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Spatial optimization of residential urban district - Energy and water perspectives

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Abstract

Many cities around the world have reached a critical situation when it comes to energy and water supply, threatening the urban sustainable development. The aim of this paper is to develop a spatial optimization model for the planning of residential urban districts with special consideration of renewables and water harvesting integration. In particular, the paper analyses the optimal configuration of built environment area, PV area, wind turbines number and relative occupation area, battery and water harvester storage capacities, as a function of electricity and water prices. 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.

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.

Assuming a built environment area equal to 75% of the total available area, the results show that the reliability of the renewables and water harvesting system cannot exceed the 6475 and 2500 hours/year, respectively. The life cycle costs of integrating renewables and water harvesting into residential districts are mainly sensitive to the battery system specific costs since most of the highest renewables reliabilities are guaranteed through the energy storage system.

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Keywords: Optimization, genetic algorithm, renewable energy, hybrid power systems, water harvesting, residential urban districts.

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1. Introduction

According to the World Health Organization, more than half of the current world's population (53%) lives in urban areas [1]. 6.3 billion people are projected to live in cities by 2050 [2]. The sustainability of cities around the world is thus 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 both policies and technical solutions [3].

The aim of this paper is to integrate hybrid power systems and water harvesting techniques to provide a sustainable solutions for the urban water-energy nexus.

The integration of hybrid power systems in the urban environment has been studied thoroughly in previous studies. In particular, the optimization of hybrid power systems and energy efficiency techniques have been studied to design net zero energy buildings (NZEBs) [4-6] and, on a larger scale, net zero energy districts (NZED) [7, 8]. Similarly, rainwater harvesting systems assessment and optimization have been conducted as technical solution to face the exacerbation of water issue in urban areas [9-11].

Compared to previous studies, the novelty of the present work is to develop a general optimization tool to study the integration of renewables and water harvesting in the urban environment in order to achieve high sustainability standards. This tool allows to study the reliability of renewables and water harvesting system in residential districts compared to electricity and water loads, respectively. The optimization tool uses a spatial perspective rather than a system 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 between the built environment area (BEA) (defined as the area comprising the building and the garden), area for the installation of renewables, urban leisure area (mainly green areas) and road network area within 1 km^2. The model considers the following renewables: building integrated photovoltaic systems (BIPV) (function of the BEA), ground mounted photovoltaic systems (PV), wind turbine and battery system. The water harvesting system comprises the harvesting area, assumed equal to the roof area (function of the BEA) and effective PV area, and the water tank. A typical residential district for the city of Gothenburg, Sweden, is taken as example to identify the main BEA parameters. The developed model can be used for the design of new urban districts or to evaluate the performances of existing urban districts under an energy, water and economic viewpoints to promote renewables and water harvesting integration.

2. Methodology

A conceptual framework of the proposed optimization model is given in Fig. 1. In a residential km^2 there can be a combination of different areas with different intended uses, proportions and layouts. The BEA determines the electric and water loads. In this study we assumed that the BEA is structured into single family houses (5 people). The electric load refer to the electric consumption for appliances, heat pump for heating and cooling, and water pumping and it is equal to 5000 kWh/year [12]. The water load has been assumed equal to 1000 litres per day assuming five occupants and a specific water consumption of 200 litres per person and day [13]. The BIPV area is a function of the BEA since it has been set that half of the roof is used to install BIPV system. The water harvesting area is function of the BEA since it has been assumed that the entire roof is used to collect rainwater. It is also function of the PV area since the effective PV area has been assumed as a further water harvesting area. The green and road network areas have been set equal to 10 and 12% of the entire 1 km^2, respectively. This assumption has been made based on the photointerpretation of a typical residential district in Gothenburg, as shown in Fig. 2. The same approach has been used to evaluate the building and garden areas for a typical residential house. The PV area refers to the area used to install ground mounted PV plants considering a land use factor (defined as the ratio between solar panels area and total area) of 50% due to the high latitude of Gothenburg. The wind turbine area refer