughly especially for off-grid applications. Ma et al. studied the optimal integration of solar, wind and hydro pumped storage systems for a few hundred kW microgrid in a remote island in Hong Kong [4]. The authors concluded that for an optimal design of a standalone hybrid power supply system, the combination of wind and solar energy is essential [5]. Using a particle swarm optimization algorithm, Shang et al. studied the optimal size of the battery capacity in solar/wind/diesel standalone hybrid power system for a tropical island near Singapore [6]. The authors focused in particular on optimal dispatch of the stand-alone system to minimize the operation costs and at the same time increase the penetration level of renewables. Gan et al. developed a software tool for sizing off-grid hybrid renewable energy systems using a location in Scotland as a case study [7]. The developed tool was intended to support project management in evaluating the batteries and diesel generator capacities based on the renewable available resources both for short and long term operation using a life cycle cost approach. Maleki and Pourfayaz studied the optimization of hybrid renewables based power system for a specific site in the South of Iran [8]. In particular the authors focused on the evaluation of different evolutionary algorithms for optimum sizing of a solar/wind/battery hybrid system to meet the load demand while minimizing the total annual cost and loss of power supply probability.

The integration of hybrid power systems into on-grid areas as distributed generation system has become a recent research topic for high energy performances buildings. González et al. studied the optimization of a grid-connected hybrid renewables based power system compared to a given electricity demand for case study in Catalonia [9]. Using particle swarm optimization, García-Triviño et al. studied the optimal power control of a grid-connected inverter supplied from a solar/wind hybrid power system equipped with battery and hydrogen storage systems [10].

Lu et al. presented a comprehensive review on the design and control approaches of the nearly/net zero energy building highlighting the lack of optimal design and control strategies [11]. Carlucci et al. presented a multi objective optimization model for the design of a detached net zero-energy house located in the South of Italy to minimize thermal and visual discomfort using uses the non-dominated sorting genetic algorithm [12]. The authors highlighted the importance of using complex optimization problems with many objective functions to assess the effects of a large number of available building variants. Lu et al. compared the optimal design of buildings using single objective and multi objective optimization using genetic algorithm for two case studies [13]. The authors concluded that optimization of buildings with renewable energy systems can lead to better performances than the benchmark building considered in their study. Moreover, the authors verified that single objective optimization can provide the best solution while multi objectives optimization can guide designers for better trade-off solutions. Using distributed energy system for meeting the energy demand, Lu et al. proposed a multi-objective optimization approach based on genetic algorithm for a net-zero exergy district in Hangzhou, China [14]. The optimization model was to minimize the e life cycle cost of the system and at the same time maximize the exergy efficiency including twelve energy supply systems to provide power and heat. The optimization model was based on the operation time of each energy supply technology.

Similarly, rainwater harvesting systems assessment and optimization have been conducted as technical solution to face the exacerbation of water issue in urban areas. Mehrabadia et al. assessed the residential rainwater harvesting efficiency to meet non-drinkable water demands in three different Iranain cities marked out by different climate conditions (Mediterranean, humid and arid climate) [15]. The study concluded that the tank capacity is a key factor to consider for maximizing rainwater storage, the optimal water tank is strictly dependent on precipitation amount and roof area, and rainwater harvesting efficiency is dependent on climate. Hashim et al. focused on simulations and optimization of large scale rainwater harvesting [16] describing a new designing technique. The optimization model was based on the minimization of the total system costs including supplemental cost for the utility water to meet the water demand. The conducted simulations showed that roof area and water demand are the main key factors affecting the storage tank size. Chiu et al. proposed an optimization approach for rainwater harvesting systems with special consideration of energy-saving approach for hilly communities [17]. Using a water-energy nexus approach, the authors concluded that rainwater harvesting systems are both a water-saving method and also an energy-saving technique for hilly location.

Compared to previous studies, as far as the authors are aware, the novelty of the present work is to develop a general optimization tool to study the optimal integration of hybrid power systems and water harvesting techniques in the urban environment in order to achieve high sustainability standards. This tool allows to study the reliability of renewables equipped with energy storage and water harvesting system in residential districts compared to electricity and water loads, respectively. A novel aspects of the paper is to analyse the interrelation between water and power mainly assuming ground mounted photovoltaic systems as water harvesting area. A further novel aspect of the optimization tool is using a spatial perspective rather than a power and water harvester systems perspective used in previous research works to optimize the match between energy and water demand, and supply. The optimization model finds the optimal area distribution within 1 km^2 between the built environment area, and area for the installation of renewables, taking into account that part of the residential district area is used as urban leisure area and for the road network. The model considers the following renewables and energy storage system: building attached photovoltaic (BAPV) systems (function of the built environment area), ground mounted photovoltaic systems, wind turbines and battery storage system. The water harvesting system comprises the harvesting area, assumed equal to the roof area (function of the built environment area), the effective ground mounted photovoltaic area, and the water tank. The optimization model is based on annual hourly dynamic simulations of the renewables, energy and water storage systems. A typical residential district of Gothenburg, Sweden, is taken as case study to identify the main built environment area parameters.

The developed model can be used for the design of new urban districts or to evaluate the performances and provide suggestions for existing urban districts under an energy, water and economic viewpoints to promote renewables and water harvesting integration. It has to be pointed out that the developed tool represents a general integrated model that can be applied for energy and water harvesting performances everywhere and for different types of district, and it can thus represents a handy instrument for engineers, architects and urban planners.

This paper is organized as follows: Section 2 deals with the methodology applied in this study and in particular with the developed optimization model based on the simulation of several submodels, such as building, photovoltaic power, wind power, battery state of charge, and water harvester state of fill; in Section 3, the results of the optimization are presented and discussed; in Section 4 the outcomes of this study are summarized and the directions for future studies are discussed.

Please cite this article in press as: Campana PE et al. Optimization of a residential district with special consideration on energy and water reliability. Appl Energy (2016), http://dx.doi.org/10.1016/j.apenergy.2016.10.005