



Optimal planning of hybrid renewable energy infrastructure for urban sustainability: Green Vancouver

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ABSTRACT

Despite the great promise of hybrid solar-wind-biomass energy systems to power future sustainable cities, complexities associated with their optimal planning and design limit their wide-scale implementation. This study provides a novel systematic framework to identify optimal hybrid renewable solutions for urban areas at neighborhood scales. In particular, we examine the role of economies of scale in the techno-economic feasibility and environmental performance of hybrid renewable systems. For demonstration, we assess the impact of the economics of scale (at the neighborhood scales of 1/500, 1/250, and 1/100 of the city's electrical load) on the life-cycle costs of optimal hybrid renewable systems for Vancouver (Canada). Our results indicate that the total net present cost (NPC) of the optimized systems were 59, 116 and 290 million USD, while the levelized costs of electricity (COE) for the three studied scales were almost identical (0.300–0.307 USD/kWh). By comparing the proposed scenarios regarding gross atmospheric emissions, land requirements and economic performance, the mid-scale (1/250) with 6.3 MW of solar PV and 3 MW gasifier (~117 t/day biomass wastes) was preferable to the larger (1/100) and smaller (1/500) scale systems. Results from this study can help decision-makers in creating effective policies and mechanisms to advance the integration of hybrid renewable energy systems in cities.

1. Introduction

Cities are significant emitters of anthropogenic greenhouse gases (~65–75%) [1] and are also particularly vulnerable to the effects of climate change and extreme weather conditions. Hence, cities are facing increasing pressures to curb their carbon emissions through the adoption of low-carbon development strategies. Integrating renewable energy sources is among the key strategies that can address climate change while accelerating the transition to a green economy [2,3].

Over the past few years, many governments have enacted policies and programs (e.g., feed-in-tariffs, quota obligations, subsidies and tax incentives) to catalyze the integration of renewable energy sources in their jurisdictions [4–8]. For example, Portland (Oregon, US) introduced a 25% support fund per house and a 35% corporate tax deduction for using renewable energy [8]. The local government in Freiburg (Germany) provides a subsidy for integrating solar PV while purchasing the residual quantity of electricity. Aachen (Germany) supports its local communities by sharing the expenses of using renewable energy [6].

Although renewable energy generation has many advantages, there

are still some factors (e.g., low efficiency, high infrastructure cost, the reliability of supply) that stymie its large-scale application in urban regions [9,10]. For example, intermittent and variant renewables (e.g., wind, solar) are particularly challenging because they disrupt the conventional methods of operating electric grids [3,10]. Alternatively, hybrid renewable energy systems have proven effective in managing the intermittent nature of renewable energy resources and improving the system efficiency. Specifically, combined solar, wind and biomass systems can effectively address some of the concerns of standalone installations [9] (e.g., high infrastructure costs and low efficiency of solar energy systems, or large area requirements and noise pollution from wind turbines).

Despite the great promise of hybrid solar, wind and biomass energy systems, their practical implementation is limited due to the complexities associated with their optimal planning and design [9–11]. The most straightforward and most conventional sizing methodologies include average and worst-case scenario simulations based on local historical weather and climatic data. However, application of such design strategies may lead to renewable energy configurations that are oversized or defective [10–14]. Therefore, identifying an optimized

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architecture of hybrid renewable systems is key to sustainable urban energy development.

Some studies have assessed the techno-economic feasibility of hybrid renewable energy systems to minimize investment and operating costs in remote and rural off-grid communities [15–22]. For example, using HOMER software, Akinyele and Rayudu [22] techno-economic and environmental analyses of a solar photovoltaic microgrid for remote communities in a small village in Nigeria. Their results indicated solar microgrids with the potential to pay back its cumulative energy demand in about 1.6 years. Vishnupriyan and Manoharan [23] used HOMER software to study the possibility of integrating a renewable energy system with an existing grid to meet the electrical energy demand of institutional buildings located in Indian state of Tamil Nadu. The obtained results showed the optimum cost of energy of 0.109 USD/kWh for the grid-connected photovoltaic system. Nonetheless, few studies have considered the techno-economic and environmental assessment of hybrid renewables in metropolitan areas [1,24]. In a recent survey of hybrid renewable energy planning of cities, Baek et al. [24] investigated hybrid solar-wind power generation systems for Busan (one of the largest cities in South Korea). Using 2013 electricity demand data and the HOMER simulation software, they identified the optimal renewable electricity generation system for a 1/500 scaled Busan metropolitan area, with an approximate total net present cost (NPC) of 26 US million dollars and a cost of energy of \$0.399 per kWh. Although this case study discussed the economic feasibility of solar-wind hybrid systems at a community-scale of 1/500, it did not provide readers with a systematic approach to incorporate the economies of scales into the optimal planning procedure. Also, given the substantial availability of urban biomass resources worldwide (e.g., including different types of municipal solid wastes), there is an evolving need for a planning framework for an optimal design of hybrid systems including biomass (i.e., biomass-solar-wind) at neighborhood scales. Not only can the inclusion of biomass energy improve the techno-economic feasibility of hybrid renewable systems, but it can also boost the creation of local green jobs beyond the other renewables (e.g., solar, wind, geothermal, and hydropower) [25].

In this context, the primary objective of this study is to develop a systematic and straightforward approach for optimal planning of urban hybrid solar-wind-biomass energy systems, incorporating economies of scale in assessing their electrical, economic and environmental performance. Given the complexities and limitations of urban areas, we also evaluate the most economically feasible hybrid scenarios regarding their environmental performance. We further conduct a sensitivity analysis of input parameters (nominal discount rate, expected inflation rate, photovoltaic capital cost) to the levelized cost of energy. Finally, for illustration, we use the framework to plan an optimized hybrid solar-wind-biomass system at neighborhood scales in a model city (Vancouver). The City of Vancouver, located on Canada's West coast, is the largest city in British Columbia with about 631,000 residents and a land area of 115 km² [26]. Over the past few years, the city has sought to be a world leader in supporting urban sustainability through its ambitious climate change goals and actions [26]. In 2011, the City of Vancouver (from now on Vancouver) introduced a new policy strategy, entitled Greenest City 2020 Action Plan (GCAP). The GCAP has received global attention and recognition through awards such as the 'Best Green Building Policy' by the World Green Building Council in 2013 and the C40 Cities Awards for Carbon Measurement and Planning in 2015 [26]. The GCAP has been framed and promoted as green leadership that is supposed to turn Vancouver into the greenest city in the world as reflected in the name of the plan. The primary objective of this plan is to stay "on the leading edge of urban sustainability" [27] by reducing the city's CO₂ emissions in 2020 by 33% below the 2007 level and by making the city's energy supplies 100% renewable by 2050.

Owning diversified geography and large landmass, Vancouver benefits from considerable renewable energy resources including the biomass, solar and wind energy that can support the city towards

achieving 100% renewable energy by 2050 [27]. Even though almost 90% of current electricity production in the province (British Columbia) is from large hydropower dams [28,29], the city is committed to diversifying its electricity mix by increasing the share of other renewables such as solar, wind, and biomass [30,31].

In the following sections, we develop a model of the hybrid energy system and describe an approach to optimization of techno-economic and environmental performance using the Hybrid Optimization of Multiple Energy Resources (HOMER) algorithm. Using data from Vancouver, the most economically appealing systems based on the life-cycle cost analysis are described; and the impact of system scale on the economic and environmental performance is assessed. Moreover, by choosing the main model variables (i.e., nominal interest rate, inflation rate, PV capital), sensitivity analysis of the levelized cost of energy is conducted for the most economically feasible hybrid systems at the neighborhood scales of 1/500, 1/250, 1/100.

2. Model development

The hybrid system proposed for this work includes five major components: photovoltaic panels (PV), wind turbines, biomass gasifier, power converter, and battery. Fig. 1 represents a schematic of elements in the proposed hybrid system, noting that the power output of the photovoltaic system is DC, while biomass gasifier and wind turbine supply is AC. The following subsections describe system components used to simulate energy supply in the hybrid renewable energy system.

2.1. Solar photovoltaic panels

The number of panels in a solar energy system depends on the electrical load demand and the available solar intensities. In this work, we utilized a generic flat plate PV [32] with an estimated capital and replacement costs of 3000 USD for 1 kW panel [19]. Besides, we considered an annual operation and maintenance charge of 10 USD for 1 kW panel. For this work, we assumed that all panels were fixed with no tracking system. We also supposed a lifetime of 25 years for the panels plus an 80% derating factor [33]. Derating factor is a scaling factor that applies to PV array power output to account for their reduced efficiency under actual operation in comparison to the standard condition in which they were initially rated [34]. Further, the temperature effect on the panels and ground reflectance was considered 0.5% and 20% respectively. Under the utilized circumstances, the supplied power of the photovoltaic panels was calculated by [33]:

$$P_{PV\ out} = P_{NPV} \times (G/G_{ref}) \times [1 + K_T(T_C - T_{ref})] \quad (1)$$

where $P_{PV\ out}$ is power output from PV cell and P_{NPV} is rated power at the reference (standard) conditions; G is solar radiation; and G_{ref} is solar radiation at the reference condition (1000 W/m); K_T is temperature coefficient of the maximum power for mono and poly crystalline silicone ($K_T = -3.7 \times 10^{-3} \text{ } ^\circ\text{C}^{-1}$); T_C is cell temperature; and T_{ref} is the reference temperature ($T_{ref} = 25 \text{ } ^\circ\text{C}$) [33].

2.2. Wind turbine

The electrical power from wind turbine depends on the speed of wind in the area of interest. For this work, we utilized a generic 10 kW AC wind turbine [35] with an estimated capital and replacement costs of 50,000 USD. Besides, we considered an annual operation and maintenance fee of 500 USD for each wind turbine. We also supposed a lifetime of 25 years for each turbine. The power of wind turbine is obtained by Eq. (2), in which ρ is the air density, V is the wind speed and A is the wind's cross-sectional area [34]:

$$P_{Wind} = \frac{1}{2} \times \rho \times A \times V^3 \quad (2)$$

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