A two-stage multi-criteria analysis method for planning renewable energy use and carbon saving

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Submitted to

Energy

Feb 2020

ABSTRACT

Renewable energy use is critical for achieving climate change goals. It is essential to understand necessary to the priority, capacity, and number of units of renewable energy systems for generation planning. Multi-criteria analysis methods serve as an effective tool for planning renewable energy generation. In this work, a two-stage multi-criteria analysis method was developed to identify the priority and capacities, as well as the numbers of units of renewable energy technologies. Technical (capacity factor and power density), economic (benefit-to-cost ratio), and environmental (carbon dioxide equivalent emission) criteria were considered. The method was applied to plan Glasgow's renewable energy use. It was found that the planned renewable energy use configuration consists of 255 units of wind turbines (3.6 MW each), 23497 units of solar photovoltaic panels (11 kW each), 2 units of biomass combustion systems (2 MW each), and 3382 units of ground source heat pumps (22.5 kW each) corresponding to an annual carbon footprint of 109629 tonnes carbon dioxide equivalent. Sensitivity analysis was also conducted to assess the impacts of weightings in technical, economic, and environmental criteria on the decision in the configuration of renewable energy use.

KEYWORDS: Renewable energy; Decision tool; Multi-criteria analysis; Climate change; Energy storage

NOMENCLATURE

No.	Symbol	Description
1	BCR	Benefit-cost ratio
2	η_b	Boiler efficiency
3	C_b	Boiler capacity
4	η	Capacity factor
5	CAPEX	Capital Expenditure
6	COP	Coefficient of Performance
7	EUAB	Equivalent uniform annual benefits
8	EUAC	Equivalent uniform annual cost
9	GSHP	Ground source heat pump
10	GHG	Greenhouse gas
11	MCA	Multi-criteria analysis
12	NCV	Net calorific value
13	OPEX	Operating Expenditure
14	O&M	Operations and maintenance
15	P_w	Power generation
16	P_d	Power density
17	f_b	Capacity factor
18	SPF	Seasonal Performance Factor
19	PV	Solar photovoltaic

1. INTRODUCTION

Climate change has become a global community concern. Renewable energy sources are considered as the alternative energy options for fulfilling the energy demand for a low carbon future. However, the practical implementation of renewable energy is affected by the stability of energy generation which depends on meteorological and environmental conditions. Different types of renewable energy systems (e.g., wind turbine and solar systems) have been combined to develop hybrid renewable energy systems with improved efficiency and stability of renewable energy supply [1]. The sizing of system components is not only constrained by the reliability of energy supply but also the energy demand [2]. It is desirable to combine and arrange the energy generation from several renewable sources to mitigate the stability issue and balance energy supply and demand [3]. Overall electricity and heat demands are the most common input conditions for sizing renewable energy systems while emerging electric vehicle markets facilitate the design of renewable energy systems based on the concept of distributed or localized generation [4]. The practical planning of renewable energy generation is also subject to the requirements of different stakeholders, i.e. policymakers, investors, and consumers. This is reflected by the fact that multiple criteria (technical, economic and environmental) need to be considered in the evaluation of alternative configurations during feasibility studies [5].

To reduce greenhouse gas (GHG) emissions, the UK government is implementing the concept of reducing energy consumption and increasing the use of renewable energy generation technologies. In Glasgow, the government has set a 2020 maximum GHG emission target of 129741 ton $CO_{2\text{-eq}}$ (80940 ton $CO_{2\text{-eq}}$ from electricity and 48801 ton $CO_{2\text{-eq}}$ from heating) [6]. Relevant action plans have been developed, that is, renewable energy use will cover 100% of electricity and 11% of non-electrical heat by 2020 and the energy consumption will be reduced by 12% compared to the 2005 baseline level [7]. This means renewable energy needs to supply 3029 GWh electricity and 698 GWh heat by 2020.

Glasgow has plenty of renewable energy resources such as wind, solar, geothermal, and biomass that are featured by different degrees of seasonal stability. For wind energy, the power generation normally peaks during winter when the wind speed is high in the UK [8]. For solar energy, power generation was found to peak during summer when there were three to six times more solar radiation compared to winter [9]. Meanwhile, geothermal and biomass energy generation is relatively stable. For biomass energy, the power generation is affected by feedstock availability factors such as population growth, the area set aside for nature conservation, and water availability [10]. For geothermal energy, the power generation depends on thermal-fluid flow rates and groundwater temperature [11], which could be considered stable throughout the year in Scotland [12].

It is necessary to determine the proper configuration of the renewable energy combination regarding their priority, capacity, and number of units to guide practical implementation. In this case, multi-criteria analysis (MCA) can be used to achieve a compromise among different renewable technologies. MCA is one of the effective tools for energy planning. MCA has been used to assess the general performance of different planning options and to determine the most proper one by evaluating possible advantages, costs, and hazards [13]. MCA is a reliable solution for supporting the optimization and decision-making processes in complex situations consisting of various alternatives, objectives, or forms of data [14]. MCA has been widely applied for energy planning and waste management.

An MCA framework was proposed to plan the proper renewable energy generation at a regional level, and the application of the framework for Thassos, Greece indicated that wind and wind-biomass combination scenarios were the best renewable energy sources in the region followed by biomass and wind-bio-PV combination [15]. MCA was used to evaluate five energy generation methods (photovoltaic system with a battery bank, wind and photovoltaics hybrid configuration, direct connection of photovoltaics, wind only, and diesel generator) for Reverse Osmosis desalination process in terms of economic, environmental, technological and societal indices [16]. An MCA framework was developed for ranking renewable energy supply in Turkey and identified that hydropower was the priority choice followed by geothermal power, regulator, and wind power [17]. MCA was used to identify appropriate technologies for treating food and biodegradable waste in Japan and found that anaerobic digestion was the best treatment option [18]. MCA was used by a panel of residents and stakeholders to identify the methods of waste paper management on the Isle of Wight out of seven recycling, recovery and disposal options and suggested that island-based gasification and recycling were the best options while exporting to the mainland for incineration or landfill were the least preferred options [19].

An MCA method has been used to assess the energy efficiency of residential buildings in China [20]. This study defined indicators using parameters like effectiveness, feasibility, completeness, and multi-attribute decision-making rules. [21] presented three methodologies to pinpoint the sensible combination of the technologies of building energy systems. The analysis considered such factors as the potential effect on the environment, effective energy use in the building, and economic rationality. The results highlighted the need to apply the decision-making processes to choose the sensible combination of energy system resources.

The study also showed that wood boilers along with photovoltaic systems and integrated solar collectors constituted a rational configuration of building energy systems.

[22] raised issues related to the design and execution of low-energy objects in Polish conditions. An MCA and economic analysis were carried out based on the AHP method to figure out whether or not it was worth having greater investment expenses to modify the standards of energy-efficient complexes that meet the fewest energy consumption requirements. The variants that had optimal characteristics owing to the diverse preferences of investors are the design and materials of structural partitions. [16] evaluated five alternate energy generation types for a Reverse Osmosis desalination process. The technological, economic, environmental, and social parameters were considered in the MCA. It revealed that the direct association of the Reverse Osmosis unit with photovoltaic is the most important disregarding the tendency for decision making. The analytic hierarchy process recommends the Hybrid configuration (wind and photovoltaics) when the economic considerations are greater in weight as the most suitable system. [23] developed an MCA methodology by linking the Technique for Order of Preference with the Analytic Hierarchy Process (AHP) based on their Similarity to Ideal Solution (TOPSIS). The aim is to back the choice of four typical flat roof kinds in conformity with their support to sustainability; such choice is based on the performance of several signs that are in line with the United Nations Sustainable Development Goals. The findings documented that the green roofs were the most sustainable alternate of all the scenarios assessed, in terms of their recycling, cost, insulation, energy, water, and ecosystem-related strengths.

In summary, MCA has generally been used to select a proper energy technology option based on a single-stage evaluation for small-scale applications. There are limited studies that utilize

MCA in the design of city-scale renewable energy systems that are subjected to emission targets and a specific energy demand. The increasing concern about climate change has made renewable energy an important topic in the production of energy. The novelty of this study concerns the development of a two-stage multi-criteria analysis method to identify the priority and capacities, as well as the numbers of units of renewable energy technologies under a larger, city-scale. This concept aligns with the UK's energy policy that aims to promote renewable energies use, energy savings, improved energy efficacy. The developed model will be applicable to city-level renewable energy planning of other countries.

Specifically, a two-stage MCA method is developed for renewable energy planning. Compared with existing methods that mainly focus on the selection of the proper renewable technologies, this method has the capacity of not only prioritizing renewable technologies and deciding the proper capacity of each renewable energy technology route but also determining the optimal number of units for each technology route, that are critical factors for planning renewable energy generation. Technical, economic, and environmental criteria are considered in the MCA to design energy systems that are reliable, cost-effective and environmental friendly [18]. It is worth noting that social impact or acceptance is an important criterion in many MCA, especially, in the ones evaluating energy systems closer to the public. However, this work focuses on developing a new MCA method for planning renewable generation under a larger, city-scale. The scope of analysis is defined by considering technical, economic, and environmental criteria, which are relevant to investors and policymakers and whose data is with higher certainty and availability than social criterion-related data. The method can be used to incorporate the social acceptance criterion whenever it is required, and relevant data is available.

2. METHODS

The city where the planning of renewable energy for carbon saving will take place in Glasgow. The approach that will be deployed is known as a two-stage MCA method. It will be used with relevant criteria parameters (technical, environmental, and economic) to determine the proper configuration of renewable energy deployment in Glasgow with a goal to meet emission targets and energy demands. The stages of the two-stage method include value, determination of criteria parameters, grade "translation" based on a given grade scale, and determination of the relative importance of each criterion or each sub-criterion. The MCA was carried out using Microsoft Excel.

As shown in Figure 1, the MCA framework consists of two stages. The first stage consists of (1) criteria parameter determination in the decision support tool process; (2) a database on the selected criteria for each of the renewable energy technologies; and (3) values of the selected criteria for each of the components. In this stage, the renewable energy technology routes are pre-defined and depend on various factors such as energy demands, existing use, and environmental background. To illustrate the application of the framework to plan renewable energy generation in Glasgow in Figure 1, wind turbine and solar PV are considered to generate electricity while bioenergy and ground source heat pump (GSHP) is considered to supply heat based on the existing use of relevant technologies in the city.

The second stage consists of (1) MCA-based scoring for different energy generation sizes that can be used to generate a ranking and select the proper generation size from each type of renewable energy technology based on designated criteria; (2) identification of the optimal unit for each type of renewable energy technology based on the selected generation sizes that can fulfill city's energy demand and emission target, with the consideration of land availability and priority usage of different renewable energy technologies as obtained by the first stage. The two-stage MCA will decide the priority, optimum capacity, and numbers of units of renewable energy technologies that are able to fulfill a specific energy demand and emission target.

2.1. Criteria

Three criteria, i.e. technical, economic, and environmental, were considered in the MCA to support the decision-making processes of investors and policy-makers.

2.1.1 Technical

The technical criterion denotes the technical characteristics of renewable technology as represented by a capacity factor (η) and power density (P_d). The capacity factor is defined as a measure of how much energy can be converted from the energy design capacity of a renewable energy system.

$$\eta\,(\%) = \frac{\text{Energy output (kWh)}}{\text{Energy design capacity (kWh)}} \tag{1}$$

The power density is a measure of how much energy can be converted from a unit area of land used for the development of the renewable energy technology system [24]. A higher power density means more efficient utilization of land and thus is preferred by stakeholders.

$$P_d(\text{W/m}^2) = \frac{\text{Power Output (W)}}{\text{Area Required (m}^2)} \tag{2}$$

2.1.2 Economic

The economic criterion is based on the benefit-cost ratio (BCR) which is calculated by dividing the equivalent uniform annual benefits (EUAB) by the equivalent uniform annual cost (EUAC) [25]:

$$\mathrm{BCR} = \frac{\mathrm{EUAB}}{\mathrm{EUAC}} \tag{3}$$

where EUAB is calculated by multiplying the total energy generation with a corresponding tariff; EUAC is calculated by the addition of annual Capital Expenditure (i.e. CAPEX) and Operating Expenditure (i.e. OPEX) which are calculated as:

$$\text{Annual CAPEX}=\text{CAPEX} \times \frac{r(1+r)^T}{(1+r)^T - 1} \tag{4}$$

$$\text{Annual OPEX} = (\text{OPEX}_{var} \times \text{Total energy generation}) + (\text{OPEX}_{fix} \times \text{Total power}) \tag{5}$$

where r=0.5% is the interest rate in the UK [26], T=20 years is the lifespan of a system [27], OPEX_{var} is the variable O&M cost (£/kWh), and OPEX_{fix} is the fixed operating and maintenance (O&M) cost (£/kW). It is worth noting that the lifespans of renewable energy systems vary and depend on the types of technologies, design, and environment. To simplify the application of the proposed MCA method for the case of Glasgow, a lifespan of 20 years is assumed which have been also used by various existing studies. For example, a lifespan of 20 years was used to evaluate the profitability of four types of renewable technologies (biomass, hydro, photovoltaic, and wind) for power generation in Italy [28]. The term economic cost estimation of a geothermal power plant was conducted based on actual plant data which included a lifespan of 20 years [29]. BCR > 1 indicates that the annual benefits of unit generation outweigh its annual costs and thus a higher BCR is preferred by stakeholders.

2.1.3 Environmental

The environmental criterion is the amount of GHG emission (g $CO_{2\text{-eq}}$/kWh) per unit energy generation. It is a measure of how much the GHG emission produced per unit energy generation of a renewable energy technology [30]. A lower GHG emission is preferred by stakeholders. There are other environmental factors (e.g., eutrophication potential, acidification potential, particulate matter formation, ecotoxicity, etc) [31] that are relevant for energy generation planning. However, the main target of the case study in this work is to fulfill the energy and carbon abatement targets. Hence, the GHG emission per unit energy generation is considered as the environmental criterion. Multiple environmental criteria can be incorporated into the proposed MCA method whenever they are relevant.

2.2. Classification

Different renewable technologies are classified based on their capacities as shown in Table 1. The capacity classification considers government regulatory requirements and existing use of the technologies in Glasgow. Technical, economic, and environmental criteria will be estimated for each size of a specific renewable energy technology route to determine the best capacity based on which the number of units of each renewable technology route will be decided.

2.3. Criteria Value Determination

The estimation of the criteria parameters for different renewable technologies was presented as follows:

2.3.1 Technical Value

The values of technical parameters for different renewable technologies are estimated based on relevant meteorological and environmental conditions.

(a) Wind

For wind energy, the power generation (P_{w}) depends on the wind speed and area swept [32]:

$$P_{\mathrm{w}}=\begin{cases} 0 \quad \text{for} \quad v \le v_{\mathrm{ci}} \text{ or } v \ge v_{\mathrm{co}} \\ \frac{1}{2}\rho C_p A_w v^3 \quad \text{for} \quad v_{\mathrm{ci}} \le v \le v_{\mathrm{r}} \\ P_r \quad \text{for} \quad v_{\mathrm{r}} \le v \le v_{\mathrm{co}} \end{cases} \tag{6}$$

where ρ=1.225 kg/m^3 is the density of air (kg/m^3), C_{p}=30.1% is the wind power coefficient [33], A_{w} is the area swept by rotor blades (m^2), v is the wind speed (m/s), v_{ci} is the cut-in speed (m/s), i.e. the minimum wind speed for electricity generation, v_{co} is the cut out speed (m/s), i.e. the maximum wind speed above which the rotor is stopped to prevent structural damage and v_{r} is the rated wind speed (m/s), i.e. the one for rated power generation. For wind turbines of different capacities, the wind speed is adjusted by considering the heights of wind turbines as shown in Table 2, which will be used to calculate the monthly electricity generation from wind turbines. The land area required by a wind turbine is estimated by $(5d)^2$ with d being the diameter of a rotor blade [34].

(b) Solar PV

For solar PV, the power generation (P_{s}) depends on the solar irradiation and solar panel area [35]:

$$P_{\mathrm{s}}=A_{\mathrm{s}}\times H_{\mathrm{solar}}\times\eta_{\mathrm{s}}\times PR\times f_{\mathrm{orientation}} \tag{7}$$

where A_{s} is the total solar panel area (m^2), H_{solar} is the solar irradiation (kW/m^2) as listed in Table 3 for Glasgow, η_{s} is the efficiency of solar PV (obtained from product specification), PR=75% is the performance ratio [35], and $f_{\mathrm{orientation}}$=1 is the orientation factor [35]. The area required by solar PV depends on the dimension specification and capacity (Table 1).

(c) Geothermal

For geothermal energy (GSHP), the ground source heat generation (P_{g}) depends on the temperature drop across the heat pump and flow rate [36]:

$$P_g = Z \times \Delta\Theta \times S_{cwat} \tag{8}$$

where Z is the flow rate from the borehole(s) supplying the heat pump and ranges from 1 to 2 litre/s [12], $\Delta\Theta$=4 K is the temperature drop across the heat pump [37], and S_{cwat}=4180 J/(K·L) is the specific heat capacity of water.

GSHP uses a compressor that consumes electricity to extract energy from a low-temperature heat source and transforms it into energy at the desired temperature level [37]. The maximum efficiency is defined by the Seasonal Performance Factor (SPF) which represents a long-term average Coefficient of Performance (COP) for the entire heating system [38]. SPF is further expressed by

$$\mathrm{SPF} = \frac{P_h}{P_e} \tag{9}$$

where P_h is the total heating effect (W), and P_e is the total electricity consumed (W). $P_h = P_g + P_e$ and P_g is the ground source heat (W). SPF is estimated to be 3.9 [39]. The area required for unit geothermal heat generation is 400 m^2/kW [12].

(d) Bioenergy

For bioenergy, the heat generation (P_b) depends on the capacity and efficiency of bioenergy reactor, feedstock types, and the net calorific value (NCV(MJ/kg)) of feedstock [40]. The heat generated per year (kWh/year) is

$$P_{b1} = C_b \times f_b \times 8760 \tag{10}$$

where C_b is the boiler capacity (kW) and f_b is the capacity factor. The heat generated per ton of feedstock (kWh/ton) is

$$P_{b2} = \mathrm{NCV} \times \eta_b \times 0.2778 \times 1000 \tag{11}$$

where η_b is the boiler efficiency. 0.2778 is the unit conversion factor (from MJ to kWh). The feedstock use (ton/year) is calculated by dividing P_{b1} by P_{b2}. The land area required is calculated by considering the average yield of feedstock (wood chips) that is around 1000 ton per km^2 per annum [41]. The wood chips have a heating value of 12.5 MJ/kg [40].

Two types of bioenergy technologies, i.e. combustion and gasification were considered. For each type of technology, three capacity categories, i.e. 20 kW, 200 kW, and 2 MW were further considered to represent the current use in Scotland. The capacity factors of 20 kW, 200 kW, and 2 MW are 29%, 59%, and 91%, respectively [42]. The average efficiency (η_b) for combustion is 75%, while gasification is 77.5% [43].

2.4. Economical parameters

The installation cost of a wind turbine in Europe is £1500/kW, and the corresponding fixed O&M cost is £22.5/kW/year [44]. The variable O&M cost was neglected. The revenues of wind turbine come from the sale of electricity to the grid (5.24 p/kWh) and from the Feed-in Tariff (8.46 p/kWh for capacity < 50 kW; 5.01 p/kWh for 50 kW ≤ capacity < 100 kW; 2.15 p/kWh for 100 kW ≤ capacity < 1.5 MW; 0.66 p/kWh for capacity > 1.5 MW) [45].

For solar PV, the installation cost of solar PV in the UK is £1125/kW, and the O&M fixed cost is £10.5/kW/year [44]. The O&M variable cost was neglected. The revenues of solar PV come from the sale of electricity to the grid (5.24 p/kWh) and from the Feed-in Tariff (3.61 p/kWh for capacity < 10 kW; 3.83 p/kWh for 10 kW ≤ capacity < 50 kW) [45].

The installation cost of GSHP in the UK is £1000/kW [46]. the O&M fixed cost is £5/kW/year [47], and the O&M variable cost is £0.056/kWh [48]. The revenue of GSHP is dictated by the non-domestic renewable heating incentive system (9.36 p/kWh for Tier 1 and 2.79 p/kWh for Tier 2) [49]. According to OFGEM [50], for the first 3066 hours (35% of a year), the Tier 1 tariff is effective, with any further heat being payable at the Tier 2 tariff.

The installation cost of biomass combustion is £1410/kW, while the fixed O&M cost and variable O&M cost (excluding fuel cost) are £28.2/kW/year, and £0.00375/kWh [51]. The cost of wood chips cost is £65/ton or equivalently £0.025/kWh in terms of energy production [40]. The total variable cost is £0.029/kWh.

The installation cost of biomass gasification is £1605/kW, while the fixed O&M cost and variable O&M cost (excluding fuel cost) are £32.1/kW/year and £0.00375/kWh [51]. Considering the cost of wood chips (£0.025/kWh), the total variable cost is around £0.028/kWh. The revenue of bioenergy use is dictated by the non-domestic renewable heating incentive system (4.42 p/kWh for biomass combustion, 4.64 p/kWh for biomass gasification with capacity $<$ 200 kW; 3.64 p/kWh for biomass gasification with 200 kW $\leq$ capacity $<$ 600 kW; 1.36 p/kWh for biomass gasification with capacity $>$ 600 kW) [49].

2.5. Environmental Parameters

The environmental parameter was considered using the reported median value of life cycle GHG emissions for each type of renewable technology. For a wind turbine, it is 11 g CO_{2-eq}/kWh of electricity generation [52] and for solar PV, it is 46 g CO_{2-eq}/kWh of electricity generation [53]. For geothermal energy, it is 70 g CO_{2-eq}/kWh of heating generation [54, 55]. For bioenergy, it is 18 g CO_{2-eq}/kWh of heating generation for combustion and 22 g CO_{2-eq}/kWh of heating generation for gasification (without considering the soil application of biochar from gasification) [56]. The economic and environmental parameters are summarized in Table 4.

2.6. Multi-criteria Analysis

MCA is a complementary approach to cost-benefit analysis using criteria weights [57]. It starts by identifying the values of considered criteria which are then ‘‘translated’’ into grades based on a given grade scale. The grading scale used in this project begins from ‘‘1’’ for poor performance to ‘‘10’’ for good performance, as seen in Table 5.

The next stage of MCA is the determination of the relative importance of each criterion or each sub-criterion (i.e. parameters under each criterion) by following a weighting procedure: a pairwise comparison with a preferential ranking of two components [57]: (1) if A is more important than B, it is reflected with a ‘‘+’’ and A receives 3 points; (2) if A is equally important to B, it is reflected with a ‘‘0’’ and A receives 2 points; (3) if A is less important than B, it is reflected with a ‘‘-’’ and A receives 1 point.

These earned points determine the relative importance of each criterion or sub-criterion. The economic criterion is considered more important than the technical and environmental ones, while the technical and environmental criteria are considered equally important in the analysis for Glasgow.

The technical criterion has two sub-criteria, i.e. the capacity factor and power density. In Glasgow, the usage of land is crucial due to the limited land available for the development of renewable technology. Hence, the power density is considered more important than the capacity factor. The score of each technology route is calculated by adding the products of the grade of criteria and their weights:

$$\text{Score} = \sum \text{grade}_i \times \text{weight}_i \tag{12}$$

i=1, 2, and 3 denote the technical, economic and environmental criteria, respectively. The higher the score, the better the technology choice.

2.7. Land Availability

The number of units for each type of renewable energy technology is calculated by dividing the total available land area by the land area required for one unit of the system under the proper capacity. For wind energy, the available land is estimated to be 25% of 368 km^2 potential wind site in the Clyde Valley region, or equivalently 92 km^2 [58]. For solar energy, the available land is 5.5 Km^2 for ground-mounted solar photovoltaic (PV) system panels [59] and 8.8 km^2 for house solar PV [60, 61] or equivalently a total of 14.3 km^2. For geothermal energy, the available land is estimated to be 0.1% of 4.8×10^3 km^2 mined areas in Scotland Midland Valley or equivalently 48 km^2 [12]. For biomass energy, the available land is 14.8 km^2 [62].

3. RESULTS AND DISCUSSION

The decided capacity and priority of the technology options were presented followed by the number units in this section. The overall energy supply profile and carbon footprint of the proper configuration were also presented. The results of the sensitivity analysis were presented to identify the most significant factors.

3.1. Capacity and Priority

The grading assignment for wind turbines of different capacities is shown in Table 6. The score for the technical criterion increases as the capacity is the highest (0.75) for the capacity of 3.6 MW which corresponds to the highest capacity factor (34.2%). The score for the economic criterion is the highest under the capacity of 10 kW, 1 MW and 3.6 MW corresponding to a case either with a low capital cost (10 kW) or a high capacity factor (1 MW and 3.6 MW). The score for the environmental criterion is the same among the different cases as the same GHG emission data (per unit energy generation) is used [52]. The proper generation capacity is the one that receives the highest total score. It is shown in Table 6 that the proper capacity for wind turbine deployment in Glasgow is 3.6 MW.

The grading assignment for solar PV of different capacities is shown in Table 7. The cases of 2 kW and 3 kW receive the lowest score for the technical criterion. The case of 11 kW performs best regarding the economic criterion. All cases receive the same score for the environmental criterion as the same GHG emission data (per unit energy generation) is used [53]. The case of 11 kW has the highest overall score (5.94) and 11 kW is considered as the proper capacity for solar PV implementation.

The grading assignment for GSHP of different capacities is shown in Table 8. The two capacity cases considered have the same score and thus they are considered to perform equally well. The capacity of 22.5 kW was used in the subsequent analysis.

The grading assignment for bioenergy of different capacities is shown in Table 9. For both combustion and gasification, the capacity of 2 MW has the highest score for the technical criterion. For combustion, the capacity of 2 MW has the highest score for the economic criterion, while for gasification, the capacities of 20 kW and 200 kW have the highest score for the economic criterion. This partly reflects our consideration that gasification is more suitable for small-scale, distributed applications as compared to combustion [63]. Under the same capacity, combustion has a higher score than gasification in terms of the environmental criterion. Overall, the optimal bioenergy choice is 2 MW combustion.

The priority use of renewable energy (Table 10) is resolved by comparing the scores of the optimal capacities of the technologies in terms of electricity and heat generation, respectively. Table 10 shows that the renewable electricity generation should prioritize wind turbine (3.6 MW) and have solar PV (11 kW) as the second choice (i.e. solar PV will be needed unless the electricity generation from wind turbine installation on the land available cannot satisfy the electricity demand.). Bioenergy (2 MW) should be prioritized, while GSHP (22.5 kW) is the second choice for renewable heat generation (i.e. GSHP will be needed unless the heat generation from bioenergy installation on the land available cannot satisfy the heat demand.).

3.2. Number of Units

The number of units for the optimal implementation of each renewable technology is calculated by dividing the available land area for the technology by the optimal capacity, considering the priority use of renewable energy. The numbers of units for renewable technologies are listed in Table 10. It is shown that for priority technologies wind turbines and bioenergy, the available land areas are fully utilized, and the total implementation includes 255 wind turbines and 2 combustion-based bioenergy plants. However, using wind energy and bioenergy is not enough to meet the respective electricity and heat demands and solar PV units and GSHP are needed to supplement the electricity and heat supply, respectively. In other words, the land usage of solar PV and GSHP reflects the amount of energy demand that cannot be fulfilled by the energy supply from wind turbines and biomass combustion. There should be 23497 units of solar PV panels which take up 16% of the available land area. 3382 units of GSHPs are needed which takes up 47% of the available land area.

3.3. Energy Supply Profile

The numbers of renewable technology units are determined by considering the yearly electricity and heat demands of Glasgow. However, monthly electricity and heat demands are featured by seasonality, that is, the energy demand peaks in winter (December – February), while dips in summer (June – August). The monthly energy demands in 2020 for Glasgow were estimated based on the monthly energy use profile of Scotland [64] as shown in Figure 2 (a). Meanwhile, due to the seasonal variation of meteorological factors (i.e. solar irradiation and wind speed), the electricity generation from wind turbines and solar PV varies seasonally as well. Although the electricity generation from 255 wind turbines and 23497 units of solar PV matches the demand annually, Figure 2 (a) shows that the monthly electricity generation during April – October falls short of the demand while the one from November – March exceed the demand. Hence, it is necessary to implement energy storage systems to balance the monthly electricity demand and generation.

Systems of flow battery energy storage – vanadium redox battery were considered for electricity storage, as they are suitable for large-scale implementation [65] and long-period storage [66], and are competitive in terms of efficiency, cost, system life, maintenance, and safety [67]. The efficiency of the storage systems is 85% [67]. As shown in Figure 2 (b), the accumulated electricity peaks in March (460 GWh), based on which the capacity of the electricity storage is estimated to be 62 MW vanadium redox battery. Figure 2 (b) also shows the charging and discharging profiles of the electricity storage to balance the demand and generation. The maximum electricity discharged is around 140 GWh and happens in September. Overall, to meet the renewable electricity supply target in 2020, the renewable electricity generators consist of 255 units of wind turbines (3.6 MW), 23,497 units of solar PV panels (11 kW), and 62 MW vanadium redox battery.

There is a similar mismatch between monthly heat demands and supplies as shown in Figure 3 (a). During the period of April – October, the monthly heat supplies are always higher than the demands, while the heat demands are higher than the heat supplies during the period of November – March. A system of thermal energy storage - sensible heat storage was considered to balance the monthly heat demands and supplies. The efficiency of the system is 70% [68]. Figure 3 (b) shows that the accumulated heat peaks at 85 GWh and happens in October. The corresponding capacity of sensible heat storage is estimated to be 14 MW. The maximum heat discharging happens in July and is around 25 GWh. Overall, to meet the renewable heat supply target in 2020, the renewable heat generators consist of 2 units of biomass combustion (2 MW), 3382 units of GSHP (22.5 kW), and a 14 MW sensible heat storage system.

3.4. Carbon Footprint

Without the energy storage systems, the renewable energy use that meets the targets of 3029 GWh renewable electricity and 698 GWh renewable heat has a carbon footprint of 43078 ton $CO_{2\text{-eq}}$ for electricity and 47207 ton $CO_{2\text{-eq}}$ for heating. Energy storage systems contribute to additional GHG emissions. Based on the unit carbon footprint of vanadium redox battery, 40.2 ton $CO_{2\text{-eq}}$/GWh as reported by [69], the electricity storage system that will store 460 GWh electricity has a carbon footprint of 18494 ton $CO_{2\text{-eq}}$/GWh. Based on the unit carbon footprint of sensible heat storage, i.e. 10 ton CO_{2-eq}/GWh [54], the heat storage system that will store 85 GWh heat has a carbon footprint of 850 ton CO_{2-eq}. Hence, the overall carbon footprint of renewable energy use with energy storage components has a carbon footprint 109630 ton CO_{2-eq} which is still lower than the 2020 maximum GHG emission target of 129741 ton CO_{2-eq}.

The results obtained in this work are generally consistent with some of the existing studies for city-scale planning. For example, [70] illustrated that the Scottish Government has developed heat maps for Glasgow and studied the priority of renewable energy. Energy consumption benchmark and building use data were used to model the distribution of energy consumption. It was found that the priority of electricity generation should be given to wind turbines due to its low cost. Wind turbines were reported to be one of the least carbon energy resources in and around the town which is consistent with one of the environmental basis used by our study.

[71] performed an MCA to select the proper electricity generation technologies for Lithuania. The analysis was based on a combination of AHP and an Additive Ratio Assessment method and considered five aspects, i.e. economic, technological, environmental, social and political. The results showed that biomass technologies should be given a priority among all the renewable electricity generation technologies. [72] selected the most suitable alternative renewable energy for Istanbul using an integrated VIKOR-AHP methodology. The analysis considered a variety of factors such as technical, energy, cost of operation and maintenance, investment cost, employment creation, land use, social acceptability, and emission of nitrogen oxide and carbon dioxide. The results showed that wind energy should be given priority. [73] proposed an AHP-based MCA approach to assess five sources of renewable

energy for power generation in Saudi Arabia. The five sources of renewable energy considered included wind, biomass, solar PV, and solar thermal. Technical, economic, socio-political, and environmental aspects were considered. The results revealed that the most viable renewable energy technology is solar photovoltaic, which was followed by solar thermal. Wind energy was ranked number three because of its high performance in technical and economic aspects.

3.5. Sensitivity Analysis

A sensitivity analysis is conducted to assess the impacts of weightings in technical, economic, and environmental criteria (relevant importance) on the decision in the configuration of renewable energy use. The analysis above is referred to as Case 1 where the economic criterion is most important. Two more cases, i.e. Case 2 and Case 3, are further considered with the technical and environmental criteria being the most important one, respectively. The results of the MCA analysis for all three cases are listed in Table 11.

Table 11 shows that both Case 1 (base case) and Case 3 prioritize wind turbines (3.6 MW) for renewable electricity generation while prioritizing bioenergy (2 MW) for renewable heat generation. However, Case 2 for which the technical criterion is the most important, solar PV (11 kW) is prioritized for renewable electricity generation while bioenergy (2 MW) is still the priority for renewable heat generation. The changes in priority ranking further affect the number of implementation units. For case 2, the optimal numbers of units are 95323 and 176 for solar PV and wind turbines, respectively, while they are 2 and 3382 for bioenergy and GSHP, respectively. The capacity of the vanadium redox battery is 29 MW (versus 62 MW for Case 1 and 3) to ensure the balance between monthly electricity demands and supplies. The corresponding carbon footprints for renewable electricity generation and energy storages are 72904 and 9461 ton $CO_{2\text{-eq}}$, leading to an overall carbon footprint of 129572 ton $CO_{2\text{-eq}}$ (versus 109629 ton $CO_{2\text{-eq}}$ for Case 1 and 3), which is only slightly lower than the carbon emission target.

4. LIMITATIONS

The practical planning and deployment of renewable energy can be subjected to requirements outlined by the stakeholders, consumers, investors, and policymakers. The same can be reflected by the reason that different methods including environmental, economic, and technical need to be considered in the evaluation process for renewable energy planning. Normally, the problem with decision-making stems from the fact that each stakeholder has more than one goal to meet. On most occasions, there is a trade-off between different goals, depending on the level of interests shown by the stakeholders involved.

Risks related to viable energy projects rely basically on numerous factors and regulatory procedures; moreover, they also differ in accordance with the various stakeholders' viewpoints involved in the investment sector. Policymakers are concerned with proficient policy schemes and effective designing, providing suitable incentive levels to possible renewable energy project investors, meeting the government targets. For that reason, future research is needed to test the methodology in terms of different policy schemes during both the design and deployment stages.

A wider sensitivity analysis is suggested in future work. Probabilistic concepts can be introduced to consider potential uncertainty in the values of criteria parameters. It will potentially be incorporated into the proposed method of this in the future to understand the possible ranges of configurations suggested. Additionally, it will be interesting to apply the proposed MCA for the renewable energy planning of different cities, which will accumulate a systematic database to guide renewable planning under an even larger scale (e.g., a country or region scale) and to achieve consensus about low carbon development among different cities or countries.

5. CONCLUSIONS

The sizing of the components of a renewable energy system is not only confined by demand but also the reliability of the energy supply. Therefore, it is essential to arrange and combine the generation of energy from different renewable sources to balance the issue of stability and demand. In this work, a two-stage multi-criteria analysis method was developed to identify the priority and capacities and the numbers of units of renewable energy technologies under a larger, city-scale. Technical (capacity factor and power density), economic (BCR) and environmental ($CO_{2\text{-eq}}$ emission) criteria were considered for developed the model. The method was applied to plan Glasgow's renewable energy use. The estimated capacity and priority, numbers of units of renewable energy technologies and the energy supply and carbon footprint of the decided configuration have been studied for the case of Glasgow.

The major novelty of this work includes:

- Developing a two-stage MCAM to identify the priority and capacities, also the numbers of units of renewable energy technologies under a larger, city-scale;
- Applying the method to plan renewable energy implementation in Glasgow to meet the city's renewable electricity and heat supply targets;
- Estimating the carbon saving potential of the identified proper configuration with respect to the city's emission target;
- Applying a sensitivity analysis to assess the impacts of weightings on the decision.

Specifically, when the economic criterion was most important, the analysis showed that wind turbines and bioenergy should be prioritized for electricity and heat generation, respectively. The renewable energy use plan consists of 255 units of wind turbines (3.6 MW), 23497 units of solar PV panels (11 kW), 2 units of biomass combustion systems (2 MW), and 3382 units of GSHPs (22.5 kW).

To balance monthly energy demands and supplies, the renewable energy use needed to be supported by 62 MW vanadium redox battery and 14 MW sensible heat storage. The annual carbon footprints for electricity and heat generation, energy storage, and the overall renewable energy use were 43078 ton $CO_{2\text{-eq}}$, 47207 ton $CO_{2\text{-eq}}$, 19344 ton $CO_{2\text{-eq}}$, and 109629 ton $CO_{2\text{-eq}}$, respectively, which fulfilled the emission target of 2020 for Glasgow. Sensitivity analysis showed that solar PV would be prioritized for electricity generation, which increased the total carbon footprint to 129572 ton $CO_{2\text{-eq}}$ when the technical criterion was most important. It is recommended that future studies should be done to incorporate the probabilistic concept into the method to account for potential uncertainties and to gather a systematic database on the renewable energy planning of different cities or countries.

ACKNOWLEDGMENT

This research is partially supported by the University of Glasgow's John Robertson Bequest Award.

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