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Spatial optimization of residential urban district - Energy and water perspectives

Pietro Elia Campana[a,*], Steven Jige Quan[b,c], Federico Ignacio Robbio[d], Anders Lundblad[a,e], Yang Zhang[e], Tao Ma[f], Jinyue Yan[a,e]

[a]School of Business, Society & Engineering, Mälardalen University, Box 883, Västerås SE-72123, Sweden
[b]Sino-U.S. Eco Urban Lab, College of Architecture, Georgia Institute of Technology, North Avenue, Atlanta GA 30332, USA
[c]Sino-U.S. Eco Urban Lab, College of Architecture and Urban Planning, Tongji University, Shanghai 200092, China
[d]ABB AB, Tvärleden 2, Västerås SE-72159, Sweden
[e]School of Chemical Science & Engineering, KTH Royal Institute of Technology, Teknikringen 42, Stockholm SE-10044, Sweden
[f]Renewable Energy Research Group (RERG), Department of Building Services Engineering, The Hong Kong Polytechnic University, Hung Hom, Kowloon, Hong Kong

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.

[*] *Corresponding author. Tel.: +46-021-101469;*
E-mail address: pietro.campana@mdh.se.

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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 to the sum of the acoustic influence areas of each installed wind turbine. The acoustic influence area has been calculated from the sound pressure level of the generator assuming to keep the noise emissions below 40 dB according to the Swedish regulations [14]. A 30 kW wind turbine mounted on a 60 meters tower has been chosen as reference generator to be easily integrated in residential areas. The rated sound level is 40 dB at 30 m from the tower base and the corresponding influence area is 15000 m^2. The battery balances the mismatch between energy production and consumption. The electric grid is considered as back-up for the PV-wind-battery system while the dumped power production is assumed to be sold into the grid. Similarly, the water harvester balances the mismatch between water harvested and consumed. The climatic data have been taken from a global climatic database, Meteonorm [15]. All the renewables capital costs have been taken from NREL database [16]. The investment costs related to the water harvesting system have been taken from Hashim et al. [10].

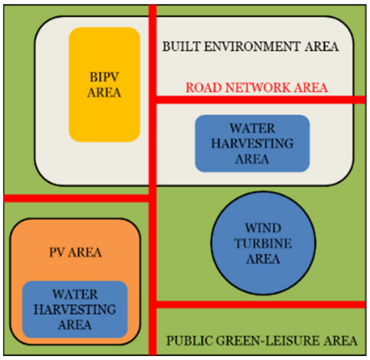

Fig. 1. Conceptual framework.

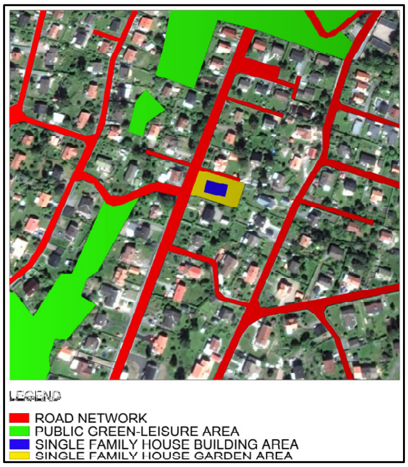

Fig. 2. Photointerpretation of a residential area.

The optimization process finds the area distribution that minimize the life cycle costs (LCC) of renewables and water harvesting systems and at the same time maximizes their reliability. In this work, the optimization is based on hourly dynamic models of the PV system, wind generator, battery and water harvesting system charge and discharge. The decisional variables of the optimization problem are the following: BEA, PV area, wind turbine area, battery and water harvester capacities.

The current version of the model allows to optimize the areas distribution but it does not provide any information regarding the spatial location of the decisional variables.

3. Results and discussions

The results of the optimization process in terms of a typical Pareto front are depicted in Fig. 3. The results show the mutual relationship between LCC and reliability of renewables (Reliability REN). The results refer to three different scenarios regarding the BEA, corresponding to the 25, 50 and 75% of the total available area (0.2, 0.4 and 0.6 km^2, respectively). The results show that the LCC increase with the increase of the reliability REN. Moreover, LCC and reliability REN are functions of the BEA and related electric load. A parity of reliability REN, the LCC increase with the increase of the BEA due to the high electric load.

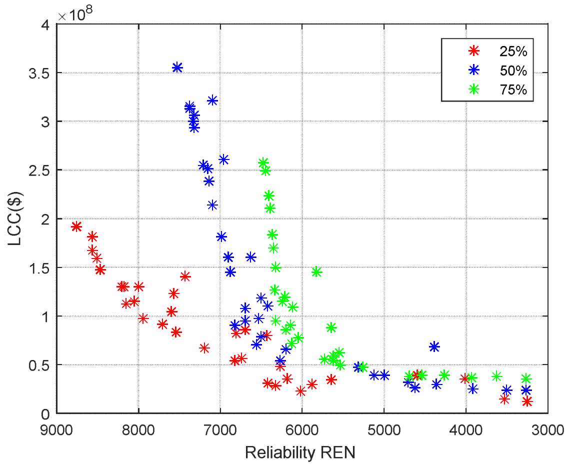

Fig. 3. Relationship between LCC and reliability of renewables (Reliability REN).

The optimization results regarding the reliability of the water harvesting system (Reliability WHS) are depicted in Fig. 4.

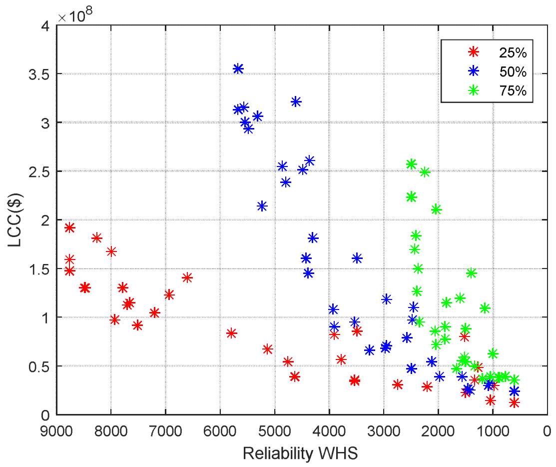

Fig. 4. Relationship between LCC and reliability of water harvesting system (Reliability WHS).

Similarly, the LCC increase with the increase of the reliability and BEA, mostly due to the high cost related to the water harvester. It has to be pointed out that, assuming a BEA equal to 75%, the reliability of the renewables and water harvesting system cannot exceed the 6475 and 2500 hours/year, respectively. This is due to the high electricity and water demand compared to the electricity production and water harvested, respectively. Those results are also tightly linked to the particular climatic conditions of the selected site. A summary of the optimization results for the scenario corresponding to a BEA equal to 50% (renewables and water harvester reliabilities and the corresponding values of the decisional variables, and LCC) is given in Table 1. In all the presented optimization results, power produced from PV systems is preferred to wind power system due to lower cost of electricity produced. In all the optimal configurations, the levelized cost of electricity (LCOE) and water (LCOW) range between 0.3- 1.3 $/kWh and 1.0-4.0 $/m3, respectively. The effect of the variation of some sensitive parameters on the LCC is depicted in Fig. 5 (the base case refers to the 50% scenario with highest renewables and water harvesting system reliabilities). The battery and the PV system specific costs are the main sensitive parameters affecting the overall LCC. This is due to the high battery capacity and PV area to maximize the reliability of the renewables compared to the electric load.

Table 1. Optimization results assuming the built environment area equal to 50% of the available area.

Reliability REN (hours)	Reliability WHS (hours)	Area PV (km^2)	Area wind turbine (km^2)	Battery (MWh)	Water harvester (m^3)	LCC (M$)
7527	5681	0.316	0.045	222.236	8391	354.92
7377	5681	0.316	0.045	187.845	8387	313.47
7099	5231	0.295	0.045	108.672	7386	213.77
6989	4296	0.280	0.015	86.489	3554	181.78
6559	2959	0.178	0.015	10.138	1670	70.07
4998	1984	0.071	0.000	0.953	677	38.72
3914	1416	0.001	0.000	0.479	401	25.00

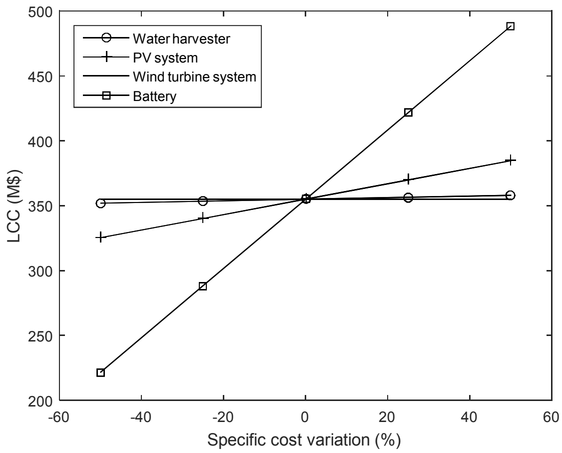

Fig. 5 Effect of specific cost variation on the life cycle costs.

4. Conclusions and future works

This study present an optimization model to evaluate the optimal area distribution among built environment, renewables and water harvesting system in a residential district of Gothenburg, Sweden.

The optimization process minimizes the life cycle costs (LCC) of renewables and water harvesting systems and at the same time maximizes their reliabilities.

The results show that renewables cannot exceed 6475 hours reliability at a levelized cost of electricity equal to 1.3 $/kWh, assuming a built environment area that covers 75% of the study area. Similarly, the water harvesting system cannot cover the water load for more than 2500 hours resulting in high levelized cost of water. Those results are also bounded to the specific climatic conditions of the chosen site.

The model will be further developed to also study other type of urban districts. Moreover, other services, such as wastewater treatment and transportation, renewables and sustainable solutions will be included in the optimization process. Other sites with different climatic conditions will be studied as well.

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