Automation in Construction 37 (2014) 98–109

Contents lists available at ScienceDirect

Automation in Construction

journal homepage: www.elsevier.com/locate/autcon

Risk-based group decision making regarding renewable energy schemes using a stochastic graphical matrix model

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ARTICLE INFO

Article history:
Accepted 17 October 2013
Available online 12 November 2013

Keywords:
Multi-criteria decision making
Simulation
Graph theory
Sustainability assessment
Renewable energy
Energy policy

ABSTRACT

Improvements to sustainability are generally measurable based on their environmental, economic, and socio-cultural effects. This study applied this concept by developing and empirically testing a risk-based method for assessing renewable energy policy. An integrated theoretical framework is proposed for analyzing group decision-making regarding renewable energy (RE) policy selection. The proposed graphical matrix approach combined with Monte Carlo simulation compares alternative RE schemes by identifying and measuring critical performance indicators with acceptable reliability. The mathematical model reliably prioritizes alternatives using majority voting to address uncertainty in multi-criteria decision making process. A case study using historical data from previous RE development projects to confirm the feasibility of this approach. Compared to the conventional deterministic method, the stochastic graphical matrix approach provides more reliable estimation accuracy, decision quality, and efficiency in selection of sustainable renewable energy. The systematic approach provides policy makers information for use in evaluation by synthesizing the judgments of a panel of experts.

1. Introduction

Renewable energy (RE) offers a promising solution to the numerous environmental and social problems associated with fossil and nuclear fuels [16]. However, many barriers to sustainable development (SD) still exist within the RE system life-cycle. For instances, barriers to hydropower include the numerous people and animals displaced by the inundation associated with new dam construction, whereas barriers to geothermal energy schemes include adverse effects on local communities from improper waste management such as through the offensive smell of geothermal processing water that results from hydrogen sulfide and contamination with ammonia, mercury, radon, arsenic and boron [13].

Furthermore, implementing sustainable RE has environmental, as well as social and economic effects. Although SD problems are well recognized, the literature on applying sustainability concepts in RE schemes remains inadequate. To help decision makers cope with complex sustainability issues, evaluation indicators must reflect the overall RE system and subsystem interactions. This study thus proposes an integrated theoretical framework for analyzing the group decision-making process during RE scheme selection.

Although numerous studies have demonstrated diverse applications of RE, methods of selecting the optimal RE scheme based upon sustainability evaluation have still been relatively neglected. To fill this gap, this investigation develops a reliable multi-criteria decision making (MCDM) method that considers sustainability indicators (SIs) when comparing alternative RE schemes. Depending on the sustainability requirements, decision makers can then select from alternatives synthesized from the goal set. Consequently, the available options should be comprehensively evaluated during the MCDM process.

This study proposes a risk-based MCDM that uses graphical matrix modeling together with Monte Carlo simulation (MCS) to facilitate decision making with adequate reliability. The proposed systematic approach enables decision makers to identify and measure the critical SD indicators and thus to compare the influence of different RE schemes on those indicators. The results provide policy makers with useful information for decision making regarding RE schemes where sustainability is a key consideration by synthesizing judgments by an expert panel.

This study analyzes the benefits of applying MCS to develop a probabilistic model for comparing RE schemes by increasing the reliability of pre-conceptual MCDM estimation. A case study using actual historical data from previous RE development projects confirms the feasibility of the proposed decision making approach. The remainder of this paper is structured as follows. The next section reviews the literature on decision making techniques and the SD of RE schemes. Section 3 then describes the research methodology, including SI determination, and the probabilistic model. Next, Section 4 uses empirical data to demonstrate the proposed decision making approach. Finally, Section 5 presents concluding remarks.

2. Background information

Globally, RE sources have varied applications. Although RE sources have been proven suitable substitutes for conventional fuels in most

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http://dx.doi.org/10.1016/j.autcon.2013.10.010

Nomenclature

k_i,k_j	Measurement parameters of the attribute when the selection comprises alternatives i and j
E_i	Attribute factor represented by node i
$S = \{S_{ij}\}$	Importance of attributes i and j represented by an edge
d_{ij}	Directed edge or arrow of attribute i in relation to j
L	Largest scale importance value
$f(x)$	Probability density function
$E[g(X)]$	Expected value of $g(X)$ as function of random variable X
$\mathfrak{M}$	Solution space of variable$_x$
N	Number of realizations generated for the simulation
$f_M(X)$	Empirical point-mass function
$\delta_{\widetilde{X}_{(i)}}$	Delta-Dirac mass
$\widetilde{X}_{(i)}$	Spatial dimension
$E_N(g)$	Tractable sums
x $[a,c,b]$	Lowest, mode, and highest value for attribute x
Y	Random variable for generating user-defined distribution
U	Uniform distribution function
$F(u)$	Interval of uniform distribution (0,1)
H	Selection factor matrix H
M	Number of alternative RE schemes

applications, their contribution to total energy use remains low despite considerable technological advances and the economic competitiveness of RE energy with conventional fuels [25]. Hence, planners and decision makers must identify and suggest interventions to overcome barriers to the penetration of such alternative energy sources. However, besides the need to develop appropriate policy measures, the exploitation of sustainable energy should be based on a new conception of energy planning procedure and new conceptions of sustainability. The significance of various indicators in decision making thus is important. Additionally, moving from a single decision maker to a multiple decision-maker setting significantly complicates the analysis. This study applies decision making science to a real-life problem by using group decision making (GDM) to identify RE schemes that are consistent with sustainability concepts.

2.1. Overview of decision making techniques

Decision making, which is the process of identifying the best among all feasible alternatives, is an important problem in all sciences [3]. Decision makers must choose among quantifiable or non-quantifiable criteria. Because objectives are frequently mutually exclusive, the final compromise frequently depends on decision-maker preferences. Multiple Criteria Decision Making (MCDM) is one decision making tool that can help managers make accurate decisions. MCDM manages the process of making difficult decisions in the face of apparently equal objectives. A decision generally involves three elements: alternatives, consequences and preferences [6]. Decision outcomes are often unreliable and uncertain, but few studies have proposed methods of optimizing decision making under uncertainty while maintaining reliability.

MCDM approaches have been increasingly successfully applied to real-world problems [19]. Particularly, MCDM techniques have been increasingly applied to sustainable energy management [25]. For instance, Pohekar and Ramachandran (2004) reviewed the literature to determine the applicability of various MCDM methods in sustainable energy planning [25]. Common MCDM methods include the weighted sum method, weighted product method, analytical hierarchy process, preference ranking organization method for enrichment evaluation, elimination and choice translating reality, technique for ordering preferences based on similarity to ideal solutions, compromise programming, and multi-attribute utility theory. Numerous variations of these techniques have also been developed.

The two main decision making approaches are deterministic and probabilistic. The latter are superior in considering risk, uncertainty and reliability. Industrial applications of MCDM methods include graph theory and the matrix approach (GTMA), an alternative form of MCDM that is especially suited for RE planning, which is an increasingly important area. This study integrated GTMA with MCS to deal with uncertainty when making decisions regarding RE schemes.

2.1.1. Graph theory and matrix approaches

GTMA is a method of solving various problems involving complex criteria and highly dependent relationships across different levels [20,26,28,40]. Like other MCDM methods, GTMA is a logical and systematic approach that considers inherent errors and multiple qualitative and quantitative attributes simultaneously, which is especially important when studying interconnections among elements in both natural and man-made systems. A direct graph (digraph) is useful for visually representing the relative importance of different attributes [27]. Moreover, the objective of GTMA is to offer a simplified and consistent decision-making approach that minimizes computation while emphasizing decision-making methodology.

Darvish (2009) used GTMA for contractor selection [9]. Kumar et al. (2010) represented the architecture/structure of an electroplating effluent treatment plant using graph theory, matrix-algebra and permanent function [20]. Rao and Gandhi (2002) applied GTMA to assess the machinability of work materials before choosing the best work-tool combination for a given machining operation [39]. Furthermore, Venkatasamy and Agrawal (1997) used GTMA to optimize price to quality for an automotive vehicle [40]. Past studies have confirmed the effectiveness of GTMA as a deterministic method of making broad decisions supported by expert judgment.

Although numerous studies have demonstrated GTMA to be effective [9,20,26,28–30], conventional GTMA generates single-point estimation which are often unreliable and do not consider probabilistic range to distinguish adjacent importance values when comparing attributes assessed by different experts. Moreover, although GDM can be incorporated into GTMA using the weighted value method [27], GDM has limited robustness, especially when expert judgments bias the performance score for an alternative option. Notably, the best GDM alternative is that with the highest performance score. Thus, to address uncertainty in attribute comparisons by expert panels, this study designed a novel risk-based MCDM technique that probabilistically represents expert judgment by integrating conventional GTMA with MCS.

2.1.2. Monte Carlo simulation method

Monte Carlo simulation (MCS) is a risk-analysis technique that facilitates the application of decision science to management decisions [7]. Generally, MCS uses computers to generate pseudorandom numbers and convert them to real-world responses via inverse functions under existing mathematical equations and assumed probability distributions. Moreover, owing to its high efficiency, MCS is frequently used to solve complex or nonlinear physical problems or problems involving uncertain parameters. Because a probabilistic range reflects the varying outcomes for corresponding likelihoods, using MCS for stochastic simulation is the simplest method of probability analysis [11].

Specifically, MCS is a standard probabilistic technique for conceptual estimation and decision making [17]. MCS approximates solutions to problems involving computational mathematics using random processes and minimizes subjectivity in human decision making. MCS also optimizes group evaluations. The advantage of MCS is its limitation of Monte Carlo approximation error. Additionally, MCS can provide a starting point for negotiations by aggregating decision maker preferences. The key strength of the Monte Carlo method is in making decisions that involve uncertainty or numerous variables.

Elkjaer (2000) combined MCS with conventional calculation using successive principles [12]. The method used stochastic simulation to