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A fuzzy multi-criteria spatial decision support system for solar farm location planning

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A B S T R A C T

In recent years, investment in solar energy has increased substantially across countries. Thus, selecting convenient locations for solar farms has become a fundamental problem when determining the investment required due to differences in climatic factors, the type and availability of land, transportation infrastructures, and the quality of power lines. Multi-Criteria Evaluation approaches based on crisp data are generally used in the selection process of optimal locations. However, despite being crisp, the data available when considering the evaluation criteria of the different alternatives constitute a discrete approximation performed on a spatial grid of potential locations. Thus, we introduce a three-stage fuzzy evaluation framework designed to account for the imprecision inherent to the evaluations when identifying the most convenient location for constructing solar power farms. First, we implement ANFIS (Adaptive Neuro-Fuzzy Inference System) on the set of grid intersection crisp data points and derive a coherent set of approximations per each potential discrete location and evaluation criterion. Then, the fuzzy AHP (Analytic Hierarchy Process) method is used to determine the weights of the different criteria considered from the linguistic evaluations provided by different experts. Finally, we define a set of if-then rules combining the different ANFIS evaluation criteria and their weights within a FIS (Fuzzy Inference System) whose output is used to determine the most convenient location for constructing a solar power farm. The efficacy of the proposed evaluation framework is demonstrated through its application to the Iranian regions of Kerman and Yazd.

1. Introduction

Energy is a key element of sustainable development, economic growth and welfare [3]. Thus, the unequal distribution of oil resources in the world may result in economic and political conflicts, both now and in the future [36]. In addition, the world demand for energy is expected to increase substantially in the coming years, with oil consumption increasing from 86 million barrels per year in 2007 to a potential amount of 104 million barrels per year by 2030 [8].

Energy resources can be divided into three groups: fossil fuels, renewable and non-clean resources. While most of the world energy supply is based on fossil oil, it is widely known that fossil fuels have a significant impact on the world ecology and climate. In this regard, increasing concerns about environmental pollution have resulted in an incremental use of renewable energies through the 21st century [43]. Moreover, the reduction in their reserves has led the prices of oil and other fossil fuels to exhibit a consistently increasing trend. Therefore, most of the world countries have adopted new policies to reduce energy costs – together with the resulting pollution – [18,21,24,28]. emphasized the importance that key technologies have for the decarbonisation of the electricity sector and the gain in the efficient provision of energy.

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Renewable energies – solar, wind, biomass and geothermal – are clean resources with low environmental impacts characterized by their low costs and almost unlimited supply [49,63]. In this regard, solar energy has some advantages relative to the other types of renewable energy, which range from environmental benefits and government incentives to the availability of flexible locations [64]. Griffiths [26] presented a demand-supply model for solar energy illustrating its commercial viability in several Middle East and North Africa countries based on the improvement of relative costs and the availability of solar resources. However, collaboration between the private and the public sector is generally needed in order to overcome the budget constraints faced by poor countries and provide them with access to different renewable energy services [58].

The selection of locations for solar power plants is a complex process due to the different security, economic, environmental, and social requirements that must be considered [68]. Locations with the best solar resources cannot always be selected and several other factors play significant roles in selecting convenient locations. These factors can be categorized into economic, environmental and social classes [65]. Therefore, the use of multi-criteria decision making models becomes necessary.

Several multi-criteria evaluation methods have been used in problems involving the selection of locations. These positioning methods are described in the literature review section below. It should be emphasized that these studies generally focus on real-valued criteria whose realizations, despite being crisp, constitute a discrete approximation performed on a grid of potential locations.

That is, consider a grid mapping discretely a given set of potential locations distributed on a continuous surface. A subjective approximation must be applied by the experts when assigning values to each discrete point per evaluation criterion. At the same time, each criterion differs in relative importance and must therefore be ranked according to the subjective judgments of different experts. The approximate nature of both evaluations must be accounted for when selecting a location. In this regard, a Fuzzy Inference System (FIS) based on a sufficiently large amount of if-then inference rules can be implemented so as to smooth out the inherent imprecision and provide a coherent final evaluation.

Therefore, in order to account for the imprecision inherent to the realizations being evaluated, we introduce a three-stage fuzzy decision support framework designed to identify the most convenient location for constructing solar power farms.

a. In the first stage, a team of experts is selected to identify the main decision criteria. After retrieving the data required from different maps, ANFIS (Adaptive Neuro-Fuzzy Inference System) is implemented on the set of grid intersection points defining the regions being analyzed. ANFIS allows us to derive a coherent set of approximations per each potential discrete location and criterion.
b. Then, the fuzzy AHP (Analytic Hierarchy Process) method is used for determining the weights of the different criteria from the evaluations provided by different experts.
c. Finally, we define a set of if-then rules combining the values of the different evaluation criteria obtained from ANFIS and their weights within a FIS whose output is used to determine the most convenient location for constructing a solar power farm.

The main contribution of the current model is defined by its capacity to account for different types of imprecision while incorporating a FIS to smooth it out and provide a coherent evaluation. This is in contrast with the general approach followed by the models described in the literature review section, where ANFIS is used as a final evaluation method and fuzzy AHP is incorporated within multiple-criteria decision-making (MCDM) settings without explicitly accounting for its approximate nature.

We validate the efficacy of the proposed evaluation framework through its application to the Iranian regions of Kerman and Yazd. However, it should be noted that due to their inherent imprecision, the final evaluations obtained could differ if different experts were contacted to select and weight the criteria or different if-then rules would have been defined.

The remainder of the paper is organized as follows. Section 2 provides a short review of the related literature. Section 3 describes the ANFIS methodology, while Section 4 focuses on the FIS. Section 5 illustrates the case study and the proposed method at work. Section 6 concludes and suggests potential extensions of our model.

2. Literature review

A basic review of the positioning literature that encompasses several multi-criteria and decision support methods follows.

Farahani et al. [23] surveyed the literature on multi-criteria location problems across three main categories including bi-objective, multi-objective and multi-attribute problems. Standard MCDM techniques are commonly used in the positioning literature. For example [38], developed and tested different facility allocation models based on efficiency measures obtained from data envelopment analysis (DEA). Achillas et al. [1] proposed a decision support system for the optimal location of electrical and electronic waste treatment plants using ELimination Et Choix Traduisant la REalité (ELECTRE) III as a MCDM analysis technique. Tavana et al. [62] presented a group decision support system based on the Preference Ranking Organization Method for Enrichment Evaluation (PROMETHEE) for the evaluation of alternative pipeline routes. Similarly [20], integrated a geographical information system (GIS) and the PROMETHEE IV method to locate shelters and emergency services in urban evacuation planning.

Alternatives to the standard multi-criteria location techniques can also be found in the literature. Dogan [19] proposed an integrated approach that combined Bayesian networks and the total cost of ownership to address the complexities involved in selecting an international facility for a manufacturing plant. Datta [17] designed a multi-criteria multi-facility methodology implemented in Microsoft Excel to generate scenarios for locating facilities in rural underdeveloped regions. Xu et al. [66] defined a multi-criteria location model determined by the spatial coverage of the alternatives that was used to solve the location problem of earthquake evacuation shelters.

Among the diverse methods applied, AHP has been consistently implemented as a decision support tool when performing multi-criteria spatial decision analyses [29]. In particular, AHP has been used in MCDM location models to weight the importance of the criteria considered by the corresponding GISs. Applications to positioning problems include, among many others, the planning of potential uses of land for agricultural development [5], the assessment of land capability for spatial development [2], the clearance of mine hazards [40], highway alignment [67] and the evaluation of flood hazard potentials [51].

As noted by Ref. [44]; about three quarters of the papers published on GIS multi-criteria location analysis between 1990 and 2004 focused on deterministic information. The literature has recently started to increasingly incorporate multi-criteria methods accounting for imprecision and fuzziness in GISs, since such a feature was expected to improve their analytical capacity [35]. For example [45], applied the concept of efficiency defined by DEA to location-allocation models within a fuzzy environment.

Similarly to the crisp scenarios described above, AHP has been