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Multicriteria GIS modeling of wind and solar farms in Colorado

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ABSTRACT

The majority of electricity and heat in Colorado comes from coal and natural gas; however, renewable energy sources will play an integral role in the state's energy future. Colorado is the 11th windiest state and has more than 250 sunny days per year. The objectives of this research are to: 1) determine which landcover classes are affiliated with high wind and solar potential; and 2) identify areas that are suitable for wind and solar farms using multicriteria GIS modelling techniques. Renewable potential (NREL wind speed measurements at 50 m above the ground and NREL annual insolation data), landcover, population density, federal lands, and distance to roads, transmission lines, and cities were reclassified according to their suitability. Each was assigned weights based on their relative importance to one another. Superb wind classes are located in high alpine areas. Unfortunately, these areas are not suitable for large-scale wind farm development due to their inaccessibility and location within a sensitive ecosystem. Federal lands have low wind potential. According to the GIS model, ideal areas for wind farm development are located in northeastern Colorado. About 41 850 km^2 of the state has model scores that are in the 90–100% range. Although annual solar radiation varies slightly, inter-mountain areas receive the most insolation. As far as federal lands, Indian reservations have the greatest solar input. The GIS model indicates that ideal areas for solar development are located in northwestern Colorado and east of Denver. Only 191 km^2 of the state had model scores that were in the 90–100% range. These results suggest that the variables used in this analysis have more of an effect at eliminating non-suitable areas for large-scale solar farms; a greater area exists for suitable wind farms. However, given the statewide high insolation values with minimal variance, solar projects may be better suited for small-scale residential or commercial projects.

1. Introduction

Greenhouse gases concentrations have risen over the last 250 years from greater fossil fuel use, modern wide-scale agriculture, and land use alteration [1]. According to ice core data, current carbon dioxide and methane concentrations are greater than at any point in the last 650 000 years [1]. Although fossil fuels are still plentiful and inexpensive, the threat of global warming has caused many to explore a switch to alternative, renewable energy sources.

Approximately 98% of energy produced in Colorado comes from fossil fuels [2]. More specifically, 72% of electricity comes from coal and 75% of homes rely on natural gas for heat [3]. Despite this, it is projected that renewable energy sources, such as wind and solar power, will play an integral role in the future. Colorado is the 11th windiest state [2,3]. Estimates suggest that Colorado, with more than 250 sunny days per year, could generate as much as 83 000 000 MW-hours of electricity from solar technologies on a yearly basis [2,3]. The Governor's Energy Office has shown interest in exploring clean, renewable energy by supporting outreach programs such as the Wind for Schools program for rural teachers and students. An anemometer loan program has recently been created to examine local wind potential. Financial incentives for investing in renewable energy are numerous [2]. With the passing of the American Recovery and Reinvestment Act, Governor Ritter believes that Colorado's New Energy Economy will be enhanced, providing new green jobs across the state [2]. With renewed interest and financial support, geographic areas that are ideal for large-scale wind and solar farms must be located.

Suitability mapping involves using a variety of data sources in which weights are assigned to geographical criteria. Data are often imported into a Geographic Information System (GIS), which combines potentially unrelated data in a meaningful manner. Weights that emphasize the relative importance of one criterion to another are often determined by managers, research specialists, stakeholders, or interest groups to enhance decision-making. A variety of environmental, transportation, planning, waste management, water resources, forestry, agriculture, housing, and natural hazard applications have been undertaken using GIS multicriteria modeling techniques [4–15].

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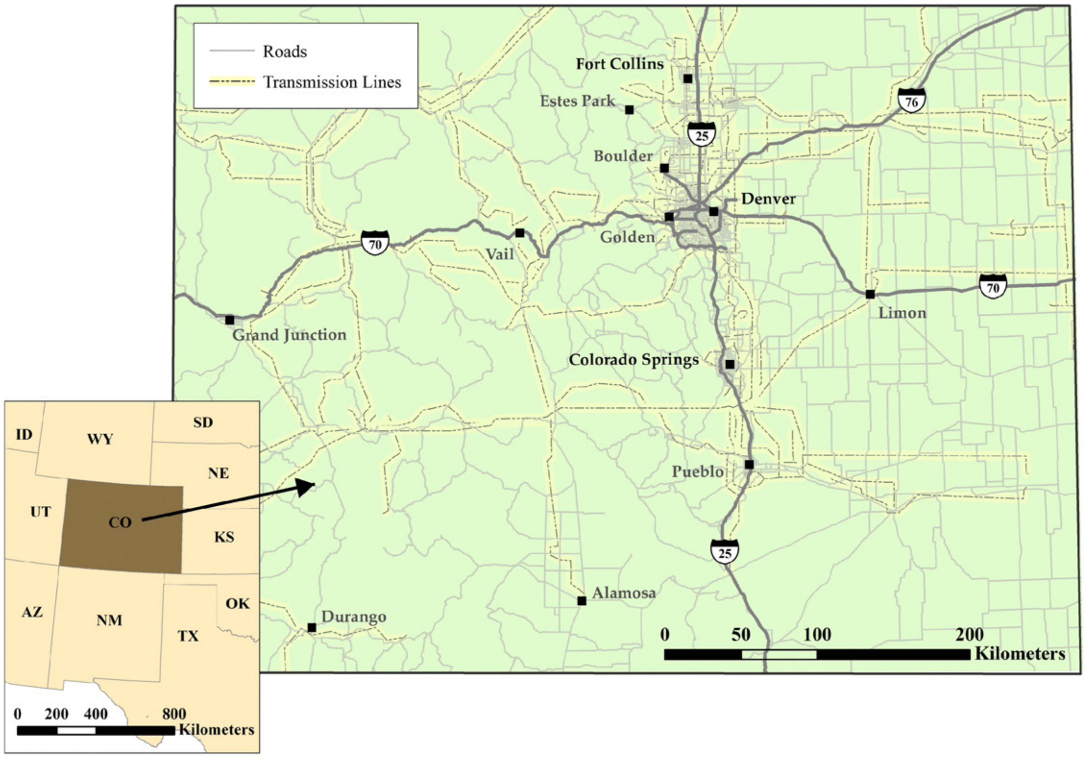

Fig. 1. Location of major roads, cities, and transmission lines in Colorado.

Multicriteria analysis in a vector data model (discrete point, line, and polygon representations) often involves Boolean operators such as AND or OR [16]. An AND operator (intersection) can result in rigid solutions – a variable meets the criterion or it does not. An OR operator (union) is very liberal – results will be included even if a single variable meets the criterion. Multicriteria analysis in a raster data model (continuous grid-based representations) allows more trade-off among variables – a low score on criterion can be offset by a high score on another [16]. GIS data model selection can lead to different optimal solutions [16]. For the aforementioned reasons, most researchers prefer using a combination of data models to control the degree of substitutability among criteria.

Questionnaires reveal that common criteria and meaningful weights are often difficult to define [17]. According to surveys of the public and private sectors, criteria for wind farms include avoiding mountain summits, steep slopes, woodlands, or dense populations. Ideally, sites should also be close to roads and the existing power grid system [17,18]. When modeling solar farms, the number of sun hours, irradiance, temperature, and aspect must be taken into account to maximize potential. Geographic variables such as landcover or vegetation that increases shading, access to highways for maintenance and repair, population density, and location of substations also play a role [19].

The objectives of this project are twofold: 1) explore which landcover classes have high wind or solar potential in Colorado based on existing National Renewable Energy Laboratory (NREL) data sets; and 2) identify areas are suitable for wind or solar farm development using multicriteria GIS modelling techniques.

2. Methods

The following variables were obtained from digital databases: NREL wind speed and solar potential classes, landcover, population density, federal lands, and location of roads, transmission lines, and

Table 1
GIS criteria used to model wind and solar farms.

Variable	Ideal Conditions	Original Data	Type	Final Data	Type	Possible Values	Weight	Original Resolution	Final Resolution
Wind Potential	NREL Class 7 (superb)	Categorical	Grid	Categorical	Grid	[0.14, 0.29, 0.43, 0.57, 0.71, 0.86, 1.00]	3	200 m	1500 m
Solar Potential	Maximize W/m^2/day	Continuous	Grid	Continuous	Grid	[0–1]	3	40 000 m	1500 m
Distance to Transmission Lines	Closer to Transmission Lines	Discrete	Line	Continuous	Grid	[0–1]	2	NA	1500 m
Distance to Cities	Far Away from Cities	Discrete	Point	Continuous	Grid	[0–1]	1	NA	1500 m
Population Density	Low Population Density per Block Group	Categorical	Polygon	Categorical	Grid	Discrete Values Ranging from [0–1]	1	NA	1500 m
Distance to Roads	Close to Roads	Discrete	Line	Continuous	Grid	[0–1]	1	NA	1500 m
Landcover	Short Vegetation, Subdued, Stable Topography	Categorical	Polygon	Categorical	Grid	[0.33, 0.67, 1.00]	1	NA	1500 m
Federal Lands	Not in Federal Lands	Categorical	Polygon	Categorical	Grid	[0, 1]	1	NA	1500 m

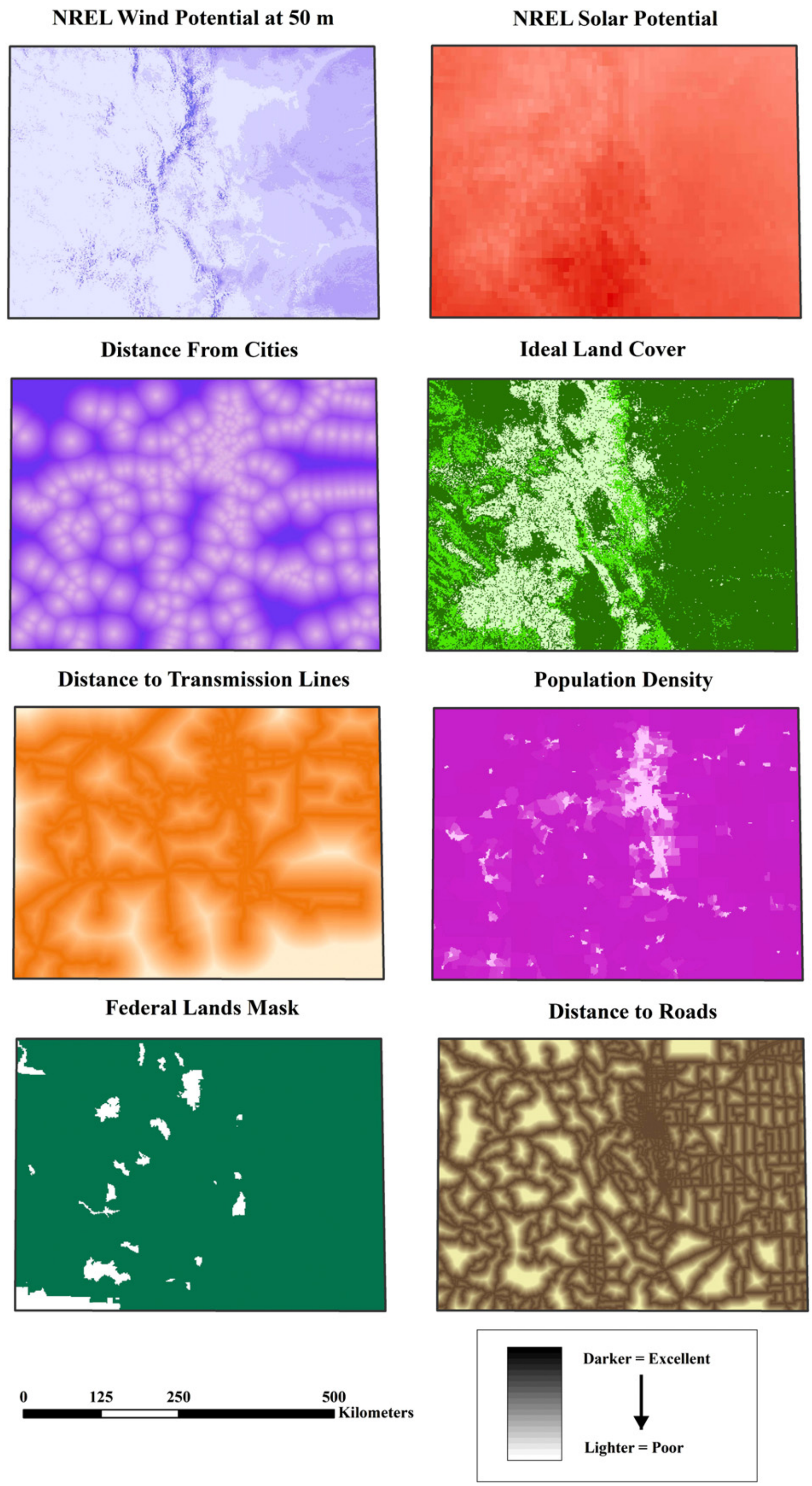

Fig. 2. GIS variables used to model ideal locations for wind or solar farms.

cities (Fig. 1). Wind speed categorical GIS data were obtained from NREL. The data are based on wind speeds measured at 50 m above the ground and are considered a TrueWind solution that has been adjusted based on surface roughness and historical data. The data were produced during 2003–2004 at a 200 m resolution and contain seven categories ranging from poor (1) to superb (7). Certainty of classes was determined by evaluating the abundance and quality of wind data, complexity of the terrain, and geographic variability.

Annual direct normal solar radiation GIS data for concentrating systems, which track the sun throughout the day, were also obtained from NREL. The insolation values were derived from a Climatological Solar Radiation (CSR) model, which incorporates cloud cover, water vapor, trace gases, and aerosols in the atmosphere to estimate total insolation [20]. Grid cells were output at a 40 km resolution and were validated with ground measurements [20].

Using ArcGIS 9.3©, the seven wind categories and the solar radiation estimates were rescaled from 0 to 1 by dividing by the maximum value in the grid. Each data set was resampled to 1500 m using an averaging filter. Wind and solar data were given a weight of three, the greatest weight given its importance compared to the other variables (Table 1).

Transmission lines vector files were also obtained from NREL. A distance grid was calculated at a 1500 m resolution. The grid was rescaled from 0 (least desirable, far away) to 1 (ideal, close) based on proximity to the existing transmission line network. Distance to existing transmission lines was given a weight of 2, the second highest weight assigned to the input variables (Table 1).

Point locations of cities were obtained, and a distance grid was generated. The grid was rescaled from 0 to 1 at a 1500 m resolution. In order to avoid NIMBY opposition, locations that were farther away from cities were considered more suitable for renewable energy development. Distance from cities was given a weight of 1 (Table 1). Population density data were obtained from census block groups for 2000. Since the data consisted of polygons, it was necessary to convert the block groups into a grid with a 1500 m resolution. The data were then standardized from 0 to 1; ideal conditions exist where population density is the lowest. Population density was also given a weight of 1 (Table 1). GIS data containing Colorado roads were obtained, and a distance grid was produced at a 1500 m resolution. In order for easy construction and repair, locations that were closer to existing roads were considered more suitable. Distance to roads was also given a weight of 1 (Table 1).

Landcover were categorized according to their suitability for development. Three classes were created. Ideal locations contained short vegetation, such as shrubs, prairie, grasses, scrub, steppe, agriculture, logged areas, or barren lands, which would not impede wind or reduce solar insolation. Areas that were not as suitable contained sparse, but taller vegetation (piñon, juniper, or ponderosa woodlands) or wetlands, which would be difficult to develop due to their ecologic importance. Non-ideal landcover contained pine, subalpine, and aspen forest or areas that would be difficult to develop based on their inaccessibility, instability, or degree of existing development. Dunes, bedrock scree, ice, cliffs, canyons, alpine tundra, developed areas, and mines fell within this category. Landcover data were given a weight of 1 (Table 1).

Federal lands were used as a mask to filter areas where publicly or privately funded renewable energy projects may be difficult to implement. Areas such as National Parks, National Monuments, and Native American Reservations were assigned a value of 0 to remove them from the analysis, whereas the remaining areas were assigned a value of 1 (Table 1). Each of the data sets, categorized from poor to excellent (0–1), are provided in Fig. 2.

Table 2
Pre-model mean wind scores for various landcover types. Percentages were derived by scaling NREL wind potential data for Colorado from 0 to 1.

Landcover	Mean NREL Wind Potential	Area (km^2)
Rocky Mountain Alpine Fell-Field	58%	576
Rocky Mountain Foothill Limber Pine-Juniper Woodland	57%	11
Rocky Mountain Alpine Bedrock and Scree	49%	2932
Western Great Plains Sandhill Prairie	48%	18
Rocky Mountain Dry Tundra	46%	2504
Western Great Plains Cliff and Outcrop	43%	86
North American Warm Desert Wash	43%	2
Wyoming Basins Low Sagebrush Shrubland	42%	32
Central Mixedgrass Prairie	37%	106
Western Great Plains Shortgrass Prairie	36%	45 493
Western Great Plains Sandhill Shrubland	36%	8703
Chihuahuan Creosotebush, Mixed Desert and Thorn Scrub	36%	5
Western Great Plains Mesquite Woodland and Shrubland	36%	9
Agriculture	35%	53 037
Southern Rocky Mountain Juniper Woodland and Savanna	33%	2187
Western Great Plains Foothill and Piedmont Grassland	31%	4365
Invasive Perennial Grassland	29%	2007
Inter-Mountain Basins Cliff and Canyon	29%	5
Inter-Mountain Basins Wash	29%	11
Western Great Plains Floodplain Herbaceous Wetland	27%	828
Rocky Mountain Subalpine-Montane Riparian Shrubland	25%	2734
Rocky Mountain Lodgepole Pine Forest	25%	7016
Rocky Mountain Alpine-Montane Wet Meadow	25%	1346

Table 3
Pre-model mean wind scores for Federal lands.

Administrative Type	Mean NREL Wind Potential	Area (km^2)
National Park or Monument	28%	2626
Waterway or Wilderness Area	27%	4718
National Forest or Grassland	25%	64 193
Military Reservation	21%	671
Wildlife Refuge	17%	333
Indian Reservation	15%	4316

3. Results

3.1. *Landcover characteristics of NREL wind potential data: pre-model*

In order to understand the landcover characteristics that are correlated with the NREL wind potential classified data, the data

Table 4
Pre-model mean solar scores for various landcover types. Percentages were determined by scaling NREL solar potential data for Colorado from 0 to 1.

Landcover	Mean NREL Solar Potential	Area (km^2)
Inter-Mountain Basins Active and Stabilized Dune	95%	128
Inter-Mountain Basins Semi-Desert Shrub Steppe	94%	3431
Inter-Mountain Basins Playa	94%	36
Southern Colorado Plateau Sand Shrubland	93%	9
Inter-Mountain Basins Greasewood Flat	90%	2345
Rocky Mountain Subalpine-Montane Limber-Bristlecone Pine Woodland	90%	338
Southern Rocky Mountain Pinyon-Juniper Woodland	90%	4811
Barren Lands, Non-specific	89%	11
North American Arid West Emergent Marsh	89%	38
Invasive Annual and Biennial Forbland	89%	632
Southern Rocky Mountain Montane-Subalpine Grassland	88%	7220
Colorado Plateau Blackbrush-Mormon-tea Shrubland	88%	110
Western Great Plains Mesquite Woodland and Shrubland	87%	9
Southern Rocky Mountain Juniper Woodland and Savanna	87%	2187

Table 5
Pre-model mean solar scores for Federal lands.

Administrative Type	Mean NREL Solar Potential	Area (km^2)
Indian Reservation	92%	4322
Military Reservation	84%	671
Wildlife Refuge	84%	333
National Forest or Grassland	83%	64 193
Waterway or Wilderness Area	81%	4718
National Park or Monument	81%	2626

Table 6
Area covered according to GIS wind model scores. Mean wind scores based on NREL wind potential data are provided for each class.

GIS Model Score	Mean NREL Wind Potential	Area (km^2)
90–100%	94%	41 850
80–89%	64%	720 675
70–79%	39%	6 961 275
60–69%	21%	11 574 225
50–59%	16%	5 478 975

were overlaid; mean scores and areas were tabulated before the GIS model was run (Table 2). High elevation sites (fell-fields, limber pine forests, juniper woodlands, bedrock, scree, and tundra) have the strongest winds since these are exposed surfaces near mountain or ridge summits (Table 2). Although sandhill prairie grasses have a high mean score, their area is limited to only 18 km^2. Although shortgrass prairies and agricultural land occupy the most area, their wind potential scores fall near the middle (fair and good wind categories) compared to other landcover classes (Table 2). Federal lands have low wind potential (Table 3). Scores are the highest for National Parks and Monuments, but only average 28%, which corresponds to a NREL moderate to poor ranking.

3.2. Landcover characteristics of NREL solar potential data: pre-model

Inter-mountain basins (dunes, shrubs, steppe, and playas) have the greatest potential for solar development based on NREL solar data (Table 4). The largest area (7220 km^2) includes montane and subalpine grasslands. The mean NREL solar score for this landcover category is 88%. Overall, mean NREL solar scores are high for all landcover categories (Table 4). This indicates that there is minimal variation in insolation received over much of the state.

NREL solar data indicate that Indian Reservations have a high potential for solar development (Table 5). National Forests or Grasslands have the greatest area (64 193 km^2) and have an average NREL solar potential score of 83% (Table 5). Again, all scores for Federal lands are high, since the majority of the state receives high amounts of solar radiation with minimal variation.

3.3. Areas of high wind potential: GIS model

According to the multicriteria GIS wind model, larger wind farms should be located in northeastern Colorado (Fig. 3, Table 6). North of Fort Collins, a cluster of high scores exists. Model scores in the foothills of the Rockies between Estes Park and Boulder are also high (Fig. 3). These areas are located on the more densely populated eastern half of the state, so they could provide electricity to some major urban centers. Other isolated patches of high GIS model scores are located at remote sites in the Colorado Rockies. These may be ideal for ski resorts or sparsely populated communities to develop small-scale wind farms for powering ski lifts or other facilities.

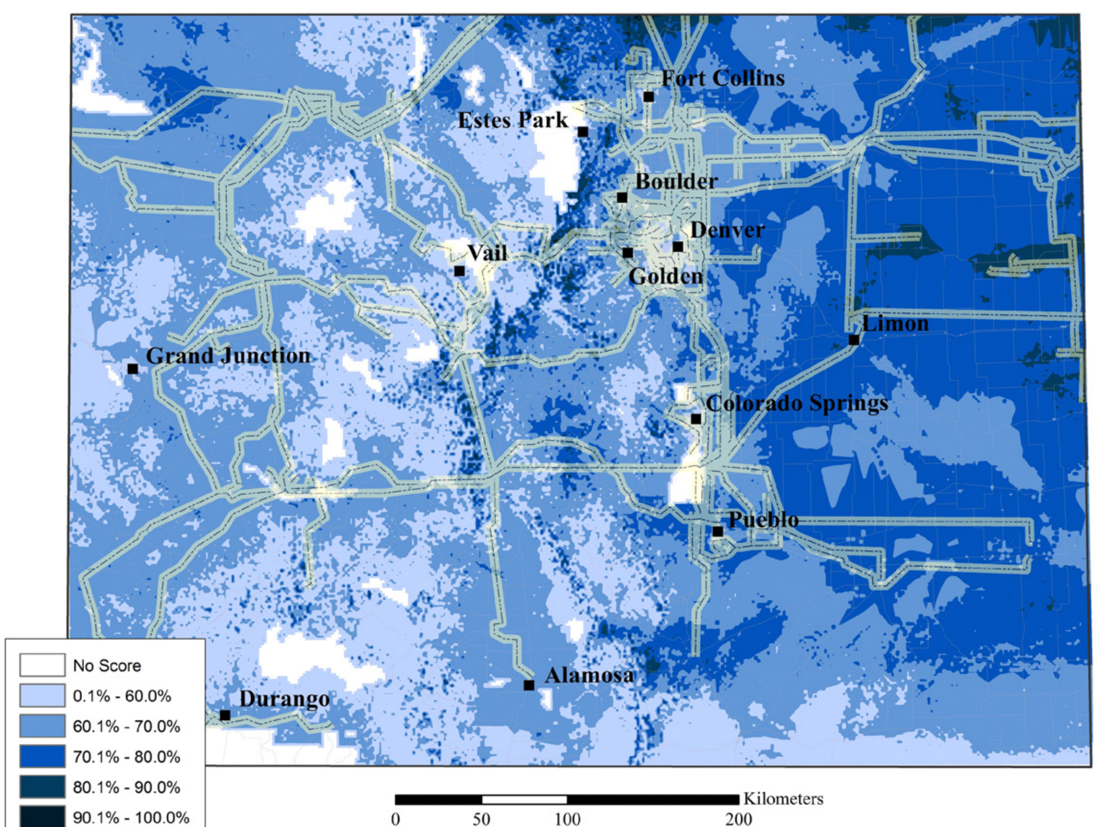

Fig. 3. Ideal wind farm locations in Colorado according to GIS model criteria.

3.4. Area of high solar potential: GIS model

Ideal areas for solar farms are located in two distinct sections of Colorado: east of Denver and in the northwestern part of the state in Moffat County near Dinosaur National Monument (Fig. 4, Table 7). Although GIS model scores vary significantly, NREL solar potential data indicate that there is only a slight difference between model classes since most of the state receives sufficient insolation (Table 7). The site in eastern Colorado should be explored in more detail for future development given its proximity to Denver. The site in northwestern Colorado is close to a transmission line; however, the potential to deliver solar power across the state may be limited.

Table 7
Area covered according to GIS solar model scores. Mean solar scores based on NREL solar potential data are provided for each class.

GIS Model Score	Mean NREL Solar Potential	Area (Km^2)
90–100%	81%	191
80–89%	81%	317
70–79%	81%	648
60–69%	82%	2822
50–59%	82%	5717

4. Discussion

4.1. A comparison of suitable and current wind farm locations

Wind farms have recently been established in several sections of Colorado. As part of the Colorado Green Project, a wind farm and a working cattle ranch occupy an 11 000 acre plot of land in Prowers County in southeastern Colorado. According to the GIS model, scores within this county are greater than 70%, indicating that this is indeed a favorable site for development. Since turbines occupy little ground space, this provides ranchers with an additional source of income [21]. In the northern part of the state, Ponnequin wind farm, located between US Highway 85 and Interstate 25 along the Colorado–Wyoming border, also has high GIS model scores; most are greater than 85%. Colorado State University has plans to develop a wind farm on Maxwell Ranch, northwest of Fort Collins. GIS scores in this region vary from 72 to 97%, which suggests an excellent location for a future wind farm. Babcock and Brown and BP Alternative Energy recently opened Cedar Creek wind farm, a 274 turbine facility located about 60 km northeast of Fort Collins [22]. The GIS model, however, did not identify this area as an excellent location with scores ranging from about 60–68%.

4.2. A comparison of suitable and current solar farm locations

A few electricity generating solar farms currently exist in Colorado. Near Alamosa, SunEdison operates an 80-acre farm and sells the generated power to Xcel Energy to serve about 2500 homes [23]. GIS multicriteria scores only range from about 10–25% near Alamosa. Near Carbondale, Colorado, located west of Vail, the Colorado Rocky Mountain School and the Aspen Skiing Company initiated a solar project to help power ski lifts and about 20–30 homes [24]. GIS scores are only 6–12% in this area. Denver International Airport, which had solar panels installed in 2008, has similar results; GIS scores only range from 5 to 20%. However, Table 7 indicates that NREL solar potential does not vary significantly among GIS model classes. The GIS variables included in this analysis were selected based on their ability to support large-scale solar operations. Since Colorado receives high total direct insolation, it is

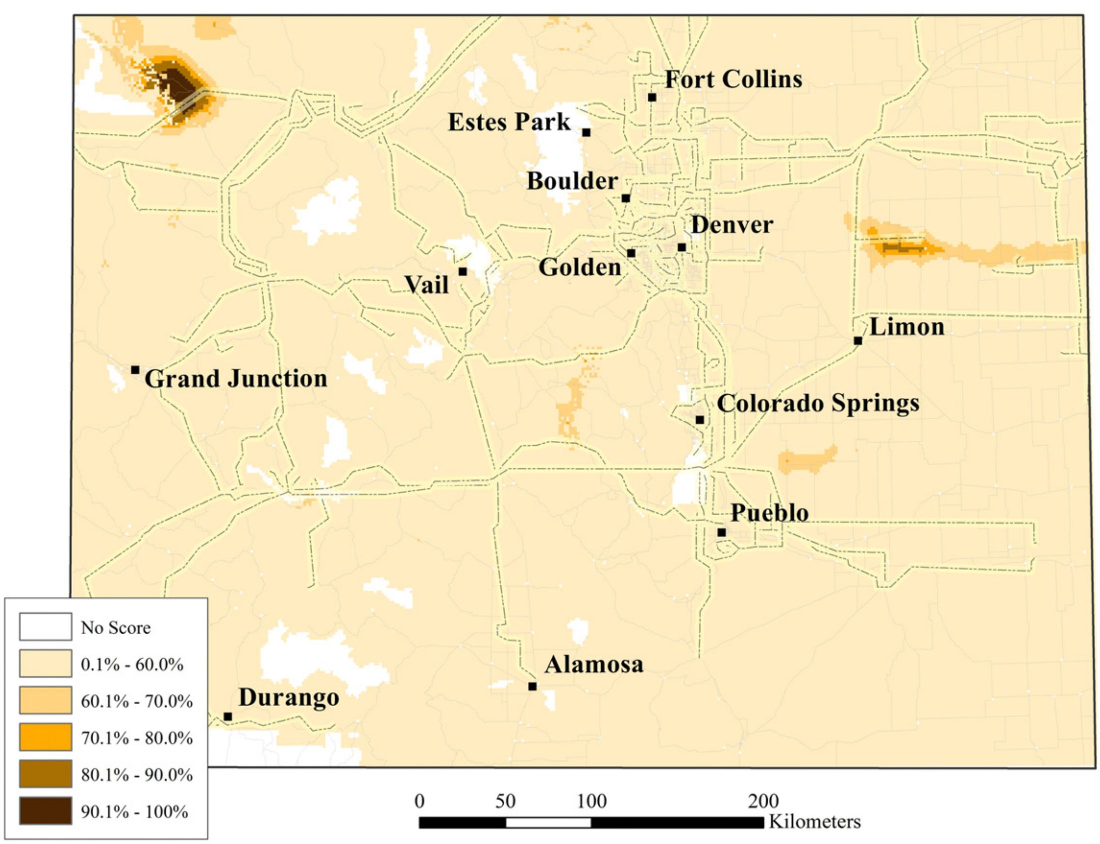

Fig. 4. Ideal solar farm locations in Colorado according to GIS model criteria.

more advantageous to evaluate solar potential on a local scale basis for homes or businesses rather than a regional facility that is capable of supporting a large population and numerous homes.

4.3. Multicriteria GIS model evaluation

When undertaking a multicriteria GIS modeling project, well-defined variables and weights that logically influence the modeling results are needed. For instance, the variables used in this analysis have a greater impact on the solar GIS model. About 191 km^2 fall in the 90–100% class for the solar GIS model, whereas 41 850 km^2 fall in the 90–100% class for the GIS wind model. Since solar radiation is high throughout the state, the influence of the other GIS variables is greater. The solar GIS model may be more useful as a filter to identify areas that have a greater degree of suitability compared to others. However, given the statewide high insolation values, most places are likely suitable for some form of small-scale solar project.

Ideal sites for solar and wind farms need to be verified in the field with wind speed and insolation measurements. Local residents may also have to be surveyed to ensure that there is minimal opposition or to help design a contemporary structure that blends with the natural landscape. Field validation should also examine ecological variables such as sensitive habitats or migratory routes for birds or bats; although some evidence suggests that wind farms may not increase bird or bat mortality [25].

Other multicriteria variables should be examined to meet the demands of investors, utilities, governmental agencies, and environmentalists [26]. For instance, weaknesses in the existing electricity system could be located by using Thiessen polygons borders [27]. Collaborative decision-making could be improved by combining different criteria or altering weights [28]. Not only would this create a flexible problem-solving environment for planners, but it would also allow users to conduct a sensitivity analysis to understand the influence of each variable and effectiveness of the model [29].

5. Conclusions

GIS overlay techniques were used to examine the relationship between landcover classes and NREL solar and wind potential data. High elevation sites have the strongest winds since these are exposed surfaces near mountain or ridge summits, whereas Federal lands have low wind speed. Wind potential scores are the highest for National Parks and Monuments, but only average 28%, which corresponds to a NREL moderate to poor ranking. Inter-mountain basins and Indian Reservations have the greatest potential for solar development based on NREL solar data. Overall, mean NREL solar scores are high for all landcover categories, indicating that there is slight variation in insolation received over much of the state.

The multicriteria GIS wind model suggests that wind farms should be located in northeastern Colorado. These areas are located in the denser populated eastern part of the state, providing a renewable energy source for a growing Front Range corridor. North of Fort Collins, a cluster of high scores exists in which wind farms should be developed. Much of this area corresponds with a proposed site that will provide Colorado State University with wind power. Other isolated patches of high GIS model scores are located at high elevation sites in the Colorado Rockies and may be ideal for ski resorts to develop small-scale wind projects.

Ideal areas for solar farms are located east of Denver and in the northwestern part of the state. Although GIS model scores vary significantly, NREL solar potential data indicate that there is only a slight difference between model classes; the variables included in this analysis have a greater effect at eliminating non-suitable areas. Since Colorado receives a large amount of total direct insolation, it is more advantageous to evaluate solar potential on a local scale for homes or businesses. The GIS model is better equipped at detecting regional renewable energy facilities that are capable of supporting large urban populations.

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