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Original Research Article

A value tree for identification of evaluation criteria for solar thermal power technologies in developing countries

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ABSTRACT

The diversification of electricity generation is necessary for the sustainable development of developing countries and to reduce greenhouse emissions. Solar thermal power technologies are advancing and expected to play a significant role in energy portfolios in the future. Accordingly, it is essential to identify comprehensive combination of criteria for assessing these technologies. Various researchers used different parameter combinations for multiple criteria evaluation in renewable energy portfolio planning. The novelty of the proposed approach lies in the structured deliberation and the following analysis to formulate a combination of assessment parameters for solar thermal power technologies based on data providers' judgment. A generic value tree of evaluation parameters is therefore obtained for solar thermal power technologies in developing countries. Expert elicitation was conducted through the Delphi method, with a total of 140 data providers from multidisciplinary solar thermal power fields affiliated in educational institutes, research centers, governmental organizations, and industrial companies from 32 countries participating in the survey. Five impact categories and nineteen performance measures were combined following a comprehensive literature review to derive a preliminary value tree. Based on participants' judgments, as expressed during two rounds of Delphi questionnaires, parameters with importance and consensus degrees > 50% were incorporated into the final value tree. Each parameter had a variation coefficient of < 29%. The output of the process is an aggregated value tree, consisting of 31 performance measures categorized under four main impact categories (technical, economic, environmental, and social). Technical and economic impact categories were rated as most important and achieved the highest degrees of consensus. At performance measures level, economic feasibility obtained the highest level of importance and consensus degrees, followed by reliability, capital cost, storage hours, and water consumption. The recommendations of this work can be utilized as a foundation for stakeholder assessment of regional solar thermal power utilities planning in developing countries.

Introduction

World population is increasing and, as a result, so is the demand for electricity. Furthermore, increasing urbanization and electrification require large-scale investment in electrical energy infrastructure, especially in developing economies, where numerous large projects are underway. Renewable energy sources (RES), which have the potential to act as alternatives to conventional energy sources, have received substantial attention, owing to their positive contribution to sustainable development and reduced emissions. Solar and wind energy have been pioneering renewable energy technologies, after hydropower [1], and there is significant solar energy potential in many areas around the globe. The harvesting of solar energy is conducted either directly, by converting sunlight into electricity using photovoltaic (PV) modules, or through collecting solar heat and transferring this into electricity, which is known as concentrated solar thermal power (CSP). Cumulative CSP capacity reached over 4 GW in 2014 [1]. Its advantages include cheap thermal storage and the ability to directly utilize heat in applications; as a result, researchers are anticipating significant potential for global CSP growth. The International Energy Agency (IEA) envisions that 11% of global electricity will be generated through solar thermal sources by 2050 [2]. In order to ensure

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sustainable development, exploitation of this potential must be accompanied by proper planning.

Problem statement

The selection of generating technology can be considered one of the most important aspects of the decision-making process for power plant projects. Decisions during the early stages of planning are inherently associated with high levels of uncertainty; nevertheless, they dictate future performance. The evaluation of energy projects has evolved from focusing only on financial perspectives, to also considering several other aspects, including the environment. Cavallaro [3] found that, in many cases, traditional evaluation methods (such as cost to benefit analysis (CBA)) and main financial indicators (such as net present value (NPV)) are not adequate to deal with all energy project components. As the complexity of energy portfolio planning increases, it becomes more difficult to identify an alternative that can maximize all decision criteria. It is therefore necessary to consider use of multi-criteria decision analysis (MCDA) to support such decision-making processes.

MCDA methods are widely utilized in the evaluation of electricity generation technologies to facilitate inclusion of different quantitative and qualitative aspects associated with utility projects. Stakeholders' judgment is often included at the weighting stage to evaluate selected criteria, either through ordinary surveying [4,5] or through the Delphi method [6]. The stage of selecting the combination of evaluation criteria is critical for the accuracy of the assessment process. It is however noticed that researchers commonly consider self-definition of the evaluation criteria through literature with no explicit explanation of how the decision criteria are determined. Accordingly, different combinations of evaluation criteria are adapted based on researchers' perspectives.

Expert elicitation is a key step performed prior to portfolio analysis of renewable energy projects. It is useful for quantifying uncertainty associated with the scarcity of historical data. The latter is a characteristic of renewable energy project planning in developing countries [7], with these countries being the intended beneficiaries of this study. With respect to previous literature, this research contributes to the body of knowledge through a structured expert solicitation with the involvement of large number of worldwide data providers to obtain the aggregated perspectives. This study aimed to explicitly identify parameters combination required for evaluation of CSP technologies through a rigorous process of expert elicitation and consensus-seeking. A value tree was ultimately constructed, based on the perspectives of a heterogeneous panel of data providers from solar thermal power field including but not limited to power companies CEOs and chairmen, university professors, research fellows, power plants senior managers, managing directors, CSP design and optimization engineers, R&D leaders, and site and deputy managers. The resulted value tree can be utilized locally by stakeholders and decision-makers as inputs for evaluating solar thermal project models at planning stage, perhaps with slight modification of parameters based on individual case requirements.

Literature review

Few studies have discussed the assessment of solar thermal power technologies from a multi-criteria point of view. However, there is plenty of research relating to general assessment and selection of power energy sources and to renewable energy specifically. MCDA techniques and the Delphi method are among the most widely used methods in the regional energy planning field [8]. Multi-criteria decision techniques are utilized for the appraisal of alternatives, taking into account performance measures that influence the evaluation process. Impact categories represent the main trajectories that shape the general form of the value tree. A comprehensive assessment of parameters is necessary, prior to system modeling for evaluation.

Nixon et al. [4] utilized the analytical hierarchy process (AHP) to select an optimal solar thermal collection technology for the northwest of India. The authors suggest consideration of additional evaluation criteria in future work, as well as increasing the number of consulted experts, in order to enable more accurate results. Beltrán et al. [9] propose an analytical hierarchy process/analytical network process (AHP/ANP) model to aid CSP companies in Spain in deciding which projects to accept. The model adapts criteria selected by the technical team and consists of three phases, with each phase more rigorous than the previous one. Cavallaro [3] utilized the preference ranking organization method for enrichment of evaluations (PROMETHEE) to assess CSP technologies. In this study, twelve different alternative scenarios were defined, including changes in utility technologies and components. Seven decision criteria were defined for the evaluation process, based on technical, environmental, and economic perspectives. The novelty of the proposed approach lies in the structured deliberation and the following analysis to capture a comprehensive perspective of the adequate decision attribute combination for evaluating CSP technologies in developing countries, based on data providers' judgment. At the level of renewable and conventional energy sources, there are also many studies in the literature that discuss assessment of different technologies based on MCDA. These studies are presented in Table 1 (Section Expert elicitation) and were used for identification of parameters from the literature for energy sources assessment.

Solar thermal power technologies

Solar thermal power plants are gaining in popularity with advances in technology. In fact, some of the highest capacity solar plants globally are now using CSP. The variety of concentrated solar power technologies available nowadays is the driver of this research to exhaustively model parameters for their assessment. Solar thermal collectors are the major component of solar power systems. They work by absorbing the sun's heat (through its radiation), changing this to internal energy. The obtained thermal energy is transformed to fluid (i.e., water, oil, or air) to be either directly utilized in applications such as heating systems or converted to electricity using generating technologies such as steam turbines [10]. In addition, generated thermal energy can be stored for later use. This section outlines the most common solar collecting technologies.

Parabolic trough collectors

Parabolic trough collectors utilize curved, highly reflective, mirrored troughs that direct sunlight into a linear vacuumed glass tube attached to its focal axis. Parabolic trough collectors are configured to move in one axis from east to west, in order to follow the concentration of sunlight during the day. Parabolic troughs are used in some of largest CSP utilities in the USA and Spain [4]. The Solar Energy Generating System (SEGS) in the USA is the largest parabolic trough power plant complex in the world [11], with a capacity of 354 MW. There are many other plants with capacities of $\geqslant$100 MW in the USA, Spain, South Africa, India, and the UAE. It should be noted, however, that the selection of optimal CSP technologies is location-dependent, thus influencing most decision attributes. The best technology for the USA and Spain is not necessarily the best for other locations, which may differ economically, environmentally, socially, and politically. Thus, given increased interest in CSP around the world, it is necessary to establish a framework for assessing alternative technologies [10,12].