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Comparative analysis of bioenergy potential and suitability modeling in the USA and Turkey

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ABSTRACT

Both estimation and evaluation of electric energy potential from biomass are quite important in terms of renewable energy aims and policies. Identification of suitable locations for biomass energy facilities carries significant benefits from the rich potential for bioenergy. In this context, the paper applies a novel methodology in two study areas, namely Boulder, Colorado, United States (USA) and Selcuklu, Konya, Turkey. First, the study calculates energy potential from animal manure (i.e., cattle and sheep) and agricultural residues (i.e., corn, wheat, and barley). Second, location suitability is obtained by means of a Geographic Information Systems (GIS)-based approach that exploits fuzzy logic and the Best Worst Method (BWM). The result for bioenergy potential shows that Selcuklu (for 2019) and Boulder (for 2017) have 10,834 kW and 1,406 kW installed capacity. Differences in the pattern of suitable locations are also apparent. Selcuklu shows a broad spatial distribution of good but relatively lower suitability scores, while Boulder's scores are more localized and extremely high (approaching 0.99), due to differing patterns of steep terrain and to differing policies regulating green space. This information indicates that the electricity generation potential and facility location suitability for biomass energy clearly differ depending on differences in study area characteristics.

Introduction

International public policy agendas highlight the need to generate power from renewable energy sources in place of fossil fuels. This need is due to various factors such as environmental pollution, an increase in greenhouse gas (GHG) emissions, rising electricity prices, and depletion of fossil fuel sources [1]. In this context, significant legal decisions worldwide aim to augment the share of renewable energy sources [2]. The European Union (EU) set goals to reach a least 32 % in renewables share, to cut GHG emissions by at least 55 % [3], and to improve energy efficiency by at least 32.5 % by 2030 [4]. Turkey aims to increase the share of renewables in electricity production to 38.8 % by 2023 [5]. In the United States (USA), state-level targets to supply electricity generation from renewable energy sources by 2030 vary widely (e.g., Connecticut [48 %], New Jersey [50 %], and California [60 %]) [6]. The work reported here compares the selection of potential locations for a renewable energy generation site in Turkey and the USA, using similar criteria and an integrated methodology in two relatively similar landscapes with slightly differing landscape and land use characteristics. One goal is to evaluate the impacts of similar criteria in two international localities. Another is to evaluate the integrated methodology as applied to the site selection process.

Bioenergy can be obtained from a wide range of organic waste (biomass) sources such as animal manure, agricultural and forest residues, and commercial and municipal solid waste. The continuing supply and well-known energy conversion technology offer advantages to the adoption of biomass, making it one of the most promising renewable energy sources [7,8]. Because of design configurations and conversion pathways, anaerobic digestion (AD) is seen as a practical bioenergy production technique that contributes to energy security and sustainable development [9]. Numerous scholars have estimated and evaluated the bioenergy potential from biomass resources for different countries across the globe, for example, in Japan [10], Iran [11], Russia [12], Malaysia [13], China [14], India [15], and Italy [16] (Table A1). Other studies focus on global bioenergy potential estimation ([17–21]). For example, Chintala et al. [22] found that corn and wheat are the primary crop types having biomass potential in the northern Midwest region of the USA, but they did not estimate the biomass potential of animal

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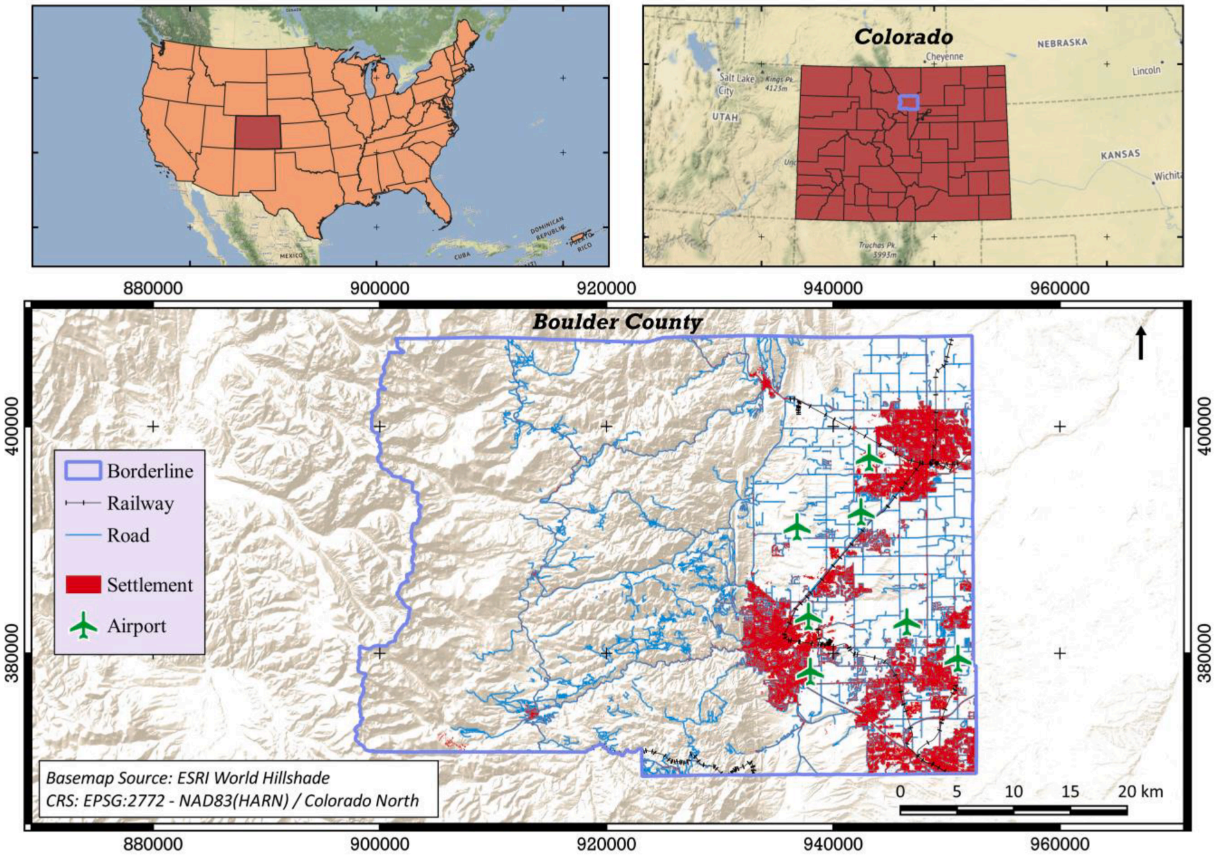

Fig. 1. The USA study area in Boulder County shows a region of smaller but fast-growing settlements and higher concentration of steep terrain in the western portion. The area contains crop farming in the east and livestock ranching in the west.

waste. In Turkey, the energy potential from animal waste and agricultural residues was calculated to be 12.8 terawatt-hours (TWh) [23] and 277.4 TWh [24], respectively. Meyer et al. [25] forecast the biogas energy potential of EU28 countries in 2030 to range between 333.3 and 638.9 TWh year^{-1}. B. Zhang et al. [26] show a spatial distribution of agricultural residue that indicates 8.6 EJ (Exajoule (1018 J)) of energy potential in China.

Determination of suitable locations for biomass energy facilities can be complicated by the necessary consideration of social, economic, and environmental factors [27–29]. For instance, Emeksiz & Yüksel [30] propose a hybrid Multi-Criteria Decision Making (MCDM) approach that considers various criteria such as climate conditions, transportation, and government incentives in order to find the best city in Turkey for a bioenergy production facility. Some studies (e.g., [31,32]) utilize Geographic Information System (GIS)-based overlay analysis without considering the relative importance of criteria. MCDM methods can assess the relative importance of different siting criteria [33,34], as do GIS-based studies [35,36]. For example, Chukwuma et al. [37] find suitable locations for a biogas power plant in the Anambra State of Nigeria by integrating GIS and Analytic Hierarchy Process (AHP) techniques. Zhao et al. [38] implement GIS and the Fuzzy-Technique for Order of Preference by Similarity to Ideal Solution (F-TOPSIS) methods for selecting the candidate locations. Jesus et al. [39] create clusters using geospatial analysis and AHP in determining suitable locations for a biodigester. Jayarathna et al. [40] identify a large number of candidate locations for biomass energy facilities in Queensland, Australia by combining the GIS-aided fuzzy logic and AHP techniques. Yücenur et al. [28] utilize MCDM to identify weights and then rank three candidate cities in Turkey for biogas facility sites. Yalcinkaya [41] implements AHP, linear fuzzy membership functions, and location-allocation analysis for finding suitable biogas plants in Izmir, Turkey.

In contrast to these previous studies, the contribution of this paper is to demonstrate the utility of an MCDM methodology within a GIS processing environment that estimates bioenergy potential and identifies suitable facility locations in two study areas. The research has two parts. The first part estimates electricity generation potential from sheep and cattle manure and from agricultural residue for two decades. The second part integrates a type of MCDM called the Best Worst Method (BWM), relying upon fuzzy logic and open-source GIS. This research applies the same methodology in study areas in two countries, namely Boulder Colorado (USA) and Selcuklu (Turkey), that have diverse geographic conditions and agricultural resource availability characteristics. The comparison between the two study areas offers insights into distinguishing bioenergy estimation based on the characteristics of the study areas.

Another reason for this comparison is to show the applicability of the applied approach for facility location selection because of the use of open data and open-source tools. It can be noted in this study that a biomass power plant is considered a bioenergy facility. The choice of the USA and Turkey study areas is that the authors of the paper are researchers in these countries who can assess and compare the specific features, policies, and strategies with respect to these countries. To the best of authors' knowledge, this paper provides the first international comparison study on bioenergy potential and facility location suitability. In the USA, the adoption of biomass as an energy source lags far behind activities in Europe, in spite of the fact that it is feasible and pragmatic in many smaller rural communities. The comparison in the paper demonstrates that is the case, showing that criteria and methods utilized to model suitable locations in countries where bioenergy is widely adopted can be applied to places in countries where adoption has been planned but not yet undertaken.

This paper contributes significant insights into how to efficiently

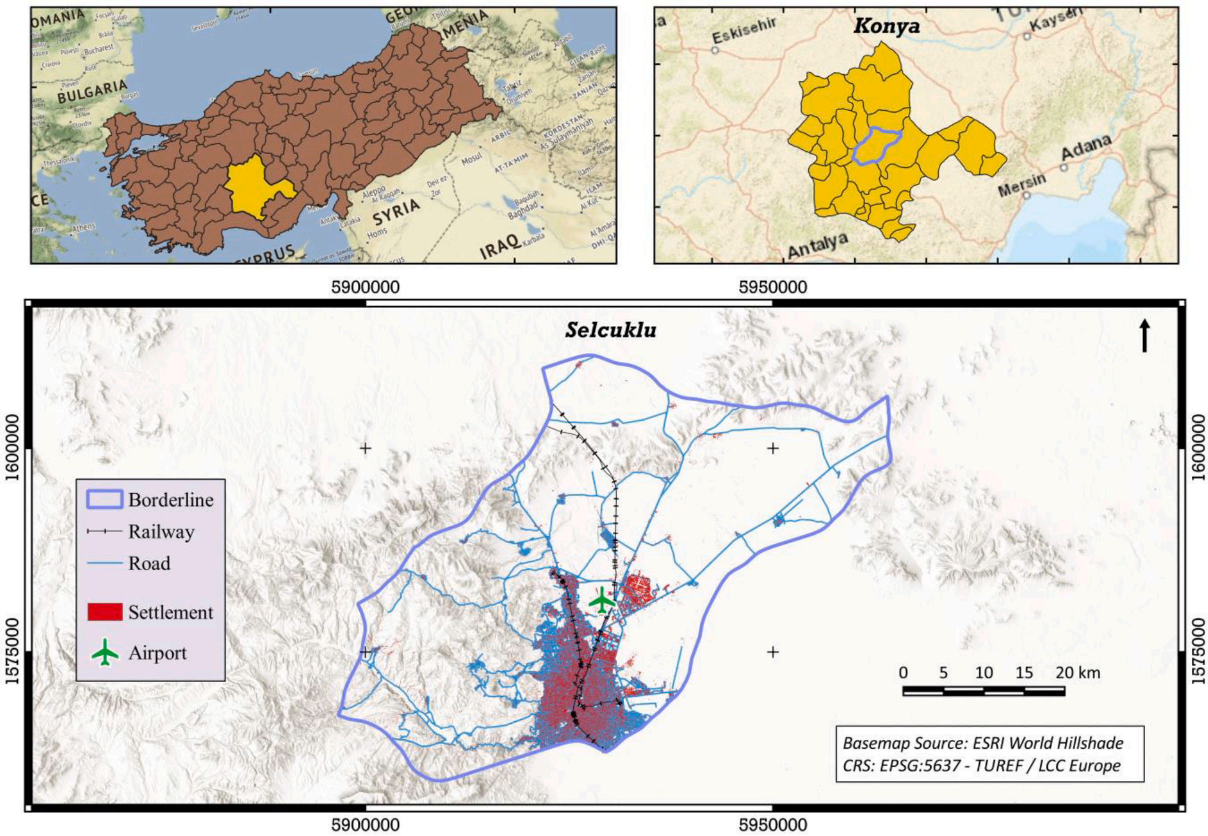

Fig. 2. The Turkish study area of Selcuklu lies at the edge of mountains to the west and north, and agriculture to the east. The town forms a core for population and development in Konya.

replicate integrated methodologies for bioenergy estimation and facility location selection. Additionally, the presented research contributes to the GIS literature on open-source data and software tools. The remainder of the paper is structured as follows. Section 2 describes the physical and economic geography of both study areas. Section 3 details materials and methods to calculate energy potential and obtain suitable locations for biomass energy facilities. Section 4 presents the results of the analysis. In the last section, the results of the research are compared across the two regions. Afterward, the contributions of the applied methodology are discussed, adding potential implications of the study.

Study areas

The two study areas in this study are shown in Figs. 1 and 2. One of these areas is Boulder County, located in the northern Front Range of Colorado, USA. Due to the forests, water bodies, and surrounding ecosystems, Boulder comprises characteristics of mountainous regions that are rapidly urbanizing in industrial and service economies [42] as well as flatter agricultural areas in the eastern half of the county. According to its Environmental Sustainability Plan [43], Boulder plans to supply 100 % of electricity needs with renewable energy by 2025. The plan also includes the reduction of county-wide GHG emissions by 90 % below 2005 levels by 2050. The population of Boulder County was 294,567 in 2010 and was estimated as 326,196 in 2019 by the U.S. Census Bureau [44].

The second study area is Selcuklu, which lies in a central district of Konya, Turkey. Konya is located in Central Anatolia, an agricultural region of the country. Selcuklu is located in a lowland area and has a steppe climate [45]. It is the largest settlement of Konya in terms of population and intensity of development. According to the Turkish Statistical Institute (TurkStat) [46], the population of Selcuklu is 662,808 in 2019. The city has a fairly high energy potential from biomass resources based on an estimation made by the General Directorate of Energy Affairs of Turkey [47]. A solar energy power plant is planned for construction within the Bagrikurt neighborhood in 2021.

Whereas federal data for Selcuklu is shared publicly every year, federal statistics for Boulder are estimated at 1 and 5 year intervals, with a full census completed each decade. This study uses the most up-to-date statistics available for both study areas. In order to work with data for comparable time periods, data selected for the study were 2007 and 2017 for Boulder and 2009 and 2019 for Selcuklu.

In addition to population, settlement density, a variety of terrain and mixed economies (service, commercial and agricultural uses), the similarity of the land area is also considered in study area selection. The areas of Boulder and Selcuklu are 1881 km^2 (726.29 mi^2) and 1931 km^2 (745.56 mi^2) respectively.

Materials and methods

Fig. 3 illustrates the framework of the methodology in this paper.

Calculating the energy potential from animal manure

First, the amount of methane generation from different types of animal manure is calculated as follows [1,48]:

$$GM_{manure} = P_{animal} \times G_{manure} \times A_{manure} \times Y_{methane} \times 365 \tag{1}$$

where: GM_{manure} is the methane generation per year (m^3 CH_4 $year^{-1}$); P_{animal} is the animal population; G_{manure} is the daily manure production of an animal (kg day^{-1}); A_{manure} is the availability factor of fresh animal manure (%); and $Y_{methane}$ is methane yield from fresh animal manure (m^3 CH_4 in tonnes of fresh animal $manure^{-1}$).

Second, the estimated methane amount that results from Equation (1) is converted to electricity generation potential by the following

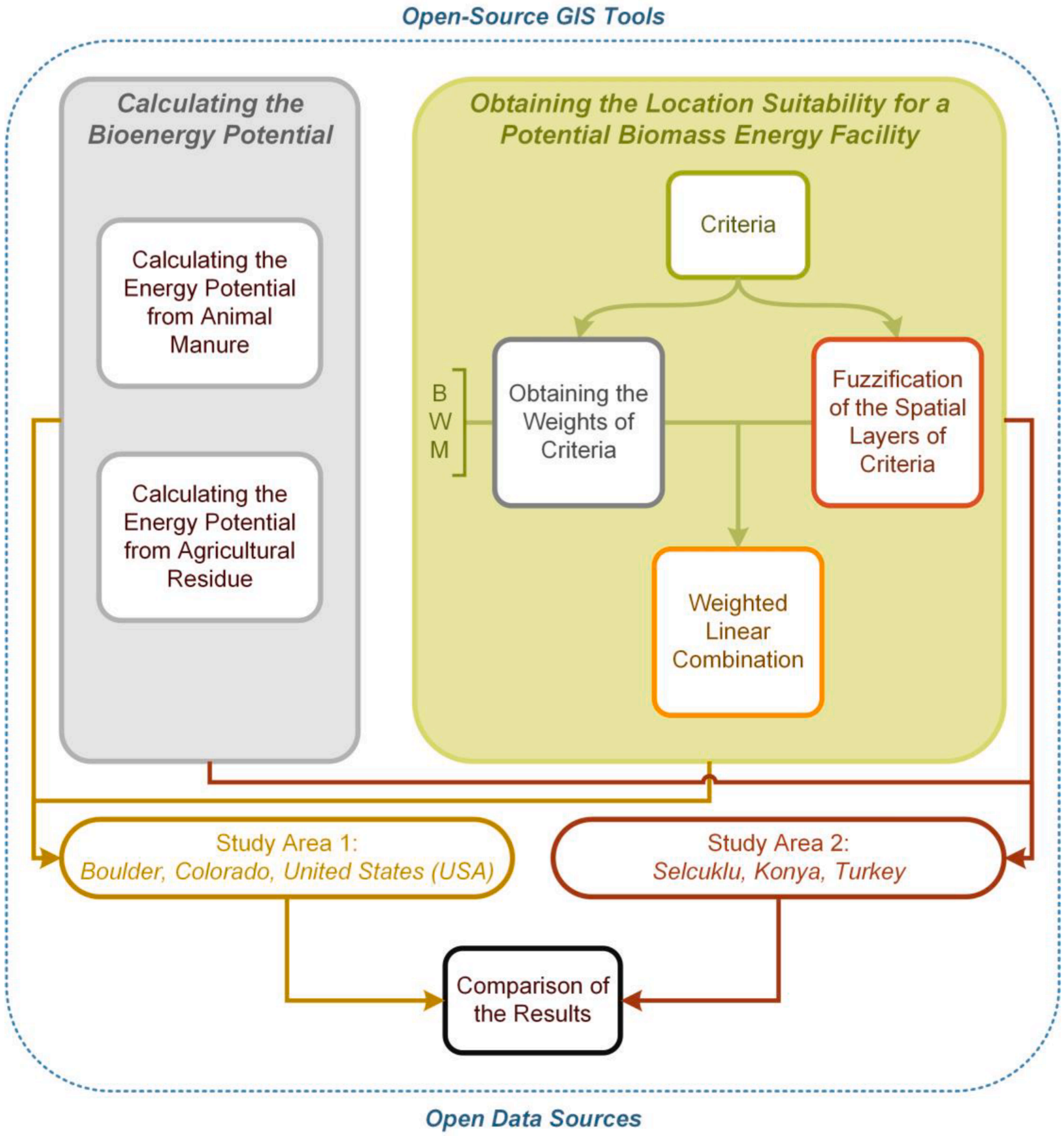

Fig. 3. The methodology of the paper.

Table 1
The number of animals by type.

Animal Type	Boulder Number	Boulder Year	Boulder Source	Selcuklu Number	Selcuklu Year	Selcuklu Source
Cattle	10,771	2007	[51]	9,940	2009	[53]
	5,986	2017	[52]	9,474	2019	[53]
Sheep	1,343	2007	[51]	74,400	2009	[53]
	955	2017	[52]	93,285	2019	[53]

equation [13,48,49]:

$$E_{biogas} = EC_{biogas} \times \frac{GM_{manure}}{R_{methane}} \times \eta \quad (2)$$

where: E_{biogas} is the electricity generation potential from biogas per year (kWh year^{-1}); EC_{biogas} is the energy content of biogas, which is utilized as 6.0 kWh/m^3 CH_4 [48,50]; GM_{manure} is the methane generation per year (m^3 CH_4 year^{-1}), which is calculated using Equation (1); $R_{methane}$ is the methane content in biogas (%); and η is the electricity conversion efficiency value of 30.0 % [13,48,50]. Cattle and sheep form the basis for calculating electricity generation potential because these animal types are dominant and common in both study areas. The numbers of

Table 2
The average values of GM_{manure}, A_{manure}, $Y_{methane}$, and $R_{methane}$ based on references in the bottom row.

Animal Type	FAM (kg day^{-1}) (GM_{manure})	Availability Factor (%) (A_{manure})	Methane Yield (m^3 CH_4 tonne FAM^{-1}) ($Y_{methane}$)	Methane Content in Biogas (%) ($R_{methane}$)
Cattle	27.8	47.3	22.1	57.8
Sheep	1.45	11.5	62.1	58.5
References	[1,13,48,54–60]	[1,11,23,25,48,61,62]	[1,48,62–68]	[69–78]

FAM: Fresh Animal Manure.

Table 3
The harvested area by crop type.

Crop Type	Study Area					
	Boulder			Selcuklu		
	Number	Year	Source	Number	Year	Source
Corn (da)	10,113.14	2007	[51]	364.00	2009	[53]
	10,376.19	2017	[52]	26,553	2019	[53]
Wheat (da)	18,696.56	2007	[51]	168,225	2009	[53]
	6,426.44	2017	[52]	156,850	2019	[53]
Barley (da)	5,410.67	2007	[51]	157,334	2009	[53]
	3,917.38	2017	[52]	238,000	2019	[53]

da: Decare, equal to 1,000 square meters, or 0.1 Hectares.

cattle and sheep are obtained from the United States Department of Agriculture (USDA) for Boulder [51,52]. The livestock statistics of TurkStat are used for Selcuklu [53]. Table 1 shows the numbers of animals by types and reference years. While it is possible that the animal manure yield and methane generation potential could differ depending on the age and breed of the animals, the total numbers of cattle and sheep are used in this study. This follows the practice used in other papers [48] when specific data on age and breed are not available. As a consequence, averaged values for fresh animal manure, availability factor, methane content, and methane yield are used to obtain estimated bioenergy potentials.

Table 2 shows the average values of variables that are used in Equation (1) and Equation (2).

Calculating the energy potential from agricultural residue

The amount of crop residue is calculated for different types of agricultural crops by the following formula [7]:

$$AR = HA \times URG \times 10^{-3} \quad (3)$$

where: *AR* is the total agricultural residue (tonnes year^{-1}); *HA* is the harvested area per year (in decare (da)); *URG* is the unit residue generation (kg da^{-1}).

The total amount of methane is then found using:

$$TMP = AR \times UMP \quad (4)$$

where: *TMP* is the total amount of methane potential (m^3 CH_4 year^{-1}); *AR* is the total agricultural residue that results from Equation (3) (tonnes per year^{-1}); *UMP* is the unit methane potential (m^3 CH_4 per tonne^{-1}).

Equation (5) obtains the electricity generation potential of agricultural residue:

$$E_{biogas} = EC_{biogas} \times TMP \times \eta \quad (5)$$

where: E_{biogas} is the amount of electricity generation potential (kWh year^{-1}); EC_{biogas} is the energy content of biogas, which is determined as 6.0 kWh/m^3 CH_4 [48,50]; *TMP* is the total amount of methane potential that results from Equation (4) (given in m^3 CH_4 year^{-1}); and η is the electricity conversion efficiency value of 40.0 % [7]. The formulas that are used in this study provide similar results with other studies that exploit different constants such as the ratio of product residue, moisture content, lower heating value, availability, and soil conservation needs. For example, the result is comparable with one study [24] that uses 13 %, 1.13, 16.7, and 15 for moisture, the ratio of product residue, lower heating value, and availability respectively. Other competing uses of crop residues were also searched in the literature without finding any specific uses beyond conventional ones [79,80].

Corn, wheat, and barley are considered in the calculation of electricity potential, since these crop types are commonly harvested for both Boulder and Selcuklu. Whereas data on harvested areas are obtained from USDA for Boulder [51,52], crop production statistics from TurkStat are used for Selcuklu [53]. Table 3 shows the amount of harvested area by crop types and the reference years of the data. Table 4 shows the values applied in Equation (3) and Equation (4).

Table 4
The values of *URG* and *UMP* based on cited references.

Crop Type	Unit Residue Generation (kg da^{-1}) (*URG*)	Unit Methane Potential (m^3 CH_4 tonne^{-1}) (*UMP*)
Corn	1,480	227.6
Wheat	325	267.8
Barley	200	319.2
References	[7,81]	[7,81]

Obtaining the location suitability for a potential biomass energy facility

The second part of the research determines the location suitability for biomass energy facilities in each study area. Facility locations are based on various criteria that can be represented spatially. The choice of criteria can affect suitability differently for different locations. For this reason, the relative importance of criteria can be obtained differentially for each study area, through MCDM methods. Criteria have been selected according to relevant literature. The same criteria (albeit with different relative importance) are used for both study areas in this research.

Criteria: Seven criteria are used in this study, including slope as well as proximity to water, roads, rail lines, green areas, settlement areas and airports. The commonly used criteria are identified and selected based on previous literature (e.g., [82]). Slope (C1) can affect location suitability in terms of the construction cost [8,27,36,82,83]. Given that the study areas have noteworthy slope variations in mountainous areas, slope is selected as one of the factors affecting the facility location selection. For this reason, areas with mild slope should be considered as highly suitable and areas that have higher slope values should be considered as less suitable or unsuitable.

Water bodies (*C*2) are needed for cooling [27,33,36,82]. The literature shares a common opinion that water bodies should be considered in the site selection of alternative locations for bioenergy facilities. In addition, the study areas have notable regions covered by water bodies. Proximity to water bodies is therefore interpreted as an important factor that needs to be considered in terms of environmental effect and facility operation efficiency. It is also important to protect sensitive habitat areas near water bodies, which complicates application of this criterion. In other words, both highly close and distant areas to water bodies might be considered as unsuitable.

Roads (C3) are important for facility locations because they are needed for the transportation of biomass residue [8,27,33,82]. In this sense, proximity to roads is one of the commonly used criteria in the literature. The main issue regarding this criterion is that current roads and distant areas to these roads should be considered as unsuitable and significantly close regions to these roads should be considered as highly suitable. Railways (C4) are considered for the same reason as roads [11,27,35,82].

Settlement areas (C5) are set aside as unsuitable for locations of biomass energy facilities to protect the quality of life aspects for local residents [27,33,36,82]. Given that urbanization and emergence of new settlement areas are increasing, proximity to settlement areas is considered a significant factor. This criterion also requires mutual considerations. Both current settlement areas and regions that are highly distant to these areas should be evaluated as unsuitable since the municipal wastes can be exploited as biomass resources.

Greenspace (green areas) (C6) should also be preserved and considered in terms of the sustainability of the ecosystem [8,27,36,82,83]. Similar to the approach to settlement areas, close or distant proximity to green areas must be considered, since wood biomass can benefit bioenergy production and at the same time, facility location should not jeopardize the green areas. The biomass energy facilities

Table 5
The data sources and types.

Data	Source/Type	
	Boulder	**Selcuklu**
Slope	USGS, 3DEP/R, 30 m [84]	EUDEM/R, 25 m [85]
Water Body	USGS, NHD/V [84]	Sentinel-2A, NDWI/R, 10 m [86]
Road Network	OSM/V [87]	OSM/V [87]
Railway Network	OSM/V [87]	OSM/V [87]
Settlement Area	NLCD (Classes: 22, 23, 24)/R, 30 m [88]	ESM/R, 10 m [89]
Green Area	NLCD, TCC/R, 30 m [88]	TCD/R, 20 m [90]
Airport	USGS, Transportation/V [84]	GDSAA/V [91]
Protected Areas	USGS, PAD-US/V [92]	GDNCNP/V [93]

R: Raster, V: Vector, OSM: OpenStreetMap, USGS: US Geological Survey, 3DEP: 3D Elevation Program, NHD: National Hydrography Dataset, NLCD: National Land Cover Database, TCC: Tree Canopy Cover, PAD-US: Protected Areas Database of the US, EUDEM: Digital Elevation Model over Europe, NDWI: Normalized Difference Water Index, ESM: European Settlement Map, TCD: Tree Cover Density, GDSAA: General Directorate of State Airports Authority, GDNCNP: General Directorate of Nature Conservation and National Parks.

should not be located near airports (C7) [11,27,34,82]. For this reason, areas with a determined distance value should be considered as absolutely suitable.

Table 5 shows the data sources, types, and (for raster data layers) spatial resolutions. As can be seen from the table, all raster data sources have 30 m or finer resolution. In this study, data are collected for two areas (in Turkey and in the USA). Six data layers for Boulder are provided by the U.S. Geological Survey (USGS), which is one of the most reliable and prolific organizations disseminating open spatial data for North America. Different data sources such as Sentinel Missions and Global Human Settlement Layer (GHSL) provide spatial data for Selcuklu. A single global data provider is available for a few data layers. For example, OpenStreetMap (OSM) provides source data for road and railway networks for both study areas. It is important to note at this point that the methodology in this paper can be applied efficiently to multiple study areas because of the provision of open-source data and software tools.

Data sources used in the present study have comprehensive metadata that provides detailed information on accuracy, precision, and resolution. This increases the trustworthiness of data considerably. It is also important to highlight that using open data that lack sufficient metadata or validation may cause unexplainable contrasts in results. A great number of countries are putting into practice the strategies that provide trusted open data for augmenting the efficiency of scientific research.

BWM: The BWM is used to identify criteria weights for this study. The method is utilized in a wide range of application areas as it carries the dual advantage of relatively low processing times and consistent results [94]. In the BWM, the Decision Maker (DM) provides pairwise comparisons that quantify the relative importance of criteria. The weights of criteria are obtained by solving a linear model with the help of these comparisons [95]. AHP is another frequently used method (see Table A2) that involves the construction of a criteria hierarchy followed by statistical pairwise comparisons of eigenvalues to establish criteria weights [96–98]. This systematic determination is considered a strength of AHP but incurs additional processing that becomes difficult to interpret for large criteria sets. There is a trend for using BWM because of the advantages in terms of processing and consistency. BWM method is thus selected because it is able to provide consistent results compared to other methods such as AHP in a quite efficient way [99,100].

All spatial analyses are conducted using open-source GIS tools, which include QGIS [101], SAGA [102], GRASS GIS [103], and GDAL [104]. It can be noted that these tools provide open-source solutions with specific spatial analytic capabilities needed to process the data. All data sources are publicly available. This means that the methodology applied in this research can be readily reproduced in different study areas anywhere in the world where data representing the warranted criteria are available.

Table 6
The fuzzy logic function types, thresholds, and references.

Criterion	Thresholds a	b	c	d	Function Type	References
C1 (°)	2	10	–	–	S(d)	[8,27,36]
C2 (m)	200	500	1000	2000	Linear	[27,33,36]
C3 (m)	100	500	1000	2000	Linear	[8,27,33]
C4 (m)	100	500	1000	2000	Linear	[11,27,35]
C5 (m)	500	1000	2000	3000	Linear	[27,33,36]
C6 (m)	200	500	1000	2000	Linear	[8,27,36]
C7 (m)	1000	2000	–	–	S(i)	[11,27,34]

C1: Slope, *C2*: Proximity to Water Body, C3: Proximity to Road Network, C4: Proximity to Railway Network, C5: Proximity to Settlement Area, C6: Proximity to Green Area, C7: Proximity to Airport, d: Decreasing, i: Increasing.

In determining a realistic spatial depiction of the seven criteria, Boolean logic might be insufficient since it is limited to presence or absence. With seven criteria, the choice of Boolean logic could result in finding no suitable areas, when a more realistic approach will identify locations that meet some criteria partially. Therefore, fuzzy logic is used, since it can account for nearby spatial context and thus intermediate values for some criteria [105]. The fuzzification of the spatial criteria is realized using different function types that can tailor the representation of criteria characteristics more realistically, reporting how closely each criterion is met within each pixel of the study areas. In this paper, thresholds for fuzzy logic function types are determined based on published literature. Two specific functions, *s-shape* and *linear*, are used in this study. While Equation (6) is applied for a linear function, Equation (7) and Equation (8) are applied for increasing and decreasing types of s-functions, respectively. In the equations below, $\mu_M(x)$ represents the fuzzified state of$x$, which expresses the specific pixel. Threshold parameters are used to depict the variances in the membership that is between 0.0 (unsuitable) and 1.0 (highly suitable).

$$\mu_M(x) = \begin{cases} 0 & x < a \\ \dfrac{x-a}{b-a} & a \leqslant x \leqslant b \\ 1 & b < x < c \\ \dfrac{d-x}{d-c} & c \leqslant x \leqslant d \\ 0 & x > d \end{cases} \quad (6)$$

$$\mu_M(x) = \begin{cases} 0 & x < a \\ \sin\left(\dfrac{x-a}{b-a} \times \dfrac{\pi}{2}\right) & a \leqslant x < b \\ 1 & x \geqslant b \end{cases} \quad (7)$$

$$\mu_M(x) = \begin{cases} 1 & x < a \\ \sin\left(\dfrac{b-x}{b-a} \times \dfrac{\pi}{2}\right) & a \leqslant x < b \\ 0 & x \geqslant b \end{cases} \quad (8)$$

Table 6 shows the function types and criteria thresholds. The spatial data layer that represents areas that are absolutely unsuitable for biomass energy facilities (as for example protected green areas) is identified by using thresholds. The eight spatial data layers are combined to a single layer that represents constrained areas. Additionally, the fuzzification tools in this study are shared publicly for interested readers [106].

WLC: To obtain suitability, the normalized spatial data and criterion weights are multiplied in a weighted linear combination (WLC) [107].

Suitability metrics are obtained using the BWM. In this methodology, the "Best" criterion refers to the variable deemed most relevant by each DM to establish suitability. Likewise, the "Worst" criterion is deemed

Table 7
The pairwise comparisons composed by DM1, DM2, and DM3. First, Best and Worst criteria are identified and then Best criterion in relation to other criteria and other criteria in relation to Worst criterion are ranked, respectively.

DM1	***BO***	C_1	C_2	C_3	C_4	C_5	C_6	C_7	
	Best Criterion: C_3	4	5	1	7	4	5	9	
	OW	4	5	9	3	4	5	1	*Worst Criterion: C_7*
DM2	***BO***	C_1	C_2	C_3	C_4	C_5	C_6	C_7	
	Best Criterion: C_1	1	2	4	9	4	3	6	
	OW	9	8	7	1	6	7	4	*Worst Criterion: C_4*
DM3	***BO***	C_1	C_2	C_3	C_4	C_5	C_6	C_7	
	Best Criterion: C_6	2	4	2	9	3	1	8	
	OW	8	6	7	1	5	9	2	*Worst Criterion: C_4*

BO: Best criterion in relation to Others, OW: Others in relation to the Worst criterion, DM: Decision-maker.

least influential. Once selected, these two are used to obtain the relative importance of other criteria by making pairwise comparisons of all other criteria relative to the Best and the Worst. Pairwise comparisons for BWM are composed by three researchers assuming differing agendas (pro-development, pro-environment, and lowest cost), and the weights are found separately for each comparison. The choice of these three different agendas (as opposed to similar agendas) can provide the most dramatic contrast in objective weights. Different agendas are reflected in the preference rankings of weights by the decision-makers, and in the outcomes as well. Each agenda is ranked independently. Then, the final weights of the criteria are calculated by averaging these weights. It is important to note that assuming the different agendas by the decision-makers can provide the objective weights and hence a holistic decision for the suitable location selection. Table 7 shows the pairwise comparisons that are composed by three DMs.

Results

Energy potential from animal manure and agricultural residue

Methane potentials from animal manure and agricultural residue are calculated separately for both study areas. Afterward, the electricity generation potentials are established from calculated methane potentials. Estimated electricity generation potentials are converted to installed capacity values based on [7]. Here, the maximum amount of electricity that can be produced by the generator is expressed as capacity. Table 8 shows the values of total methane potential, electricity generation potential, and installed capacity for both study areas in the decade. The methane potential from cattle outweighs other animal residues for both study areas in both years. In Boulder, the electricity generation potentials from cattle and sheep are estimated as 3,558 MWh year^{-1} and 16 MWh year^{-1} respectively for 2007. In Selcuklu, the electricity generation potential from cattle is estimated as 3,283 MWh year^{-1} for 2009 and approximately-four times the electricity generation potential from sheep.

It can be noted that even though Boulder has more electricity generation potential than Selcuklu based on cattle residue Selcuklu has slightly more energy potential than Boulder based on total animal manure. Boulder has a solid electricity generation potential based on the corn residue in comparison to wheat and barley residue for 2007. Selcuklu has a significant electricity potential regarding wheat and barley residue. As can be seen from Table 8, Selcuklu has an installed capacity approximately-four times higher than Boulder for the years 2007 and 2009 based on the total of animal manure and agricultural residue. The total methane potential from total animal manure in Boulder for 2017 is estimated to be 638,542 m^3 CH4 year^{-1}. The value for Selcuklu in 2019 is 1,357,487 m^3 CH4 year^{-1} for the same potential.

A similar trend regarding electricity generation potential in Boulder based on cattle and sheep residue can be seen in Table 8. Selcuklu has more electricity generation potential than Boulder with respect to cattle residue for the years 2017 and 2019. In the sense of electricity generation potential based on total animal manure, while Selcuklu and Boulder have a similar result for the years 2007 and 2009, the estimation for Selcuklu is approximately-two times more than Boulder for the years 2017 and 2019. This result is expected because Selcuklu has more suitable land cover area for animal husbandry than does Boulder.

In the context of agriculture, Selcuklu has highly concentrated areas for corn, wheat, and barley. As a result of this, the electricity generation potential of these crop types is estimated as 21,466 MWh year^{-1}, 32,763 MWh year^{-1}, and 36,465 MWh year^{-1} respectively for 2019. In Boulder, the electricity generation potential from corn and barley are calculated respectively as highest and lowest. The total installed capacity from agricultural residues (corn, wheat, and barley) is 1,179 kWh in Boulder for 2017. The same estimation is roughly ten times higher for Selcuklu. The total installed capacities of animal manure and agricultural residues are found to be similarly discrepant, with only 1,406 kWh for Boulder

Table 8
Electricity generation potential comparison.

	Total Methane Potential (m^3 CH4 year^{-1})		Electricity Generation Potential (MWh year^{-1})		Installed Capacity (kW)	
	Boulder (2007)	**Selcuklu (2009)**	**Boulder (2007)**	**Selcuklu (2009)**	**Boulder (2007)**	**Selcuklu (2009)**
Cattle	1,142,476	1,054,332	3,558	3,283	406	375
Sheep	5,076	281,205	16	865	2	99
AMT	1,147,552	1,335,537	3,574	4,149	408	474
Corn	3,406,591	122,613	8,176	294	933	34
Wheat	1,627,255	14,641,463	3,905	35,140	446	4,011
Barley	345,417	10,044,203	829	24,106	95	2,752
ART	5,379,264	24,808,278	12,910	59,540	1,474	6,797
AMART	6,526,816	26,143,815	16,484	63,689	1,882	7,270
	Boulder (2017)	**Selcuklu (2019)**	**Boulder (2017)**	**Selcuklu (2019)**	**Boulder (2017)**	**Selcuklu (2019)**
Cattle	634,933	1,004,904	1,977	3,129	226	357
Sheep	3,610	352,584	11	1,085	1	124
AMT	638,542	1,357,487	1,988	4,214	227	481
Corn	3,495,198	8,944,325	8,388	21,466	958	2,450
Wheat	559,325	13,651,440	1,342	32,763	153	3,740
Barley	250,085	15,193,920	600	36,465	69	4,163
ART	4,304,608	37,789,685	10,331	90,695	1,179	10,353
AMART	4,943,151	39,147,172	12,319	94,910	1,406	10,834

AMT: Animal Manure Total, ART: Agricultural Residue Total, AMART: Animal Manure and Agricultural Residue Total.

Table 9
The weights of criteria and their final ranking.

Criterion	DM1	DM2	DM3	Average	Rank
C1	0.1283	0.3364	0.1922	0.2190	2
C2	0.1027	0.2120	0.0961	0.1369	4
C3	0.4269	0.1060	0.1922	0.2417	1
C4	0.0733	0.0276	0.0275	0.0428	7
C5	0.1283	0.1060	0.1281	0.1208	5
C6	0.1027	0.1413	0.3158	0.1866	3
C7	0.0378	0.0707	0.0481	0.0522	6
Sum	*1*	*1*	*1*	*1*	
CR	*0.09*	*0.09*	*0.07*		

C1: Slope, C2: Proximity to Water Body, C3: Proximity to Road Network, C4: Proximity to Railway Network, C5: Proximity to Settlement Area, C6: Proximity to Green Area, C7: Proximity to Airport, CR: Consistency Ratio.

and 10,834 kWh for Selcuklu. Table 8 also shows that the installed capacity differences between Boulder and Selcuklu increase after the ten year period.

Location suitability for biomass energy facility

Table 9 lists the weights of criteria that are calculated based on the comparisons in Table 7. All consistency ratios are less than 0.1, indicating that decisions are sufficiently consistent for each agenda. C3 (proximity to road network), C1 (slope), and C6 (proximity to green area) were respectively selected as the best criteria by DM1, DM2, and DM3. While DM1 identified C7 (proximity to airport) as the worst criterion, both DM2 and DM3 selected C4 (proximity to railway network). Table 9 also shows that C3, C1, and C6 are ranked as first, second, third based on the averaging of weights. Proximity to roads is quite relevant in terms of transportation of residues and cost. In addition, it is important to note that slope has a noticeable effect on location suitability. Green areas are considered as a noteworthy factor in finding the optimal location of the biomass energy facility.

Next, the fuzzified spatial datasets (Fig. 4 and Fig. 5) of all criteria are created by using the thresholds in Table 6 for both Boulder and Selcuklu. In this way, the suitability values are normalized to range between 0 and 1 according to the criteria.

Fig. 4a presents that one part of Boulder is highly flat, increasing its suitability for the facility location. Fig. 4b shows that water bodies distributed throughout Boulder have varying suitability for the bioenergy facility. Fig. 4c and d demonstrate the proximity to road networks and the railway network. Fig. 4e illustrates highly suitable areas near settled parts of Boulder. Fig. 4f shows that areas close to green space are not suitable. And Fig. 4g shows that most of the county is suitable in terms of being distant from regional airports. Comparing Fig. 4a and 4f, one sees that while the slope criterion marks highest suitability in the eastern half of the study area, much of this region is constrained to lower suitability due to the presence of green space.

Fig. 5a illustrates that more suitable lands are more evenly distributed in the flatter areas of Selcuklu, save for proximity to water bodies (Fig. 5b). Similar to Boulder, Fig. 5c and d show areas of high suitability near road and railway networks. Fig. 5e and f indicate non-suitable areas due to proximity to settlement areas and green space areas, and note the broader distribution of green space relative to the high concentration in the flatter parts of Boulder. Fig. 5g indicates that almost all areas in the Selcuklu are highly suitable based on distance from airports, also similar to the situation in Boulder.

By means of WLC, each fuzzified spatial dataset pixel is first multiplied by its responding weight, and then the suitability dataset is found by summing the product of each multiplication. The final suitability datasets are achieved by masking unconstrained areas from this dataset. Fig. 6 and Fig. 7 illustrate suitability maps of biomass energy location facilities for Boulder and Selcuklu, respectively. Fig. 6 shows that large areas of Boulder are unsuitable for locating biomass energy facilities, because many areas are constrained due to green space, protected areas, and settlement areas. However, areas in Boulder categorized as suitable carry very high suitability values. That is to say, many suitable pixels have scores of 0.99, which is close to absolute suitability (1.00). In contrast, there are more suitable pixels in Selcuklu but with wider ranges of suitability values overall (Fig. 7). As such, the alternative locations chosen for Selcuklu lie at the edges of highest scoring regions. In addition, Selcuklu has fewer areas than Boulder constrained for green space or high slope terrain.

As mentioned before, the suitability datasets have 30 m resolution. Since the area dedicated to a biomass energy facility should be at least 4 ha as suggested in the literature, suitability datasets are resampled to 200 m resolution by averaging pixel values. Then, four alternative pixel (200 m^2) locations for biomass energy facilities are selected for both study areas. The suitability values of all alternative locations are at least 0.81 and 0.89 in Selcuklu and Boulder, respectively.

Contributions of the applied methodology

Although other published studies concentrate on bioenergy estimation, the present study provides several novel contributions, specifically related to content and methods for siting bioenergy facilities. In terms of content, this work offers new insight into how to differentiate bioenergy potential and bioenergy facility location selection depending on varying landscape, demographic and economic characteristics of different study areas. In this study, bioenergy potentials for selected kinds of animals and agricultural products are calculated for two study areas. In previous studies comparing different countries (e.g., [108]), the bioenergy potentials calculated for cities or districts are visualized using GIS technology to present the overall spatial distribution of bioenergy potential. A number of studies (e.g., [109,110]) carry out a spatio-temporal analysis for a single study area to show the bioenergy potential trends over time. One contribution of the presented research is to compare two study areas, in agricultural regions undergoing fast development.

Quite a few studies concentrate on finding the bioenergy potential for specific regions using the land characteristics of the region (e.g., [111–115]). This is because geospatial data pertaining to various factors such as terrain, climate, geology, and lithology forms an important basis to estimate bioenergy potential. The current study also adopts this approach, adding criteria on settlement and economic use of the land.

The present study also makes several methods-based contributions. In contrast with previous studies on bioenergy estimation (e.g., [7,24,48,116]), the main aim of this study is to compare international study areas. Regarding the location selection for a bioenergy facility, a number of authors rely on the MCDM approach (e.g., [11,31,36]) to find the relative importance of criteria. The presented research differs from previous studies in using BWM that is a newer and more reliable method than various MCDM or AHP [27,33,37].

Another methodological contribution is the use of fuzzification, which is seldom utilized to establish the suitability characteristics of various criteria that affect the location selection (but see for example [8,41]). The present work differs from previous studies in applying a suite of different fuzzy logic functions and thresholds. A binary suitability model indicating that sites either do or do not meet all seven criteria would not identify as many suitable locations in either study area, for a range of possible reasons relating to proximity to water, transportation, or settlement.

An additional methodological contribution relates to a chosen strategy that does not require a prior determination of candidate locations before site selection, similar to location-allocation models proposed in the literature (e.g., [117]). And where previous studies utilize only one or two of the WLC, BWM, or GIS methods for site selection of the bioenergy facility, our study integrates all three and incorporates fuzzy logic, and the analysis is stronger for having done so.

A final contribution is the exclusive use of open-source tools since this issue is not reflected to the same degree in previous studies. Open-

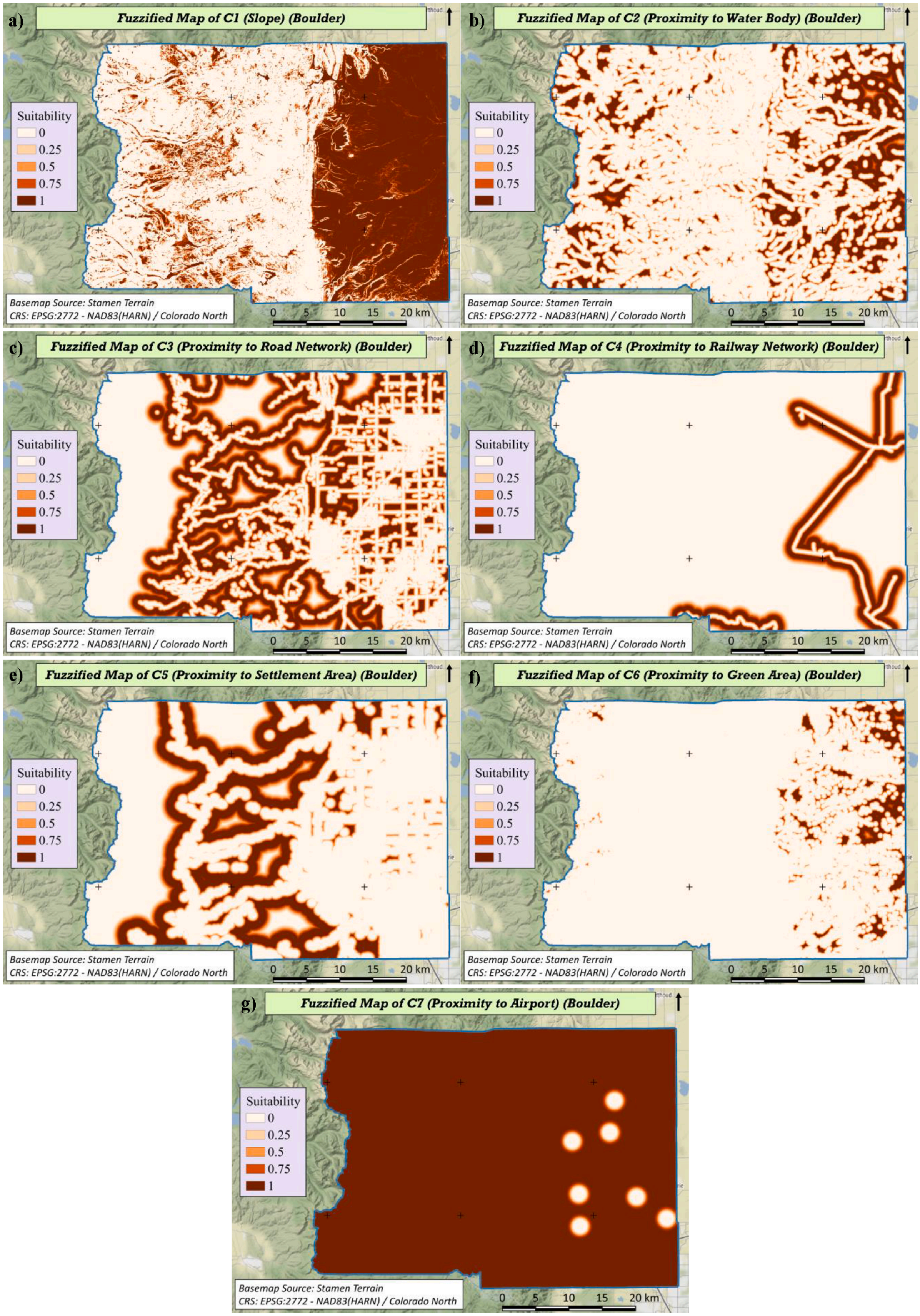

Fig. 4. Fuzzified maps of criteria for Boulder.

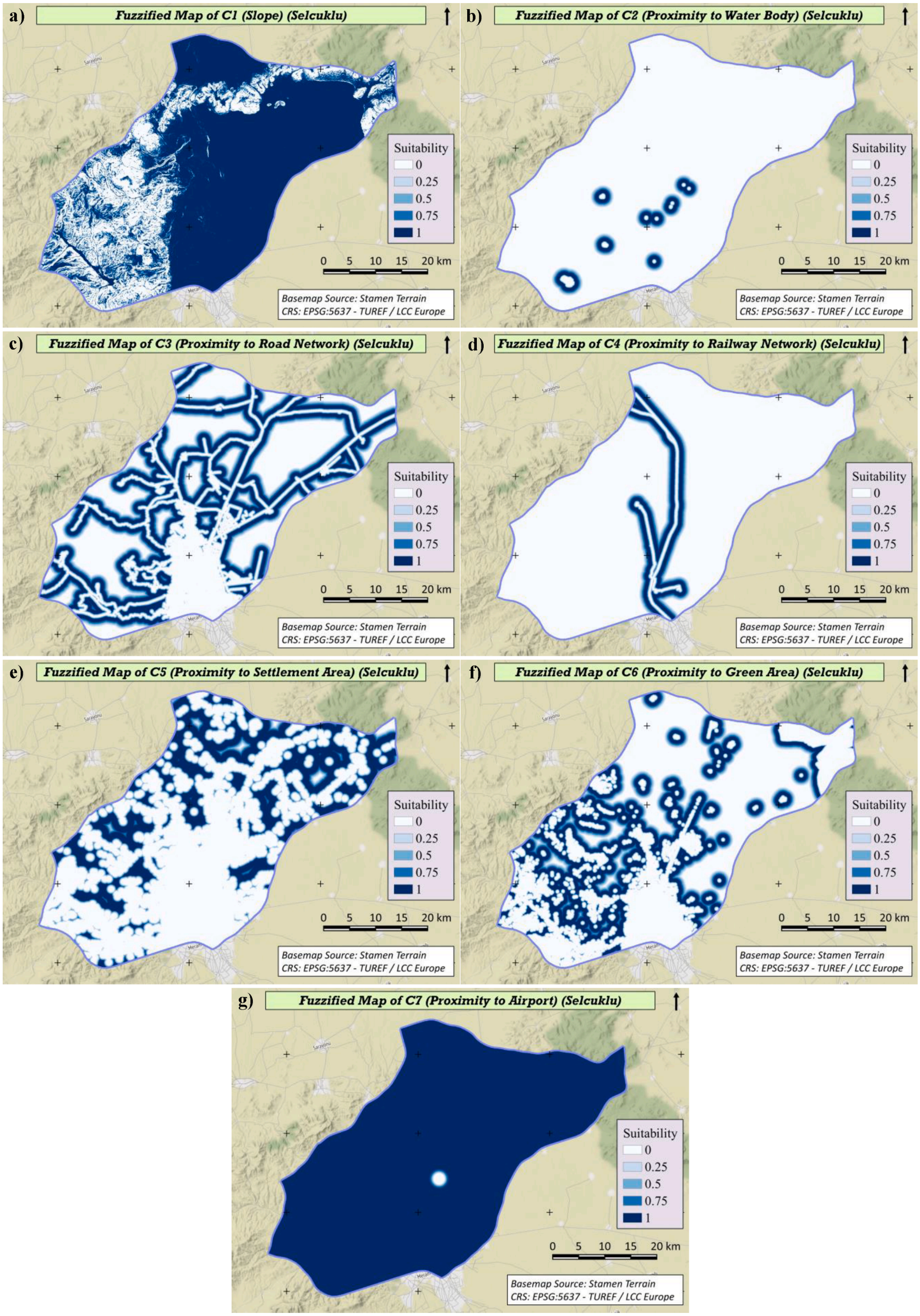

Fig. 5. Fuzzified maps of criteria for Selcuklu.

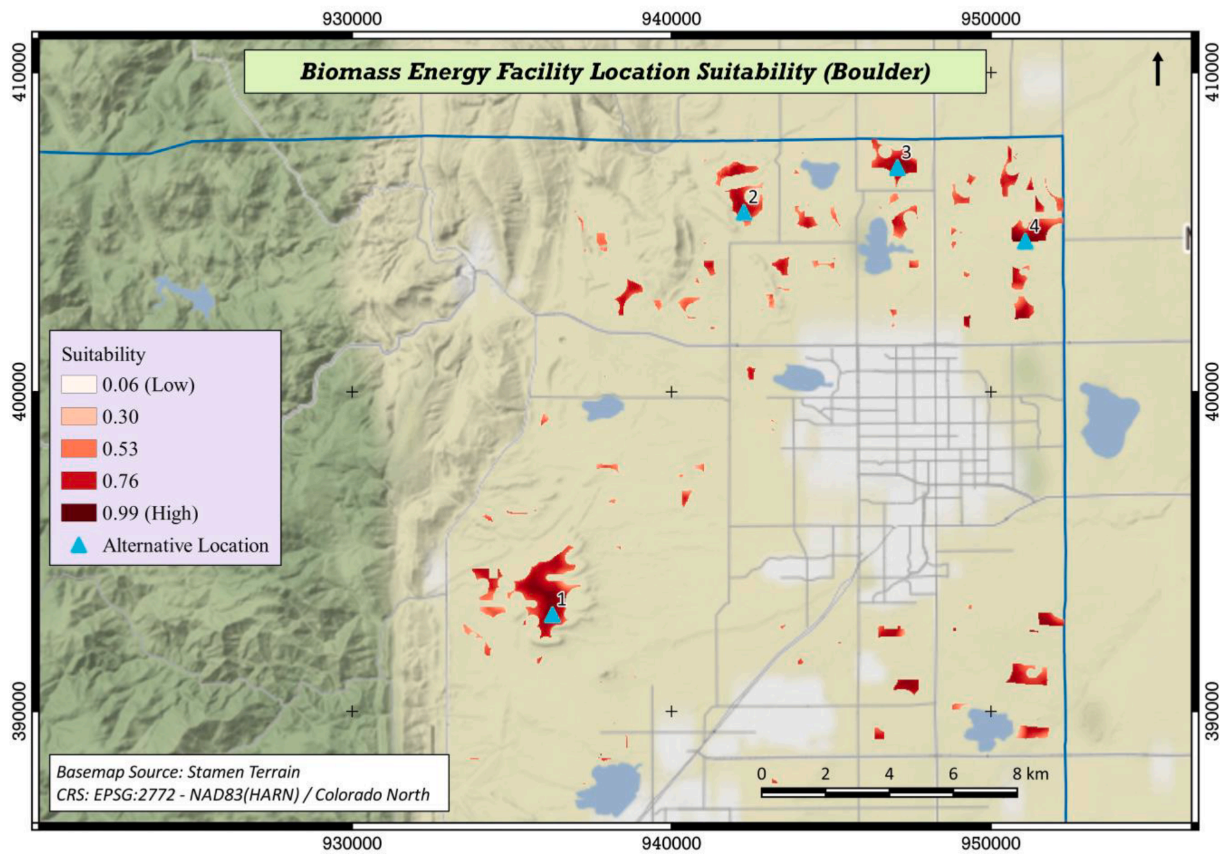

Fig. 6. Biomass energy facility location suitability for Boulder. The four alternative locations are chosen to reflect core locations in the highest scoring and largest suitability areas.

source tools make it easier for other scholars to validate the reliability and reproducibility of the research, making it possible to apply the methodology in this paper to other study areas where researchers may lack access to proprietary GIS software.

Summary and implications

This paper presents a combined approach that estimates energy potential from biomass resources and suitable locations of the bioenergy facilities. By applying the same methodology in two study areas, it is shown that energy potential and suitable facility locations can vary depending on local topography, settlement patterns, and agricultural economies. Boulder and Selcuklu are both fast-growing settlements abutting rural space, agricultural and livestock growing areas. The Selcuklu population is roughly twice as large as Boulder, in roughly the same size settlement area. Local governments in both places have stated commitments that support the adoption of renewable energy in the immediate future. Farms in both areas support crops and livestock cultivation.

In terms of biomass resources, Selcuklu shows a much more concentrated livestock resource than Boulder, with about half again as many cattle and nearly ten times as many sheep for both decades. Selcuklu also shows higher crop resources with corn, wheat, and barley as primary acreage, as shown in Table 3. Due to the higher concentration of land cover devoted to farming and livestock ranching, the Selcuklu bioenergy potential (i.e., installed capacity) is about ten times greater than in Boulder for both decades (nearly 11,000 kW versus just above 1,000 kW for the newer decade). Not surprisingly, the results demonstrate that the number of animals and the size of harvest directly affect the biomass energy potential.

Results of the facility location suitability are more interesting, showing that landscape conditions appear to have clear differential impacts on the pattern and spatial arrangement of suitable locations. Slope seems to have the primary impact, which makes sense given the physical constraint to establish an anaerobic digestor on relatively flat terrain. Boulder is relatively flat in the eastern portion and very mountainous in the western half, and this impacts the arrangement of road and rail networks, settlement density, proximity to water and open space as well as to the seven airports. Selcuklu is also characterized by mountains in the southwest portion and flatter land in the east and north, but the mountain elevations are much lower than Boulder, affording a more uniform road network to settlements throughout the study area. The two study areas differ markedly with respect to the distribution of open space, with Boulder's green space more broadly arranged within the study area. As a consequence of all of these landscape conditions, suitable locations in Boulder are quite localized but suitability scores are relatively high at every location. In contrast, Selcuklu has a much larger expanse of suitable locations, especially in the flatter portions, but with fewer very high suitability scores. In spite of these differences, four suitable facility locations were identified in each study area.

One limitation of this study is that only seven criteria have been analyzed. For example, the addition of soil type, proximity to the electricity grid or to existing power stations, or to existing clusters of farms and livestock ranching, and other criteria that might be more prominent in other study area landscapes could play a highlighted role that is not demonstrated here. Further research in a variety of landscape conditions, terrain types, and settlement patterns will be needed to better understand the role that such criteria might provide in a suitability analysis. Additional criteria that could make the model more precise include the locations of existing farms and/or agricultural areas that are exploited for obtaining the animal manure and agricultural residues.

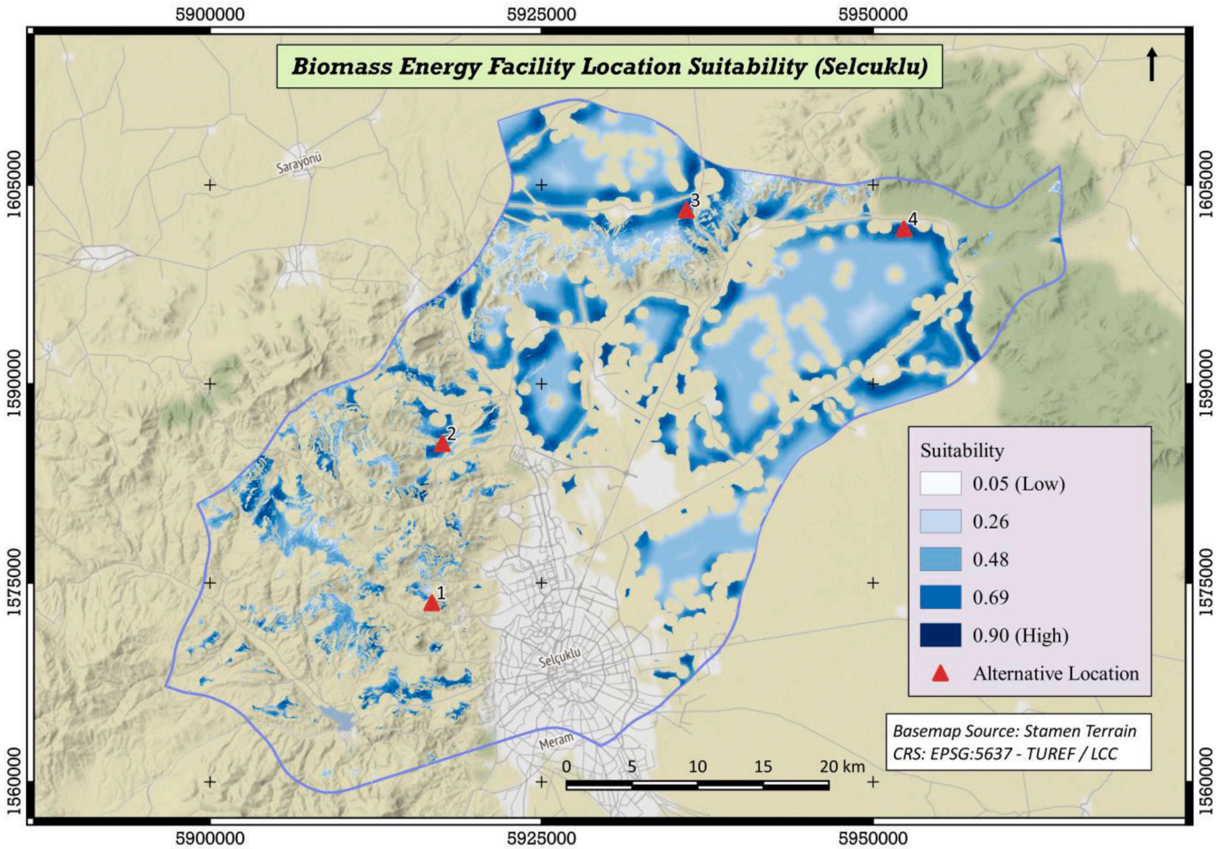

Fig. 7. Biomass energy facility location suitability for Selcuklu. The four alternative locations are chosen to reflect core locations in the highest scoring and largest suitability areas.

Such data are not available in the public domain for Boulder, but in other study areas where such information is freely available, it could be included in the location selection analysis for the bioenergy facility. Given that the economic aspect is highly significant for bioenergy applications, transportation costs as well as return of investment estimations might be included also in the analysis for the facility location selection.

Another limitation is that policy and regulations have been noted but not integrated explicitly into this analysis. For example, a regulation against siting an energy facility on wetlands, or near institutions such as schools, hospitals or prisons could have some impact on findings in other study areas. These factors did not occur in the two study areas used here, but researchers should take note in other locales. Other methodological limitations are evident in comparing among other information technology (IT)-driven models and mixed-integer linear programming models. An interesting study could compare BWM with AHP methods to establish if different suitability outcomes emerge. Alternatively, more DMs might be included the pairwise comparisons in the BWM. Also, the proposed methodology in this paper can be utilized in more study areas to enhance the proof of applicability.

The data used in this study appears to be temporally stable and representative of both areas. Dramatic land-use changes for both study areas are unlikely for either study area although population growth is expected in both regions' larger towns. In addition, similar trends to the data presented here can be seen in examining different years. Even if drastic changes do occur, they will not considerably change the implications of the primary focus on establishing suitability for renewable energy production in fast-growing semi-rural areas.

There is a solid potential to apply the model/methodology in this study to different regions of the world. One reason for this is that the results for two highly distinct regions of the world are provided showing clear and differentiated impacts of one or more criteria on the suitability models. Another reason is directly related to one of the main contributions and aims of the paper, that is using open-source tools and open data. In this regard, it is thus shown that suitable site selection results can be obtained using the existing spatial data regarding the different study areas and the same model that allows users to apply spatial analysis with fuzzy logic functions.

The presented study provides a vital aspect to bioenergy-based research in several respects. First, it contributes to the existing body of knowledge by estimating electricity generation potential. Second, it demonstrates that the BWM method facilitates efficient selection of suitable locations for bioenergy facility. Third, the paper shows how to combine fuzzy logic techniques to establish suitable locations that meet stated criteria either partially or completely, providing a realistic and repeatable methodology to systematically prioritize a range of solutions in the event that all criteria cannot be fully met. The presented study also demonstrates generalizability in applying the combined methodology to different geographic areas. A final contribution is to show that open-source GIS tools and data sources are becoming readily available in many parts of the world, reflecting the growing trend for research reproducibility and replicability. In summary, this study demonstrates that comparative suitability modeling can follow from fuzzified criteria. The comparison between different international locations can raise important points about aspects of the suitability modeling and criteria, as well as distinguishing possible impacts of differing land use and green space policies. All of these factors may need to be incorporated to achieve a fully realistic picture of the location potential for bioenergy facilities in semi-agrarian communities, in any nation.

Table A1
The details of the country-focused studies on bioenergy estimation.

Reference	Country	Context
[10]	Japan	Estimates of bioenergy potential by using the different types of the sources such as livestock residues and surplus wood
[11]	Iran	Estimates of bioenergy potential by considering the livestock manure
[12]	Russia	Estimates of bioenergy potential based on crop residues, livestock waste, forest residues, municipal solid waste, and sewage sludge
[13]	Malaysia	Estimates of bioenergy potential by taking farm animals and slaughterhouses into account
[14]	China	Estimates of bioenergy potential by considering crop residue
[15]	India	Estimates of bioenergy potential by using the crop residue
[16]	Italy	Evaluations of bioenergy potential

Table A2
The weighting methods that are used in previous works.

Reference	Method
[8]	AHP
[27]	AHP
[28]	SWARA
[30]	Multi Attribute Utility Theory (MAUT)
[33]	AHP
[34]	AHP
[36]	AHP
[37]	AHP
[38]	F-TOPSIS
[39]	AHP
[40]	AHP
[41]	AHP
[82]	Weight of Evidence

CRediT authorship contribution statement

Dogus Guler: Conceptualization, Methodology, Investigation, Formal analysis, Visualization, Writing – original draft, Writing – review & editing. **Barbara P. Buttenfield:** Conceptualization, Investigation, Methodology, Writing – review & editing, Supervision. **Georgios Charisoulis:** Conceptualization, Writing – review & editing. **Tahsin Yomralioglu:** Supervision, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendices

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