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Renewable energy selection for net-zero energy communities: Life cycle based decision making under uncertainty

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A B S T R A C T

Developing net-zero energy communities powered by renewable energy (RE) resources has become a popular concept. To make the best choices for community-level net-zero energy systems, it is necessary to identify the best energy technologies at local level. Evaluation of RE technologies has to be extended from technical and economic aspects to include environmental and social wellbeing. It is possible to identify the true costs and benefits of energy use by taking a cradle-to-grave life cycle perspective. In this study, a RE screening and multi-stage energy selection framework was developed. A fuzzy multi-criteria decision making approach was used in ranking the technologies to incorporate the conflicting requirements, stakeholder priorities, and uncertainties. Different scenarios were investigated to reflect different decision maker priorities. Under a pro-environment scenario, small hydro, onshore wind, and biomass combustion technologies perform best. Under a pro-economic decision scenario, biomass combustion, small hydro, and landfill gas have the best rankings. Triple bottom line sustainability was combined with technical feasibility through a ruled-based approach to avoid the theoretical pitfalls inherent in energy-related decision making. This assessment is geared towards providing decision makers with flexible tools, and is expected to aid in the pre-project planning stage of RE projects.

1. Introduction

The move towards developing renewable-powered communities has gained momentum with the various environmental and economic concerns associated with energy use. In addition to the various undesirable environmental impacts associated with fossil fuel use, it is also known as a rapidly dwindling resource [1]. Moreover, the unstable nature of energy prices are also creating adverse economic impacts, and the use of energy creates economic burdens on communities [1,2]. Decentralised energy generation through renewable based energy systems has long been promoted as a solution to the multitude of issues associated with conventional forms of energy supply. Community level energy plans provide a better opportunity for the developed energy systems to be adapted to local conditions and requirements [3,4].

The development of net-zero energy communities (NZE) is an extension of the sustainable community concept. In these communities, the total energy demand of a community is expected to be met through locally sourced renewable energy [5]. This ensures decreased reliance on external provisions for the community energy needs, while ensuring a clean and sustainable energy supply. In Canada, where many communities are located in remote areas lacking grid connectivity, the development of net-zero communities is especially important [6]. However, the choices made in developing NZE systems need to reflect the local realities, and should incorporate different dimensions representing technical, economic, environmental, and social suitability.

The objective of the paper is to present a framework for selecting the most viable renewable energy technologies during the pre-project planning stage of community level RE-based energy system development, based on multiple decision criteria. While RE ranking has been done in previous studies, a comprehensive and practical methodology in decision making for community energy systems which considers available options at technology level, and combines triple bottom line planning with life cycle thinking while

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Nomenclature

Acronyms

AHP	Analytical Hierarchy Process
BC	British Columbia
CSP	Concentrated solar power
GHG	Greenhouse gas
IEA	International Energy Agency
LCA	Life cycle assessment
LCC	Life cycle costing
LCI	Life cycle inventory
LCIA	Life cycle impact assessment
LCSA	Life cycle sustainability assessment
MADM	Multi-attribute decision making
MCDM	Multi-criteria decision making
MOO	Multi-objective optimisation
NZE	Net-zero energy
OTEC	Ocean thermal energy conversion
PV	Photovoltaics
RDF	Refuse derived fuel
RE	Renewable energy
RES	Renewable energy sources
RET	Renewable energy technologies
TBL	Triple bottom line
WtE	Waste-to-energy

Abbreviations and units

CAD	Canadian Dollars
GJ	Gigajoule
kW	Kilowatt
kWh	Kilowatt-hours
MW	Megawatt
O&M	Operations and maintenance
RD&D	Research, development, and demonstration
USD	United States Dollars

also integrating uncertainty into decision making, is missing in published literature. To address this gap, technical, economic, environmental and social criteria are considered in a multi-stage RET selection process which accommodates the practical realities of community level energy planning. Multi-stage selection reflects the practical realities of energy planning, as engineering decision making needs to be based on technical feasibility as well as socio-economic performance. The proposed methodology can be used in developing a robust decision support framework for planning community-level net-zero energy systems. The findings of the research will inform community developers and decision makers in energy system planning under multiple objectives and constraints, while paying attention to the interests of different stakeholder groups. Community developers can use the developed method and the resulting decision support tool to select RETs based on the local needs, and use that information for the prefeasibility assessment of the energy system.

2. Literature review

The energy system of a net-zero community is planned with the objective of supplying the community's entire energy demand with locally available RE resources [5]. A multi-dimensional perspective needs to be taken in this planning process to ensure optimal outcomes from a community level energy system. A net-zero community energy system is highly complex. When analysing and optimising such a system, it is necessary to incorporate the uncertainties and risks associated with it. Decision making for planning problems involve several categories of uncertainties. Epistemic uncertainties are a result of limitations in available data and lack of knowledge, while aleatory uncertainties are caused by variabilities in the studied system [7]. While scenario-based analysis is employed to represent possible scenarios which account for the potential variations in future outcomes, these scenarios too cannot be formulated to be fully accurate [8]. Data uncertainties are the main problem which contributes to inaccuracies in urban planning, and this issue is caused by imprecise, vague, incomplete, and qualitative data [7]. Scenario uncertainties are further caused by variations over time, especially due to the changes in external environment [8]. Due to the impreciseness and unavailability of data, it may be necessary to present the performance scores for the criteria indicators as a range instead of a crisp value, or in linguistic terms such as "high" "medium" or "low" [15].

2.1. Technical viability and triple bottom line planning

In addition to being capable of fulfilling the demand, a community's energy generation needs to be reliable, considering both supply and technical reliability [9] [10]. A main challenge associated with RE based energy supply is the fluctuations and the resulting non-dispatchability associated with sources such as wind and solar [11]. In addition, the local resource availability needs to be sufficient in fulfilling the community energy demand, and the energy resource quality is an important aspect which needs to be established with regards to technical viability. To develop a dependable and technically sound energy system, the renewable energy technologies (RET) used in a community energy system need to be tested and proven technologies with sufficient market maturity to minimise the associated risk [12,13]. Moreover, as a technology becomes more mature, the associated costs of energy generation will decrease [14]. The technical viability of a RET needs to be first established before considering its inclusion in a community energy system based on its economic and socio-environmental performance. The term "technical criteria" is used in published literature to refer to indicators which assess the technical performance of individual energy technologies in multi-criteria ranking problems, such as maturity, reliability, efficiency, and resource availability [15] [16] [17].

Traditional triple bottom line (economic, environmental, and societal aspects) have been highlighted by Felio and Lounis (2009) as a core tenet which needs to be harmonised with infrastructure-related decision making [18]. Environmental factors include resource use, emissions, and impact on water, air and soil composition, as well as the effect on animal and plant life. Economic aspects are related to the financial sustainability, while social aspect focus on the effect on the community as a whole [18].

The economic impacts of renewable energy technologies spanning their construction, operations and maintenance, repair and replacement, and end-of-life can be evaluated via life cycle costing (LCC) [19]. In developing sustainable energy systems, it is necessary to minimise the life cycle costs, and achieve grid parity where a unit of energy from renewables can be provided at an equivalent or lesser cost than that of a unit of conventional supplies [20]. This breakeven point is established with reference to the levelised cost of electricity (LCOE), which is defined as ratio of lifetime costs to lifetime electricity generated in a facility [20].

Generally, renewables are known as sources of clean energy,