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Using a sustainability index to assess energy technologies for rural electrification

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ABSTRACT

This paper introduces a method for evaluating the sustainability performance of energy technologies applied in rural electrification, using the multivariate technique called Principal component analysis (PCA).The sustainability is assessed in terms of energy technology sustainability index (ETSI). The ETSI has been used for assessing the sustainability performance of ten different energy systems in the case of India. Since this method is static in nature, the sustainability performance analysis is made for three different years (2005, 2010 and 2015) to capture technological advancements and changes in market conditions for the various technologies over time. The result shows that mature technologies such as biomass gasifiers, biogas and microhydro technologies have relatively better sustainability performance among the options analyzed. There is slight increment in their sustainability performance in the ten year period considered. Emerging technologies such as solar and wind have fairly good improvement in the sustainability performance over the studied time but still have difficulties competing with the mature technologies and conventional technologies without policy support. Analysis has been made with probable, minimum and maximum capital costs, operational and fuel costs to capture uncertainty among the input assumptions, and sensitivity has been reflected in the analysis of energy technology sustainability index (ETSI). This ETSI could help improve energy technology assessments, particularly when it comes to the feasibility of available alternatives.

1. Introduction

Providing reliable, affordable and basic energy is a must on the way to meeting the Millennium Development Goals (MDGs) [1,2]. On the one hand, there is the challenge of providing access to reliable and clean energy to 2.8 billion, and electricity to 1.2 billion people in the world [3]. On the other hand, there is also the challenge to cope with global climate change. Governments in developing countries and donors have prioritized rural electrification to reach the poorest. As a result, electricity access has increased significantly in recent years [4–6].

Nevertheless, many rural energy projects and programmes have failed to address sustainability from the start. Often the focus in many electrification projects in developing countries is given on delivering the technology, and success is measured in terms of number of installations or number of kW installed [7]. In addition to technical assistance to provide access to electricity, many programmes are made possible through large subsidies and do not pay attention to the long term viability of the endeavor, or its overall economic sustainability [8]. For instance, large numbers of diesel generators were installed by various donors for rural electrification in Afghanistan after the downfall of the Taliban regime. This was a costly effort aimed at meeting immediate needs, but not a sustainable solution. Besides continued dependency on imported fossil fuels, these efforts did not contribute to a positive learning curve around sustainable options that could be further developed over time [9].

Certainly, technology assessment is an important factor when choosing among multiple options for supplying electricity. Tran and Daim [10] provided an extensive review of methods and tools used for technology assessment. For a long time, the traditional way of making such technological assessment was a simple cost-benefit analysis among available options [11]. After the 1990s, Life Cycle Assessment became instrumental in improving technology assessment, particularly when it comes to including environmental dimensions [12]. In addition, social aspects have

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been increasingly analyzed in technology assessments [13,14]. Sustainability has gained attention in technology research, development and dissemination after the Brundtland report [15–17]. Energy technology assessments now capture different sustainability aspects [18–20]. However, there is still no single standard or common consensus on the sets of indicators that should be used for such assessments.

Defining appropriate sets of indicators to capture the performance of technologies within sustainability boundaries is a challenging job. IAEA [21] presented a comprehensive list of thirty energy-based indicators for sustainable development (EISD). Again, quantifying all these energy based sustainability indicators is difficult [22]. Efforts have been made to design tool kits and manuals for evaluating the sustainability of rural electrification [17,23–26]. Sustainability indicators and composite index are gradually used as a powerful tool for communicating sustainability performance to policy makers and the general public [27].

This paper aims at introducing a method for evaluating sustainability performance of energy technologies. For illustration purposes, the case of India is used. In the first step, indicators are selected carefully covering various sustainability dimensions. These indicators are used to compose an energy technology sustainability index (ETSI). ETSI is constructed by interlinking individual indicators using multivariate techniques called Principal Component Analysis (PCA). XLSTAT has been used as a tool for performing PCA. Energy technology sustainability index represents the relative performance of the technology in terms of (i) providing efficient and reliable energy supply, (ii) which is cost competitive, (iii) has low environmental impact and (iv) high social benefits, (v) while also observing local managerial capabilities. The index (ETSI) can help prepare better energy technology assessments taking sustainability into account and enhancing the quality of feasibility studies for given alternatives.

Following this introduction, the second section of the paper discusses various approaches used in sustainability assessment and elaborates on the methodology adopted in the study. The third section builds the theoretical framework capturing the sustainability of energy technology on the basis of which indicators are selected. The fourth section highlights various renewable energy technologies being used in India and presents the system configuration of the technologies considered in this assessment. The evaluation of selected indicators is made in the fifth section. Multivariate analysis and results are presented in the sixth section, followed by conclusions in the final section.

2. Approaches to sustainability assessment

Various alternative approaches have been used to assess the sustainability of energy systems, and some of the indicator-based approaches are discussed in this section. Evans et al. [28], Ilskog and Kjellström [29] and Lhendup [30] have discussed weighted score methods while other authors have used multi-criteria based approaches [19,31–33]. Ediger et al. [34], Doukas et al. [35] have used composite indicators using multivariate techniques such as principle component analysis (PCA) while Sikdar [36,37], Martin et al. [38], and Mata et al. [39] have used aggregated metric methods. Bhattacharyya [40], Musango and Bent [41] have discussed system analysis approaches, capturing the complex interrelationships between society, environment, technologies and governance. The characteristics of these different approaches are further discussed below.

2.1. Weighted score system

The weighted scoring system is a multi-attribute analysis. It involves identification of all indicators that are relevant to the sustainability of the project. Weights for each of these indicators are allocated reflecting their relative importance and preferences. This is again followed by the allocation of scores (rank) to each option which reflects the performance of these indicators in relation to sustainability. To make this method transparent, the weightage and ranking should be based on justifiable reasons. The weighted score for a particular indicator is obtained by the product of the weightage and the score. If there are "n" sets of indicators, then the total weightage score (WS_T) of the Technological option "T" is given by Eq. (1) [30].

$$WS_T = \frac{\sum_{i=1}^{n} W_i S_i}{\sum_{i=1}^{n} W_i} \tag{1}$$

where, W_i is the weighting factor and S_i is the score of the ith indicator. The single weighted score thus obtained for each technological option can be compared with other available technological options. Lhendup [30] used a weighted score system considering 18 indicators reflecting technical, environmental, social aspects and regulatory features related to rural energy supply alternatives. Ilskog and Kjellström [29] compare the five dimensions of sustainability viz. technical, economic, environmental, social and institutional, considering 31 different indicators belonging to these five dimensions. However, the authors use the same weighting factor for all the dimensions and indicators within each sustainability dimension. The advantage of this method is its simplicity. It evaluates sustainability using large sets of important indicators and capturing various dimensions. However, these analyses are subject to some inherent preferences when defining the weights and ranking score. This method can be made more effective for defining sustainability of specific case/project studies using a participatory approach when determining the weights and ranks [40].

2.2. Multicriteria analysis

This sustainability assessment technique involves multi-criteria representing various sustainability dimensions (viz. environmental, social, and economic dimensions). Decisions are made based on evaluation of the various criteria, taking the values and preferences of the decision makers into account [31–33]. In this method, sets of quantifiable and non-quantifiable criteria are selected based on the objectives to be achieved. Radial spider-grams are often used to present the analysis of final results [42]. Nzila et al. [32] applied multi-criteria analysis to compare biogas production systems using different types of digesters in Kenya. In their analysis, all sustainability criteria were assumed to be equally important but were scaled from zero to one whereby a higher value denoted increasing level of sustainability. In another example, Berberi and Thodhorjani [43] suggested different weight factors for various indicators. However, the work is limited to a methodological discussion.

The main advantage of multi-criteria analysis is that the analysis is made on multiple criteria related to defined objectives. Objectives are often broad and may involve potential contradictions. Therefore, the assessment is highly dependent on the preferences of decision makers [42]. Correspondence analysis incorporating users' attributes can assist when using multiple criteria for decision making. Hong and Abe [1] analyzed the sustainability of existing renewable energy based projects using multiple correspondence analysis (MCA). They identified essential users' attributes related to consumption behavior that influenced the sustainability of the project. However, the methodology demands intensive survey to acquire site specific data and consumer related attributes.