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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].

$$WS_T = \frac{\sum_{i=1}^{n} W_i S_i}{\sum_{i=1}^{n} W_i} \quad (1)$$

where, W_i is the weighting factor and S_i is the score of the *i*th 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.

2.3. Composite indicators

Sustainability can also be expressed and compared in the form of a composite indicator (CIs) which compares performance of the objects under study (viz. technologies or countries). This has been gradually recognized as an effective tool in policy analysis and for public communication [44]. Composite indicators are derived from several indicators or sub-indices selected for this purpose. These selected indicators and sub-indices are aggregated following various methodologies to give an overall score [45]. The main advantage of the CIs is that they capture complex and multi-dimensional realities, and express these in a simple way so that the general public or policy makers can easily understand [46].

There are debates for and against the construction of composite indicators [44,47,48]. The size of a set of indicators is noticeably reduced in this method without losing the underlying information base, which is obviously an advantage. However, the selection of indicators and weights could bring political disputes [44]. If the indicators are poorly constructed and assessed, the CIs will provide misleading information [44,49]. Lack of standardization in methodologies used for the construction of composite indicators, and particularly the unavoidable subjectivity associated with their construction undermine credibility [50].

Nevertheless, there are good examples. The Human Development Index (HDI), first introduced in the 1990, is one of the most widely used composite indicators even if also subject to criticism not least due to the choice of indicators used to compose the index [51]. Thus, construction/selection of indicators and their assessment are vital in the process to make this method effective. In the following sub-section we will discuss two specific methods (Aggregate Metric method and Principal Component Analysis-PCA method) that are used in constructing the composite sustainability index. In this paper, we have adopted PCA for constructing sustainability index. The construction/selection of indicators and details of the evaluation process are further discussed in section 3.

2.3.1. Aggregate metric (D value)

Deciding on the right selection among available options with multi-factorial or multidimensional characteristics is tricky. "Aggregate metric" can be used to compare sustainability among the alternatives available [37,39]. As mentioned earlier, the first key step in this process is to decide which indicators to include, and figure out the appropriate measurement for these sustainability indicators. The selected indicators should be simple and quantifiable variables, and they should be consistent with the principles of sustainability [36,38]. The evaluated indicators of single or multiple dimensions (technical economic, environmental, institutional and social) can be aggregated into one dimensionless index (D), which can be helpful when deciding on the technology selection [37]

Let us consider technology A with various sustainability indicators ($y_1\ y_2\ y_3\ y_4 \ldots y_n$), and technology B with various sustainability indicators ($x_1\ x_2\ x_3\ x_4 \ldots x_n$). Sustainability can be measured in the form of Eqs. (2) and (3), if all indicators have the same unit or are dimensionless (no unit). The weights are important as each of these indicators may not necessarily be of equal importance in terms of sustainability. In the equations, W_A and W_B represent the weight of the respective sustainability indicators of technologies A and B.

$$\mathrm{SI_A} = \mathrm{W_{A1}Y_1 + W_{A2}Y_2 + W_{A3}Y_3 \cdots + W_{Ai}Y}_n \tag{2}$$

$$\mathrm{SI_B} = W_{\mathrm{B1}}X_1 + W_{\mathrm{B2}}X_2 + W_{\mathrm{B3}}X_3 \cdots + W_{\mathrm{B}i}X_n \tag{3}$$

However, in practice, the sustainability indicators are multi-dimensional and are expressed in different units of measurement. Thus, in such cases, Eqs. (2) and (3) are not suitable for analyzing the sustainability indicators. To avoid this, Sikdar [37] suggested a method of analyzing the sustainability of two different technologies or two different states (eg. at different years) of the same technology with aggregated sustainability index "D". The sustainability can be compared in terms of metrics based on a ratio of the sustainability indicators of two different technologies or two different states of the same technology under analysis.

$$D = \left[\prod_{i=1}^{n} \left\{ W_i \left(\frac{Y_i}{X_i} \right) \right\} \right]^{1/n} \tag{4}$$

In Eq. (4), D is the aggregate index. Y_i and X_i represent the values of sustainability indicator i of two alternatives Y and X (X being the reference), and n is the number of metrics used. W_i is a weighting factor for metric m_i. Since the value for W_i is difficult to set, most studies set this value at 1, assuming all indicators are equally and highly significant [37,39,52]. However, the importance or preference of one indicator may be different from another indicator in each particular situation. When chosen metrics are not directly quantifiable, indirect assessment methods have to be used to give some numerical value to the indicator. This method can be used for comparing two or more technologies. This aggregation method is simple in nature. The limitation of this method is that, if the ratio Y_i/X_i of one of the metrics (m_i) is significantly large compared with the rest, it may dominate the result. Also, the method is not applicable in case any of the metrics have null value [37]. Further, this method faces difficulty when weightage is assigned for each metric.

2.3.2. Principal Component Analysis

Principal Component Analysis (PCA) has been used in assessing sustainability in various sectors viz. energy systems [34,35], water resources [53,54] and corporate performance of manufacturing industries [55]. This is one of the methods suggested by EC and OECD guidelines in developing the composite indicators [44,47]. PCA is a mathematical model in which the observations from possibly correlated variables (indicators) are transformed into uncorrelated principal components (PCs) using orthogonal transformation of a covariance matrix or the correlation matrix [55,56].

The principal component analysis (PCA) reveals how different variables change in relation to each other and how they are associated. The main advantage of PCA is that once the patterns in the data set are recognized, the data are compressed, without much loss of information [57,58]. The highest factor loadings are allocated to the individual indicators that have the largest variation across the observations. The individual indicators that are similar across the observations are of little interest and, therefore, are given low factor loading. In contrast to other methods, this sets weights for the indicators on the ground of their statistical significance [53]. The limitation of this method is that it is not suitable for small sets of observations [44]. The method is also sensitive to alterations in the basic data and updates (e.g. addition of new technological options) [47]. The computational steps in calculating sustainability index using PCA has been discussed in Doukas et al. [35] and Mainali et al. [59]. Steps are briefly summarized here.

Since these indicators are of different dimensions and expressed with different measurement units, normalization technique is used. If there are "n" numbers of different technologies under study and their sustainability is evaluated assessing "p" numbers of indicators, then ($n \times p$) data matrix ($X_{\mathrm{n,p}}$) is generated. Let us say that the normalized data set is represented by (Z_{np}) where each indicator/variable is normalized using Eq. (5).

$$X_{\mathrm{normalised}} = \frac{X_i - X_{\min}}{X_{\max} - X_{\min}} \tag{5}$$

where X_{min} and X_{max} are the minimum and maximum values of the ith indicator and X_i is the particular value for the specific observation (technology in our case).Then the correlation matrix (R) is determined using Eq. (6).

$$R = \frac{1}{n-1} Z^T Z \tag{6}$$

The correlation matrix (R) of the indicators represents the interrelations among the variables. Further, a large set of interrelated variables in the matrix (Z_{np}) can be represented by the product of two small dimension matrices called Principal Component Scores (PC_S) and the transpose of Principal Component Loadings (L_{pm}). This reduction in the dimensions of data matrices takes place without losing the information of the original data [53]. These PCs represent uncorrelated variables and are ordered in such a way that the first few preserve most of the variation in all of the original variables [58]. Let us assume that "m" sets of components represent all the original variables. Then,

$$Z_{np} = (PC)_{nm} (L_{pm})^T + (E)_{np} \tag{7}$$

where $(PC)_{nm}$ is the Principal Component Scores (n by m) matrix and $(L)_{pm}$ is the Principal Component Loadings (p by m) matrix and $m < p$, and T in suffix represents the transpose. "E" is the residual matrix covering the unexplained variables by the model and can be ignored.

The data matrices $(PC)_{nm}$ and $(L)_{pm}$ are acquired through Eigen analysis of the correlation matrix (R) of ($p \times p$) data variables. As mentioned before, this correlation matrix shows the interrelations among variables. Any element close to 1 or (-1) within this matrix indicates strong positive or negative correlation with the corresponding indicators. The values close to "0" will indicate that the variables are uncorrelated [35].

The Eigen analysis of correlation matrix "R" is done by solving the pth degree polynomial equation.

$$|R - \lambda I| = 0 \tag{8}$$

where, "I" is the ($p \times p$) identity or unity matrix. When this is solved, this will give us "p" pairs of Eigenvalues λ (say λ_1, λ_2, λ_3..., λ_p). Further, if "F" represents the Eigenvector with ($p \times p$) elements, then for getting these Eigenvectors, matrix Eq. (9) is solved.

$$(R - \lambda I)F = 0 \tag{9}$$

Eqs. (7)–(9) are useful in computing the principal components (PCs). The statistical program XLSTAT can be used for the computation process. As mentioned before, the first "m" numbers of components (PCs) will retain most of the variation present in the original variables. These PCs are mutually orthogonal and are uncorrelated with each other. Finally, the energy technology sustainability index (ETSI) for kth technology is represented by Eq. (10) [35].

$$(\text{ETSI})_k = \left(\frac{\lambda_1 (PC)_1 + \lambda_2 (PC)_2 + \ldots + \lambda_m (PC)_m}{\lambda_1 + \lambda_2 + \ldots + \lambda_m} \right) \tag{10}$$

PCA is a statistically stronger technique to evaluate the sustainability performance of large number of technological systems when compared to the other methodologies discussed above. Therefore, we used this method to evaluate the sustainability performance of 10 different technological systems used for rural electrification in India.

3. Constructing composite indicators

An indicator is a measure (qualitative or quantitative) of the relative position of an object under study, also providing information on how far it is from the targeted goal or reference [44]. EC [47] has suggested the use of composite indicators as an entry point for policy discussion and public interest rather than definition of a specific goal. However, once the policy is enacted, the composite indicators can be used for monitoring the results of policy implementation [48].

Construction of composite indicators starts with the development of a theoretical framework which should clearly define the phenomenon to be measured [44]. Based on this theoretical framework, a set of indicators that capture the sustainability of different technological systems are selected. These selected indicators are then quantified. Finally, the overall progress made towards sustainability is estimated in the form of energy technology sustainability index (ETSI). ETSI, a composite index, is generated by aggregating the above individual indicators using multivariate techniques-Principal Component Analysis (PCA).

We have used OECD [44] and EC [47] guidelines as reference in constructing the composite indicators presented here, paying attention to avoid the shortfalls and critics associated with CIs. ETSI have been evaluated for different years (2005, 2010 and 2015) to capture progress over time which may occur due to technological development and changes in market conditions for the technologies. Ten different technological options (off-grid technologies like solar home system, pico-hydro system, wind home system, mini grid options with micro-hydro, solar PV, wind, solar-wind hybrid, biogas, biomass gasifier and diesel generator sets) have been assessed in the case of India. The various steps followed in the construction of the composite energy technology sustainability index (ETSI) are discussed below.

3.1. Theoretical framework

The theoretical framework offers the ground for the selection of indicators and under a fitness-for-purpose principle these indicators are combined into a meaningful composite indicator [44,47]. Sustainability is a multi-dimensional issue mainly linked with three (economic, environmental and social) pillars [21,60–62]. The triple bottom line (TBL) concept established by Elkington [63] stressed the importance of evaluating sustainability not only on the basis of the economic value it brings, but also of the social value and the environmental impact it has on the surroundings. For the evaluation of sustainability of various technological systems used in rural electrification, two more dimensions (technical and institutional) are also necessary [1,64,65]. These two additional dimensions are important in analyzing the sustainability because reliability and efficiency of technologies and local capacity

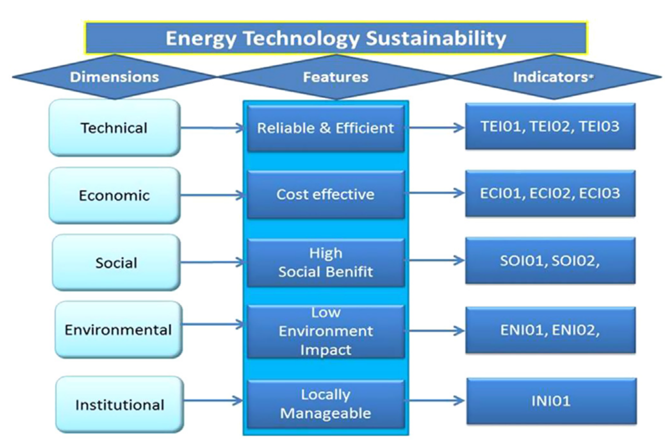

Fig. 1. Conceptual framework for analyzing energy technology sustainability, * The indicators codes are explained in Table 1.

Table 1
Selected indicators for analyzing ETSI of various technological systems.

Dimension codes	Indicators (Units)	Descriptions	References
TEI01	Energy availability (Mwh/KW/yr)	Amount of electricity provided from the technical system	[20,29,65]
TEI02	Efficiency of energy conversion (%)	Technology ability to convert the primary energy source to electricity	[19,31,33,67–69]
TEI03	System reliability	Measure of constancy of services	[33,70–75]
ECI01	Capital investment (USD/kW)	Initial investment for implementation of technical system (purchase and installation)	[19,29,31,33,65,68,69,71,76–78]
ECI02	Operation and Maintenance (O & M) cost (US_{cent}/kWh)	Required costs for regular operation and maintenance of the system	[29,33,65,69,71,72,74,75]
ECI03	Fuel Cost (US_{cent}/kWh)	Required costs for fuel procurement	[19,33,42,72,74]
ENI01	GHG emissions in gCO_2 eq/kWh	Life cycle GHG emission in using the technologies	[19,21,29,33,65,67,79,80]
ENI02	Land uses (m^2 per KW)	Amount of land use and degradation due to energy production and consumption considering life cycle	[21,31,33,74,76,77,80]
SOI01	Local employment generation (Job per MW installed power)	Number of direct local employment opportunities created (considering mainly operation of the plant)	[33,42,68,77,81]
SOI02	Compatibility of the technology with different end uses	Technical capability for using electricity for various income generating activities/ appliances.	[29,33,65]
INI01	Operational & Management capability required	Capacity/ skill required at the local level for the operation and management of the technologies.	[29,65]

to manage such technologies are of prime concern in the rural areas where the market is not yet well established.

As previously indicated, we are analyzing the relative performance of the technology (among the available options) and its role to provide efficient, reliable and cost competitive energy with limited environmental impact and high social benefits. It is important to remember that, to be sustainable in a given setting, the technology should be manageable even in cases of little local capability. Fig. 1 shows the conceptual framework covering different dimensions, features of energy technology sustainability and related indicators used to capture these features when performing the technology assessment.

The energy availability (TEI01), system conversion efficiency (TEI02) and reliability (TEI03) are important performance indicators to be captured under technical dimensions. Similarly, upfront cost of the technology (ECI01), operational and maintenance costs (ECI02) and fuel costs (ECI03) are important economic indicators to be addressed in the sustainability analysis. In addition, some environmental indicators viz. impact of these generation technologies on climate change (ENI01) and land use (EN02) need careful attention. The potential the technology has for creating positive societal impact such as employment generation (SOI01) and provision of energy for various end uses (SOI02) is also of importance in the sustainability assessment. Apart from this, the degree of institutional capability required to manage the technology (INI01) is crucial in determining the sustainability since it indicates the capacity to promote, regulate, support and monitor the dissemination and operation of the technology.

3.2. Selecting indicators

The selection criteria used for picking indicators in this study were transparency, precision, feasibility to be verified and measured, and ability to describe the sustainability of energy technological systems in the rural context. Based on the conceptual framework described in Fig. 1, sets of indicators capturing various sustainability dimensions of rural energy technologies were selected. Large numbers of study reports and research articles on energy sustainability indicators were reviewed as part of the process as discussed above (see also Table 1 for specific references on each indicator). The selected sets of indicators were then discussed in various expert fora within the university (Royal Institute of Technology) and also presented in an international conference on Technologies for Sustainable Development organized by UNESCO [66]. The feedback received from these different fora was used to redefine the indicators and make them more robust. The final sets of selected indicators for analyzing the energy technology sustainability of various technological systems are described in Table 1.

Reliable and efficient energy supplies are some features within technical dimension in sustainability assessment of energy systems. Annual availability of electricity per kW of installed capacity; ability to convert the primary energy source to electricity; and system reliability are some of indicators that have positive correlation with the energy system sustainability. On the other hand, the energy system selected has to be cost effective. The upfront cost of the technology; its O&M cost (i.e. operation, maintenance and component replacement cost) and the fuel cost are some key economic indicators which have negative correlation with sustainability. The energy system should be able to give maximum social benefit. Social indicators such as number of jobs that the technology can help generate and the type of end uses that can be satisfied (to meet societal needs), are important factors in assessing sustainability and both are positively correlated with sustainability. Energy technological systems should have minimum global and local environmental impact. Greenhouse gas (GHG) emissions and land uses are some of the environment concerns that need to be looked at and these indicators are negatively correlated with sustainability. Furthermore, rural energy technology shall be managed by local people sometimes with low level of technical and management skills in a context of weak supply chains. Therefore, technologies with low operational and management skills requirements help to guarantee long term operations.

The life cycle cost has been taken into account while evaluating the operational maintenance cost and the fuel cost of the technical system. Therefore, technology life span has not been considered as a separate indicator. Social acceptance of the technology is another social dimension that could be covered in the sustainability analysis, but this demands survey intensive data, and was not captured in this study.

In addition, maturity of the technology could be one important criterion to be considered when assessing the technological performance [70,76]. Technologies are at different stages of maturity: some may be at laboratory testing phase, others at pilot phase. Some technologies could be in the verge of efficiency improvement and some are consolidated technologies reaching the theoretical limits of efficiency [33]. The relatively emerging technologies will mature over time. It is difficult to quantify the degree of maturity of technologies. However, we have captured the change in maturity over time using other indicators such as the system efficiency and the upfront cost of the technologies.

Before making the sustainability evaluation, the potential and progress of various renewable energy technologies in India and the system configurations of the technologies under assessment are discussed in Section 4.

4. Renewable energy technologies in India

India has a formidable challenge to ensure modern energy access to its large rural population [82]. Selecting the appropriate technology is, therefore, of primary importance to guarantee sustainability. India is rich in renewable energy resources that can be used for electricity generation. It has large landmasses that receive an average hourly radiation of 200 MW/km^2 over an average 300 sunny days per year [83]. It also has a long coastline and places with high wind velocities providing ample opportunity for harnessing wind power. In the northern areas, wind power density varies from 250 to 500 w/m^2 and, in western areas; wind power density reaches 200–250 w/m^2 [84]. There is significant production of biomass and, in fact, 40% of the non-commercial energy is presently supplied with biomass including agriculture residues, wood and cattle dung. Besides, there are also abundant rivers and waterways that allow for small hydropower generation [83].

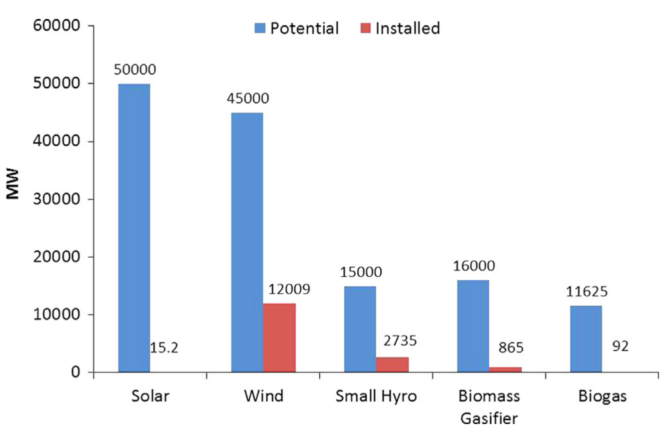

Fig. 2. Renewable energy potential and installed capacity per source, India 2010, . *Source*: [83,85–88].

Fig. 2 indicates that the exploitation of renewable energy in India is far behind the existing potential. If we look at the situation of renewable energy utilization in the rural areas (off-grid and mini grid options), the situation is even poorer. For example, out of 92 MW of harnessed electricity from biogas, only 0.44 MW of electricity is generated from small biogas plants (off-grid). Similarly, off-grid solar PV installations contribute only 20% of the total solar PV installed in India [83,85]. Thus, huge amounts of renewable resources are still untapped.

We have assessed rural electrification alternatives using renewable energy technologies viz. hydropower, solar photovoltaic, wind, electrification based on biogas, biomass gasification and conventional fossil based generation. These technologies have been analyzed based on possible alternative applications (off-grid or mini grid option and hybrid arrangements). The system configuration and the technical parameters of the technologies under assessment are listed in Table 2.

The methodology introduced in this paper can be useful for the country in comparing available alternatives for the rural electrification. This method identifies the key indicators that need to be focused for the promotion and sustainable development of various technological alternatives. Ultimately, this will help to give perspective to the potential of the different alternatives in local settings, and exploit untapped resources. The periodic monitoring of these indicators will also help to move the sustainability frontier of the energy system.

5. Evaluating the indicators

Out of 11 indicators, the quantification of 7 indicators: energy availability; energy conversion efficiency; capital investment; O & M cost; fuel cost; land use and local employment generation is straight forward. Data for these indicators were available from various secondary sources [28,89–97,111]. The capital cost and operation and maintenance (O&M) cost estimation for all these technologies across three different time slots (2005, 2010 and projected values for 2015) were based on techno-economic data available from ESMAP [89] and Bhattacharya [40] and the fuel cost assessment was retrieved from various sources [98–101].

The cost of technology is going down along with the technological improvement and scale up in the business volume. Not all

Table 2
System configuration and technical parameters of technologies assessed in India.

System configuration		Size	Conversion efficiency[a]	Capacity factor[b]	Life span[b]
Off grid	PicoHydro System (PHS)	300 watts	50	30	5
	Solar Home System (SHS)*	300 watts	15/20/22	20	20
	Wind Home System (WHS)*	300 watts	20/25/30	25	20
Mini grid	Micro Hydropower	100 kW	70	40	30
	Solar PV*	25 kW	15/20/22	20	20
	Wind*	100 kW	25/30/35	25	20
	Solar Wind Hybrid*	100 kW	20/25/30	30	20
	Biogas	60 kW	33	80	20
	Biomass Gasifier	100 kW	32	80	20
	Diesel power	100 kW	40	80	20

[a] [28,90–93].
[b] [89].
* The technology is gradually reaching maturity and efficiency improvement can be observed over time. The efficiencies mentioned are for the years 2005, 2010 and 2015 respectively.

technologies have the same reduction rate in their capital cost. The potential in the cost reduction may vary depending upon the maturity of the technology and scale of production. Some rapidly emerging technologies like solar PV and wind have significant cost reduction potential due to technological improvements and scaling up of production. For solar PV, wind and their hybrids (which are in the process of gaining maturity), the capital cost is predicted to go down by 11% to 20% in 2015 as compared to the capital cost in 2005 [89]. Further, the capital cost of technologies such as microhydro, pico-hydro, biogas and diesel based electrification is assumed to be only slightly reduced with up to 5%, whereas the cost for biomass gasifiers will be reduced by 6% to 10% [89]. Uncertainty has been incorporated in the estimation and projections of capital cost (USD/kW), O&M cost (US_{cent}/kWh) and fuel cost (US_{cent}/kWh) through sensitivity analysis of key input parameters. These costs have been presented in three possible ranges (probable, minimum and maximum values) (see Appendix A) incorporating uncertainties in equipment cost, and variation in the labor and fossil fuel cost across different locations in India. The operation and maintenance costs and fuel costs estimation are levelized unit cost at the discount rate of 10%.

Whenever possible, we used the direct quantifiable data rather than qualitative/proxy data. However, comparable quantitative data were not available for all technologies and indicators. Therefore, for indicators such as (i) system reliability; (ii) compatibility of the technologies for different end uses, and (iii) operational and management capability required, proxy data or qualitative data have been taken from various studies, and given a relative score. For example, when it comes to system reliability, the loss of load expectation (i.e. LOLE is number of hours that the load exceeds the available generation) and loss of energy expectation (i.e. LOEE is the expected energy curtailed due to load loss) are the most common probabilistic risk indices used [102]. However, this demands a generation model and the load profile over time, thus being most useful when site specific data are available [103]. Traditionally, less effort has been made for assessing reliability index associated with off-grid generation system with renewable resources [102–104]. For the small energy systems operated in the isolated rural areas, one of the proxy methods to capture reliability of the system is to look at the average capacity factor of the system [105]. Capacity factor is defined as the ratio of the real energy generated from the system in a given period, to the theoretical maximum possible that the system can produce for full time at rated power. This factor covers forced and planned outages and the intermittency of the systems. Thus plants with higher capacity factor are relatively more reliable.

As mentioned earlier, the level of expertise required to operate and manage the technological system can be a determinant for sustainability in the rural areas of developing countries. No specific study is available quantifying this indicator and, in fact, this is not trivial. Sets of sub-criteria have been developed to assess such qualitative indicators and give them a relative score. Examples of issues affecting managerial capacity are (i) complexity of the technology, (ii) degree of institutional capacity required for managing the system and (iii) the strength of supply chain [106]. Based on these subcriteria, the indicator (Operational and Management capability required) was assessed referring to previous studies dealing with these aspects [106–108]. The first issue affecting managerial capacity refers to the level of technical skill that is needed for the operation of the technological system, and the extent to which damages can be repaired using locally available resources. Technologies requiring high level of technical expertise to understand/operate are most likely to breakdown first because of mishandling, and it may take time for them to be repaired due to the lack of expertise at the local level unless a support system is in place [106]. In practice, rural energy technologies will be installed in remote locations, where institutional support from NGOs and governments are also deficient. So, technological systems with low demand for institutional support to guarantee their operation tend to be a better choice. Technologies that demand low inventory of spare parts or for which well-defined chains exist to supply spare parts and technical expertise are preferable from a sustainability point of view. Based on these facts, this indicator was evaluated for all the technologies.

The observations for all eleven indicators were made at three different years (2005, 2010 and 2015) for all ten technological systems used in India. Both indicators that are directly quantifiable and those that have been assessed with indirect methods are tabulated and shown in Appendix B. Once these indicators are assessed and quantified, the next step is to perform multivariate analysis of the data sets obtained to construct the energy technology sustainability index (ETSI).

6. Results and discussion

After introducing a method of evaluating sustainability performance of energy technologies, we have evaluated the sustainability indicators of various energy technology systems in India over three different years (2005, 2010 and 2015) (see also table in Appendix B). In this section, we have performed the multivariate analysis called principal component analysis (PCA) to construct the energy technology sustainability index (ETSI). The results provide insights on the sustainability performance trend brought up by technological advancement and changing market conditions for the various technologies.

6.1. Multivariate analysis

All the values presented in Appendix B are assigned either positive or negative sign in order to make them unidirectional depending upon their relation to sustainability [109]. Once the indicators are made unidirectional, normalization of the selected indicators is carried out using Eq. (6). The normalized values of all indicators are presented in Table 3.

Once the data sets are normalized, it is important to analyze the underlying nature of the data variables and their interrelationship. Multivariate analysis techniques like principal component analysis (PCA) are instrumental for obtaining insight of the data structure, and helpful for compressing the data set without loss of information [44]. This helps to identify the sets of variables (indicators) that are statistically "similar", and provide an interpretation of the results. This analysis is furthermore instrumental in setting weights for the indicators on the ground of their statistical significance. The statistical weighing makes the analysis neutral and data-reliant [53].

Fig. 3 shows the scree plot of the factors F1–F6. Scree plot are helpful in determining the number of factors that should be retained in an analysis. The corresponding graph represents a mathematical projection, the Eigenvalues, which reflect the quality of the projection from the 11-variables from our initial table to a lower number of dimensions. The first two factors F1 and F2 together contribute 71% of the variability. With the additional two factors F3 and F4, i.e. four factors represent around 94% of the variances of the original matrix which is already quite high. These four factors also have the highest Eigenvalue as shown by the bar chart (Fig. 3). Therefore, the analysis has focused on these two factor spaces (F1 and F2) and (F3 and F4). The corresponding four Eigenvalues have been taken in this analysis without losing significant information from the set of variables. The eigenvectors for various variables associated with factor axes (F1-F4) are tabulated in Table 4.

Table 3
Normalized values of energy indicators in India, per type of technology, 2005, 2010 and projections for 2015.

Description	Energy availability	Efficiency of energy generation	Reliability	Capital investment	O & M cost	Fuel Cost	GHG Emission	Land Uses	Local Employment generation	Compatibility of the technology to do end uses	Operation & Management capability required
Pico hydro-2005	0.167	0.636	0.167	0.860	0.984	1.000	0.936	0.813	0.000	0.250	1.000
SHS-2005	0.000	0.000	0.000	0.004	0.000	1.000	0.893	1.000	0.000	0.000	1.000
WHS-2005	0.083	0.091	0.083	0.309	0.216	1.000	0.975	1.000	0.000	0.000	1.000
Microhydro-2005	0.333	1.000	0.333	0.710	0.924	1.000	0.936	0.813	0.250	1.000	0.125
Solar PV-2005	0.000	0.000	0.000	0.000	0.251	1.000	0.893	0.819	0.150	0.500	0.625
Wind-2005	0.083	0.182	0.083	0.684	0.445	1.000	0.975	0.000	0.110	0.500	0.625
Solar/Wind hybrid-2005	0.167	0.091	0.167	0.302	0.208	1.000	0.934	0.066	0.230	1.000	0.625
Biogas-2005	1.000	0.327	1.000	0.725	0.884	0.940	1.000	0.462	0.750	1.000	0.000
Biomass gasifier-2005	1.000	0.309	1.000	0.669	0.881	0.856	1.000	0.582	1.000	1.000	0.000
Diesel gen set-2005	1.000	0.455	1.000	0.993	0.564	0.240	0.000	0.320	0.075	1.000	0.000
Pico hydro-2010	0.167	0.636	0.167	0.871	0.906	1.000	0.936	0.813	0.000	0.250	1.000
SHS-2010	0.111	0.091	0.000	0.146	0.016	1.000	0.893	1.000	0.000	0.000	1.000
WHS-2010	0.188	0.182	0.083	0.384	0.305	1.000	0.975	1.000	0.000	0.000	1.000
Microhydro-2010	0.333	1.000	0.333	0.728	0.907	1.000	0.936	0.813	0.250	1.000	0.125
Solar PV-2010	0.111	0.091	0.000	0.133	0.294	1.000	0.893	0.819	0.150	0.500	0.625
Wind-2010	0.167	0.273	0.083	0.724	0.497	1.000	0.975	0.000	0.110	0.500	0.625
Solar/Wind hybrid-2010	0.292	0.182	0.167	0.399	0.303	1.000	0.934	0.066	0.230	1.000	0.625
Biogas-2010	1.000	0.327	1.000	0.749	0.910	0.928	1.000	0.462	0.750	1.000	0.000
Biomass gasifier-2010	1.000	0.309	1.000	0.715	0.934	0.826	1.000	0.582	1.000	1.000	0.000
Diesel gen set-2010	1.000	0.455	1.000	0.999	0.590	0.089	0.000	0.320	0.075	1.000	0.000
Pico hydro-2015	0.167	0.636	0.167	0.873	0.986	1.000	0.936	0.813	0.000	0.250	1.000
SHS-2015	0.156	0.127	0.000	0.250	0.345	1.000	0.893	1.000	0.000	0.000	1.000
WHS-2015	0.292	0.273	0.083	0.442	0.502	1.000	0.975	1.000	0.000	0.000	1.000
Microhydro-2015	0.333	1.000	0.333	0.731	0.922	1.000	0.936	0.813	0.250	1.000	0.125
Solar PV-2015	0.156	0.127	0.000	0.238	0.482	1.000	0.893	0.819	0.150	0.500	0.625
Wind-2015	0.250	0.364	0.083	0.753	0.623	1.000	0.975	0.000	0.110	0.500	0.625
Solar/Wind hybrid-2015	0.417	0.273	0.167	0.475	0.499	1.000	0.934	0.066	0.230	1.000	0.625
Biogas-2015	1.000	0.327	1.000	0.756	0.929	0.914	1.000	0.462	0.750	1.000	0.000
Biomass gasifier-2015	1.000	0.309	1.000	0.734	1.000	0.792	1.000	0.582	1.000	1.000	0.000
Diesel gen set-2015	1.000	0.455	1.000	1.000	0.584	0.000	0.000	0.320	0.075	1.000	0.000

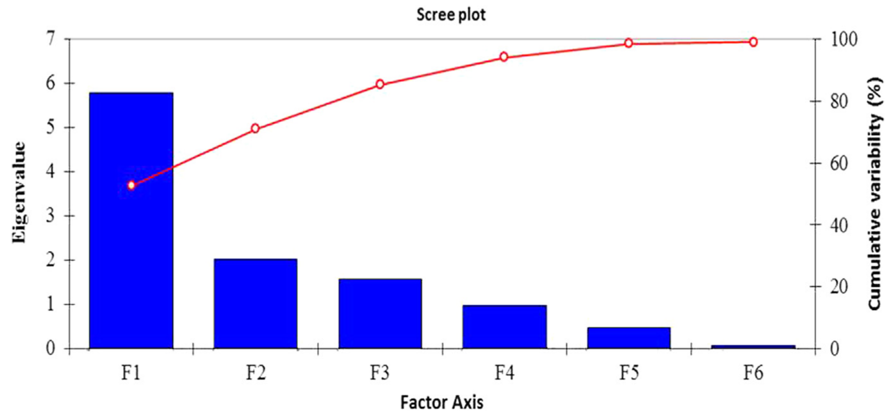

Fig. 3. Eigenvalues and factor axes with their cumulative representation of variability.

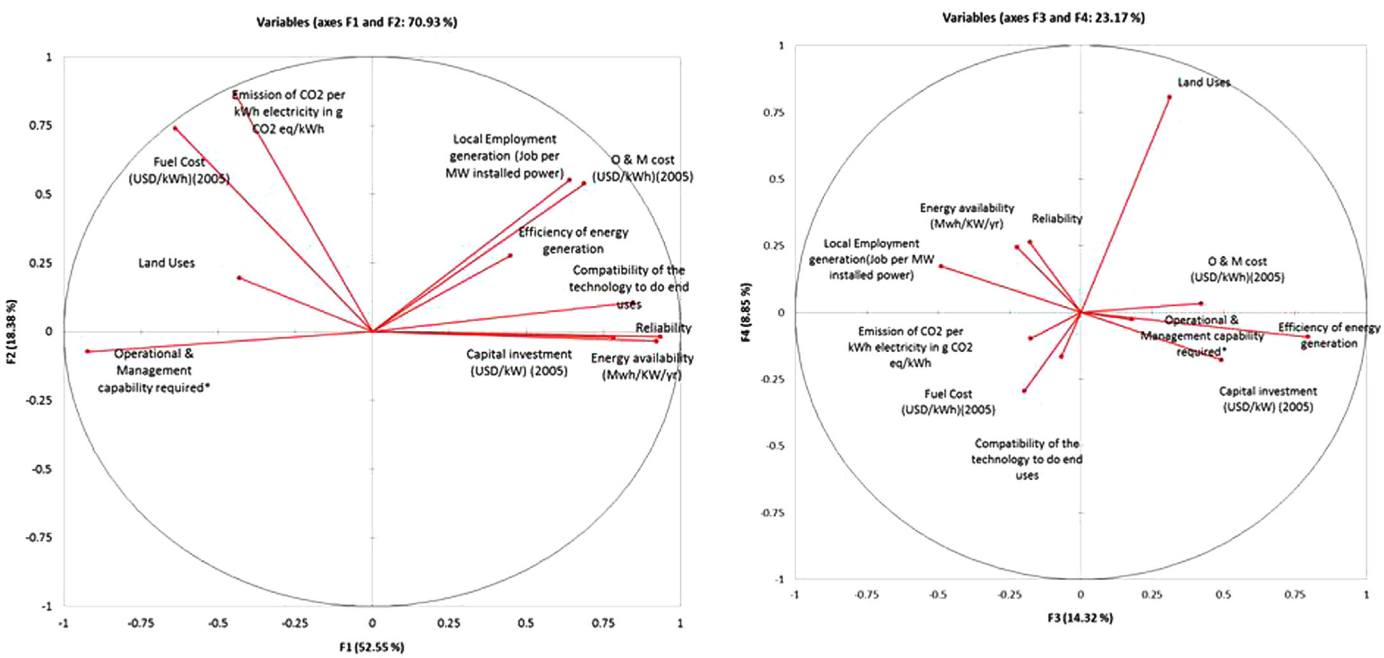

Fig. 4. Correlation circle in the factor space of (F1 and F2) and (F3 and F4).

Table 4
Computed eigenvectors.

Variables (Indicators)	F1	F2	F3	F4
Energy availability	0.384	−0.024	−0.178	0.247
Efficiency of energy generation	0.187	0.195	0.633	−0.094
Reliability (Proxy average capacity factor)	0.389	−0.013	−0.142	0.266
Capital investment	0.326	−0.014	0.391	−0.180
O&M cost	0.286	0.379	0.335	0.034
Fuel cost	−0.266	0.520	−0.055	−0.167
GHF emission	−0.185	0.607	−0.141	−0.100
Land uses	−0.179	0.137	0.247	0.817
Local employment generation	0.266	0.389	−0.391	0.176
Compatibility of the technology for different end uses	0.352	0.074	−0.158	−0.299
Operational & management capability required	−0.384	−0.051	0.142	−0.027

The variables can be plotted as points within the correlation circle in factor space using their loadings as coordinates. The correlation circles in Fig. 4 show the projection of the initial variables in the two factor spaces (left circle in F1 and F2 factor space and right circle in F3 and F4 factor space). Those variables which are closer to the circumference of the circle are well represented and associated with that factor space. If a variable is not well represented in one factor space, then it may be well represented in another factor space. Those variables which are closer to the circumference and close to each other are significantly positively correlated (r close to 1). If the variables are on the opposite direction from the center, then they are significantly negatively correlated (r close to -1). The variables that are orthogonal to each other are not correlated (r close to 0). For example, technologies that deliver more energy per year per kW of installed capacity are more reliable than others. As anticipated, "reliability" and "energy availability" have strong statistically positive correlation with each other. This can also be seen from the correlation circle in factor space (F1 and F2).

Similarly, the employment generation, and the operation and maintenance cost also have positive correlation with each other. This correlation may be explained as the human resource cost associated with the operation and maintenance, thus representing an employment generation opportunity. The variable "operation and management capacity required" is significantly negatively correlated with "reliability". The lower the operation and management capacity required, the better the technology is in terms of its reliability as there is less chance of technology failure. The variables "land uses" and "generation efficiency" were not significant in F1 and F2 factor space as they were close to the center but they have their significant presence in another orthogonal factor space, F3 and F4. These two variables are orthogonal to each other which indicate no correlation between them.

Table 5
Squared cosines of the variables (loading factor).

Variables (Indicators)	F1	F2	F3	F4
Energy availability	**0.851**	0.001	0.050	0.059
Efficiency of energy generation	0.201	0.077	**0.632**	0.009
Reliability (Proxy average capacity factor)	**0.873**	0.000	0.032	0.069
Capital investment	**0.613**	0.000	0.241	0.032
O&M cost	**0.473**	0.291	0.177	0.001
Fuel cost	0.408	**0.547**	0.005	0.027
GHG emission	0.198	**0.746**	0.031	0.010
Land uses	0.186	0.038	0.096	**0.649**
Local Employment generation	**0.410**	0.305	0.240	0.030
Compatibility of the technology to do end uses	**0.716**	0.011	0.039	0.087
Operational & Management capability required	**0.852**	0.005	0.032	0.001

Note: Values of each variable in bold correspond to the factor axis for which the loading factor is the major.

The correlation circle helps to interpret the linkage of the original variable with these factor axes. The variables "energy availability", "reliability", "capital investment cost", "O & M cost", "compatibility of the technology for different end uses" and "operational and management capacity required" are mainly associated with factor F1 whereas "GHG emission" and "fuel cost are well associated with factor F2. "Efficiency of energy generation" is mainly associated with factor F3 and "land uses" is associated with factor F4. These linkages become clear when we look at the squared cosine of the variables (loading factors) in Table 5.

Those variables/indicators which have higher correlation with other variables/indicators and have large variations across the observations (among technologies and/or with time) are loaded in first component.

6.2. Energy Technology Sustainability Index (ETSI)

Fig. 5 shows ETSI for all the technological systems in 2005, 2010 and 2015. Clearly, the biomass gasifier has the highest ETSI in all the years examined, indicating the best performance in terms of sustainability among the assessed technologies. This is followed by biogas, micro and pico-hydro systems, respectively. The sustainability performance of these mature technologies has slightly improved over time and is expected to increase further in the near future, though the increments may not be that significant. Diesel generator ranked fifth in ETSI and, in contrast with other technologies, the ETSI of the diesel generator is decreasing over time. Nevertheless, the analysis shows that diesel will remain a competitive option for electrifying rural areas compared to the solar and wind based systems.

Emerging technologies such as solar have low ETSI mainly because of their high capital cost, and low capacity factors. Wind has a relatively better position than solar technologies but is still far behind the mature technologies. As a result of significant reduction in the capital cost and increment in the conversion efficiency and energy availability, the sustainability performance of Solar PV has increased in 2010 and is expected to further increase in the near future. The sustainability performance of wind technology is also expected to increase by 2015. The solar wind hybrid has better ETSI than the individual technology itself. The

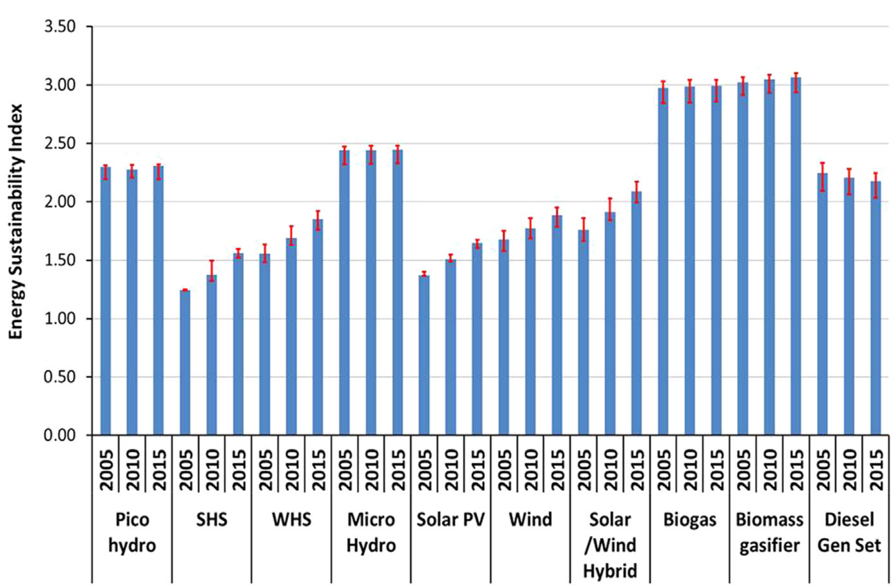

Fig. 5. Energy technology sustainability index of various technical systems (2005, 2010 and 2015).

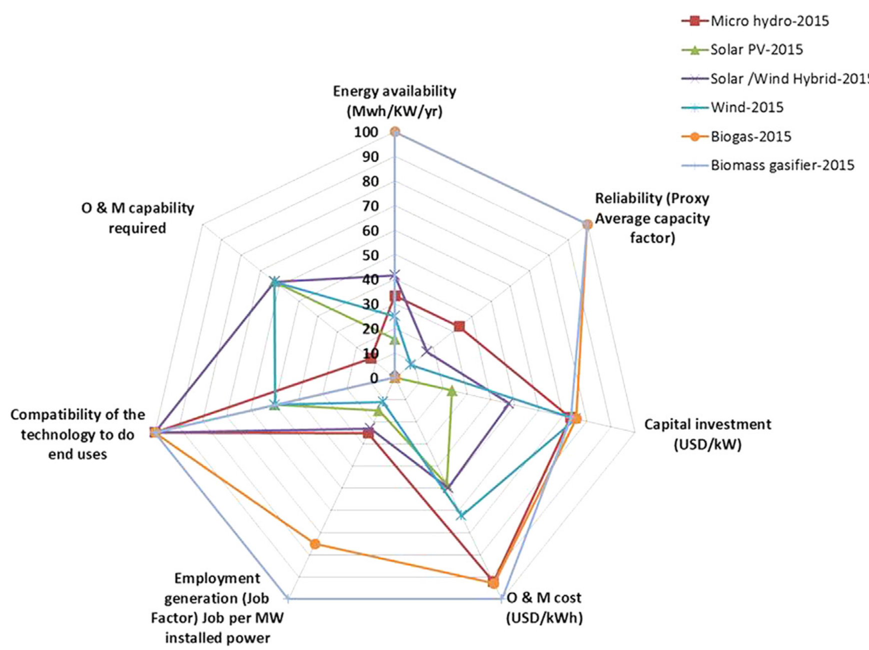

Fig. 6. Radar diagram presenting decomposition of various key indicators associated with factors F1 of Biomass gasifier, Biogas, Microhydro, Solar/Wind hybrid, Solar PV and Wind. (The highest performance for each indicator takes the value 100, and the lowest, 0).

hybrid systems' sustainability performance is also expected to increase by 2015. Mini grid technological systems have higher ETSI compared to the off-grid options.

As mentioned earlier, the estimated capital investment cost, operation and maintenance cost and the fuel cost incorporate uncertainty in the key assumptions [89–101]. Thus, the energy technology sustainability index was computed with probable, minimum and maximum costs to reflect sensitivity to key input assumptions. The blue bar in Fig. 5 represents ETSI and the red lines indicate the variations resulting from the sensitivity analysis.

The Aggregate metrics method described in Section 2.3.1 has limitation in capturing all these indicators. For examples: indicators like fuel costs, land uses and direct local employment generation are not possible to be captured as some of the technologies have zero values for these indicators. Also, if there is a large difference in the values of an indicator among various observations, there is a high risk that the indicator would determine the value of sustainability index. As discussed earlier, the sustainability assessment based on weightage average method or ranking methods used by Evans et al. [28], Ilskog and Kjellström [29] and Lhendup [30] are simple where the average ranking of various indicators are taken into account. However, this method does not differentiate among weights of various indicators. The main advantages of ETSI computed with principal component analysis (PCA) is (i) it provide the opportunity to take all these large sets of indicators in defining sustainability, and (ii) also sets weights for the indicators on the ground of their statistical significance which makes the analysis neutral and data-reliant.

The fossil fuel costs are based on market prices. However, local market prices may be influenced by government policy. Unlike high taxation of fossil fuels in Europe, fossil fuels are often subsidized in India. The damage cost of energy (i.e. the external cost of energy use) can be internalized in the fuel cost or in generation cost depending upon the different impacts caused by these various generation technologies [110]. If the damage costs are appropriately internalized in the fuel costs in the future, the diesel technology may be less attractive due to lower sustainability performance compared to emerging new technologies.

The analysis in this study was done on the actual technology cost i.e. without considering government subsidy provided for these technologies. However, we can run different subsidy policy scenarios (by reducing the capital cost as per the subsidy availability) to verify the impact the subsidy may have on the sustainability performance of the technologies targeted. Furthermore, in this paper we have considered the electricity generation only. However, some technologies viz: biomass gasifier, biogas could be used in poly-generation mode (heat plus electricity), which could further increase their sustainability performance. Still the same sets of indicators and methods can be used for integrated analysis contemplating multiple uses.

6.3. *Decomposition analysis*

A decomposition analysis helps further in extending the analysis to determine the contribution of set of indicators to the aggregated composite indicator (OECD, 2008). We have further extended the analysis by looking at the projected performance of the renewable energy systems in mini grid configuration for the year 2015 considering the indicators associated mainly with the first principal axis.

Fig. 6 shows that Biomass gasifiers has the highest values on five indicators i.e. energy availability, reliability, operational and maintenance cost, and compatibility of the technology to do end uses. On the other hand, solar PV has the lowest values on these indicators. The area coverage under the radar chart in Fig. 6 proportionate to each energy systems' overall energy sustainability.

7. Conclusion

Evaluating various energy technological systems in terms of their sustainability performance is a multi-dimensional issue. This paper has discussed various approaches used in the analysis of sustainability, and introduced a method for evaluating the sustainability performance of energy technologies used for rural electrification. The method results in a single composite indicator (ETSI). For the purpose of the analysis, the Indian case has been used. The analysis has been made for years 2005, 2010 and projected for 2015 to capture the sustainability performance trend resulting from technological advancement and changes in market conditions.

The analysis showed that biomass based technologies such as the biomass gasifier and biogas have the highest sustainability performance in the context of India. This is followed by hydro based technologies (micro-hydro and pico-hydro). The performance trend of these mature technologies shows slight increment over time. The analysis also revealed that new and emerging technologies like solar, wind and their hybrids have fair improvement in their sustainability performance over time. In contrast, the sustainability performance of the diesel generator is decreasing. Still, emerging renewable technologies have difficulties to compete with the fossil based technology in the rural context without strong policy support to reduce the high capital cost of these technologies. The analysis revealed that indicators such as "energy availability", "reliability", "capital investment cost, "O & M cost", "compatibility of the technology for different end uses" and "operational and management capacity required" play a strong role in the sustainability of energy technologies. The decomposition analysis also indicates that the area coverage under radar diagram capturing various key indicators (associated with factors F1) is proportionate to the ETSI.

This analysis has been done with secondary data at national level and the uncertainty in the data sets are covered with a band of minimum and maximum values following from the sensitivity analysis. The method in this study does have some limitations. For example, it does not consider the consumer perception about the technology. Some of the indicators are not easy to quantify and were evaluated with relative scores derived from sub-criteria for the purpose of the assessment. The improvement is a continuous and dynamic process. The quality and accuracy of such index should be enhanced with improvements in the data collection. On site assessment and periodic monitoring of some of these indicators would further improve the accuracy. Despite these limitations, the introduced method is instrumental in evaluating the sustainability performance of the technologies and can be used as an entry point in feasibility analysis and design of electrification projects in developing contexts.

ETSI can be applied for evaluating the sustainability performance of different technologies under different policy scenarios (viz. with different capital subsidy support, internalization of damage cost) with careful and appropriate adjustment of the indicators. However, it is important to remember that the energy technology sustainability index computed in this analysis is a relative index and thus only shows the relative performance trend of the technology among the technologies under assessment. ETSI provides an operational tool for decision making in a less than perfect world. Ultimately, the absolute improvement of technological systems in social, economic and environmental terms needs to be addressed by policy makers.

Acknowledgments

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Appendix A

See Fig A1.

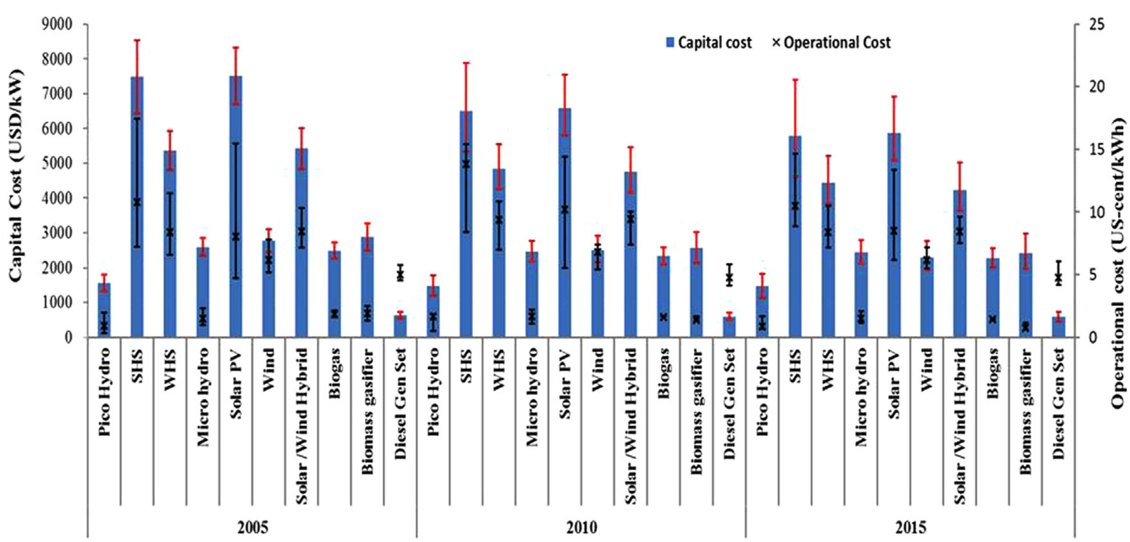

Fig. A1. Capital and operational costs estimation with 2005 as a base year.
Source: [89–101]

Appendix B

See Table B1.

Table B1
Assessed values of the indicators for different technologies.
Source: [28,89–97,111] and authors' estimations.

Description	Energy availability (Mwh/KW/yr)	Overall Efficiency of energy system	Reliability (Proxy Av. capacity factor)	Capital investment (USD/kW)	O&M cost (US_cent/kWh)	Fuel cost (US_cent/kWh)	GHG Emissions in gCO_2 eq/kWh	Land Uses in m^2 per KW	Local Employment (Job per MW installed power)	Compatibility of the technology to do end uses	Operational & Management capability required
Pico Hydro-2005	2.63	50	30	1560	0.90	0.00	56	50	0	2	6
SHS-2005	1.75	15	20	7480	10.50	0.00	90	0	0	1	6
WHS-2005	2.19	20	25	5370	8.39	0.00	25	0	0	1	6
Microhydro-2005	3.50	70	40	2600	1.49	0.00	56	50	50	5	13
Solar PV-2005	1.75	15	20	7510	8.05	0.00	90	48.5	30	3	9
Wind-2005	2.19	25	25	2780	6.16	0.00	25	267.7	22	3	9
Solar/Wind Hybrid-2005	2.63	20	30	5420	8.47	0.00	57.5	250	46	5	9
Biogas-2005	7.01	33	80	2490	1.88	1.10	5.37	144	150	5	14
Biomass gasifier-2005	7.01	32	80	2880	1.91	2.66	5.37	112	200	5	14
Diesel Gen Set-2005	7.01	40	80	640	5.00	14.04	800	182	15	5	14
Pico Hydro-2010	2.63	50	30	1485	1.66	0.00	56	50	0	2	6
SHS-2010	2.34	20	20	6500	10.35	0.00	90	0	0	1	6
WHS-2010	2.74	25	25	4850	7.52	0.00	25	0	0	1	6
Microhydro-2010	3.50	70	40	2470	1.65	0.00	56	50	50	5	13
Solar PV-2010	2.34	20	20	6590	7.63	0.00	90	48.5	30	3	9
Wind-2010	2.63	30	25	2500	5.66	0.00	25	267.7	22	3	9
Solar/Wind Hybrid-2010	3.29	25	30	4750	7.54	0.00	57.5	250	46	5	9
Biogas-2010	7.01	33	80	2330	1.63	1.33	5.37	144	150	5	14
Biomass gasifier-2010	7.01	32	80	2560	1.39	3.21	5.37	112	200	5	14
Diesel Gen Set-2010	7.01	40	80	595	4.75	16.84	800	182	15	5	14
Pico Hydro-2015	2.63	50	30	1470	0.88	0.00	56	50	0	2	6
SHS-2015	2.57	22	20	5780	7.14	0.00	90	0	0	1	6
WHS-2015	3.29	30	25	4450	5.60	0.00	25	0	0	1	6
Microhydro-2015	3.50	70	40	2450	1.51	0.00	56	50	50	5	13
Solar PV-2015	2.57	22	20	5860	5.80	0.00	90	48.5	30	3	9
Wind-2015	3.07	35	25	2300	4.42	0.00	25	267.7	22	3	9
Solar/Wind Hybrid-2015	3.94	30	30	4220	5.64	0.00	57.5	250	46	5	9
Biogas-2015	7.01	33	80	2280	1.44	1.59	5.37	144	150	5	14
Biomass gasifier-2015	7.01	32	80	2430	0.75	3.85	5.37	112	200	5	14
Diesel Gen Set-2015	7.01	40	80	590	4.80	18.48	800	182	15	5	14

References

[1] Hong GW, Abe N. Sustainability assessment of renewable energy projects for off-grid rural electrification: the Pangan-an Island case in the Philippines. Renew Sustain Energy Rev 2012;16:54–64.

[2] Narula K, Nagai Y, Pachauri S. The role of decentralized distributed generation in achieving universal rural electrification in South Asia by 2030. Energy Policy 2012;47:345–57.

[3] World Bank. Global tracking framework report for sustainable energy for all. World Bank; 2013.

[4] Mainali B, Silveira S. Financing off-grid rural electrification: country case Nepal. Energy 2011;36:2194–201.

[5] Mainali B, Silveira S. Renewable energy market in rural electrification: country case Nepal. Energy Sustain Dev 2012;6:168–78.

[6] Nouni MR, Mullick SC, Kandpal TC. Providing electricity access to remote areas in India: niche areas for decentralized electricity supply. Renew Energy 2009;34:430–4.

[7] Hulscher WS, Hommes EW. Energy for sustainable rural development. Energy Policy 1992;20:527–32.

[8] Monroy CR, Hernández ASS. Main issues concerning the financing and sustainability of electrification projects in rural areas: international survey results. Energy Sustain Dev 2005;2:17–25.

[9] USAID. Micro-hydropower in Afghanistan: an audit lessons & conclusions. South Asian initiative for regional cooperation and development. USAID; 2006.

[10] Tran TA, Daim T. A taxonomic review of methods and tools applied in technology assessment. Technol Forecast Soc Change 2008;75:1396–405.

[11] Greeley M. Rural energy technology assessment: a Sri Lankan case study. World Dev 1986;14:1411–21.

[12] Bohm E, Walz R. Life-cycle-analysis: a methodology to analyse ecological consequences within a technology. Int J Technol Manag 1996;11:554–66.

[13] Assefa G, Frostell B. Social sustainability and social acceptance in technology assessment: a case study of energy technologies. Technol Soc 2007;29:63–78.

[14] Carrera D, Mack A. Sustainability assessment of energy technologies via social indicators: results of a survey among European energy experts. Energy Policy 2010;38:1030–9.

[15] Kennedy CA. a comparison of the sustainability of public and private transportation systems: study of the greater Toronto area. Transportation 2002;29:459–93 (Springer Publisher).
[16] Delwulf J, Van Langenhove H. Integrating industrial ecology principles into a set of environmental sustainability indicators for technology assessment. Resour, Conserv Recycl 2005;43:419–32.
[17] Ilskog E. Rural electrification sustainability indicators- manual for field workers. Stockholm, Sweden: KTH Publications; 2008.
[18] Afgan NH, Carvalho MG, Hovanov NV. Energy system assessment with sustainability indicators. Energy Policy 2000;28:603–12.
[19] Jovanovic M, Afgan N, Radovanovic P, Stevanovic V. Sustainable development of the Belgrade energy system. Energy 2009;34:532–9.
[20] Onat N, Bayar H. The sustainability indicators of power production systems. Renew Sustain Energy Rev 2010;14:3108–15.
[21] IAEA. Energy indicators for sustainable development: guidelines and methodologies. Vienna: International Atomic Energy Agency (IAEA; 2005.
[22] Ugwu OO, Haupt TC. Key performance indicators and assessment methods for infrastructure sustainability – a South African construction industry perspective. Build Environ 2007;42:665–80.
[23] ESMAP. Best practice manual: promoting decentralized electrification investment. Report 248/01, World Bank, Washington DC, USA; 2001.
[24] ESMAP. The community development toolkit. ESMAP Formal Report No. 310/05. ESMAP, The World Bank. Available online at: ⟨www.esmap.org⟩; 2005 [cited 15.01.12.].
[25] Barnes D.F., O' Sullivan K. Energy policy and multi topic household surveys. Guidelines for questionnaire design in living standards measurement studies. World Bank/ESMAP. Working Paper no. 90, Washington, DC, USA; 2006.
[26] World Bank. Monitoring & evaluation: Some tools, methods & approaches. Washington, DC, USA: The World Bank; 2004.
[27] Singh RK, Murty HR, Gupta SK, Dikshit AK. An overview of sustainability assessment methodologies. Ecol Indic 2012;15:281–99.
[28] Evans A, Strezov V, Evans TJ. Assessment of sustainability indicators for renewable energy technologies. Renew Sustain Energy Rev 2009;13:1082–8.
[29] Ilskog E, Kjellström B. And then they lived sustainably ever after? – Assessment of rural electrification cases by means of indicators Energy Policy 2008;36:2674–84.
[30] Lhendup T. Rural electrification in Bhutan and a methodology for evaluation of distributed generation system as an alternative option for rural electrification. Energy Sustain Dev 2008;12:13–24.
[31] Afgan NH, Carvalho MG. Multi-criteria assessment of new and renewable energy power plants. Energy 2002;27:739–55.
[32] Nzila C, Dewulf J, Spanjers H, Tuigong D, Kiriamiti H. Multi criteria sustainability assessment of biogas production in Kenya. Appl Energy 2012;93:496–506.
[33] Wang JJ, Jing YY, Zhang CF, Zhao JH. Review on multi-criteria decision analysis aid in sustainable energy decision-making. Renew Sustain Energy Rev 2009;13:2263–78.
[34] Ediger VS, Hosgör E, Surmeli AN, Tatlıdil H. Fossil fuel sustainability index: an application of resource management. Energy Policy 2007;35:2969–77.
[35] Doukas H, Papadopoulou A, Savvakis N, Tsoutsos T, Psarras J. Assessing energy sustainability of rural communities using principal component analysis. Renew Sustain Energy Rev 2012;16:1949–57.
[36] Sikdar SK. Sustainable development and sustainability metrics. AIChE J 2003;49:1928–32.
[37] Sikdar SK. On aggregating multiple indicators into a single metric for sustainability. Clean Technol Environ Policy 2009;11:157–9.
[38] Martins AA, Mata TM, Sikdar S, Costa CAV. Framework for sustainability metrics. Ind Eng Chem Res 2007;46:2962–73.
[39] Mata TM, Martins AA, Sikdar SK, Costa CAV, Caetano NS. Biofuels sustainability evaluation through the supply chain. In: Proceedings from the 6th dubrovnik conference (25th to 29th september, 2011) on sustainable development of energy water and environment system; 2011.
[40] Bhattacharyya SC. Review of alternative methodologies for analyzing off-grid electricity supply. Renew Sustain Energy Rev 2012;16:677–94.
[41] Musango JK, Bent AC. A conceptual framework for energy technology sustainability assessment. Energy Sustain Dev 2011;15:84–91.
[42] Begic F, Afgan N. Sustainability assessment tool for the decision making in selection of energy system – Bosnian case. Energy 2007;32:1979–85.
[43] Berberi PG, Thodhorjani S. Rural sustainable development through integration of renewable energy technologies. In: Proceedings from the 6th dubrovnik conference (25th–29th september, 2011) on sustainable development of energy water and environment system. Dubrovnik; Croatia: 2011.
[44] Handbook on constructing composite indicators: methodology and user guide. OECD publication; 2008.
[45] Bandura R. A Survey of composite indices measuring country performance: 2006 update. New York. Office of Development Studies, United Nations Development Programme; 2006.
[46] Saltelli A. Composite indicators between analysis and advocacy. Soc Indic Res 2007;81:65–77.
[47] EC. Tools for composite indicators building. institute for the protection and security of the citizen econometrics and statistical support to antifraud unit I-21020 Ispra (VA) Italy; 2005.
[48] IN-STREAM. Linking sustainability with policy making. the research conducted by multi-disciplinary and international consortium of eight research organizations including ecologic institute, Berlin, Institute for European Environmental Policy, London, UK; IIASA, Luxenburg; 2011.
[49] Mayer AL. Strengths and weaknesses of common sustainability indices for multidimensional systems. Environ Int 2008;34:277–91.
[50] Cherchye L, Moesen WH, Rogge N, Puyenbroeck TV. An introduction to benefit of doubt composite indicators. Soc Indic Res 2007;82:111–45.
[51] UNDP. Human development research paper 2010/33 review of HDI critiques and potential improvements. United Nations Development Programme Human Development Reports Research Paper 2010/33, 2011.
[52] Bentzen J. Quantifying environmental sustainability using an aggregate index reflecting increasing marginal damage costs. Appl Econ Lett 2011;18:1383–6.
[53] Ali HMM. Development of Arab Water Sustainability Index Using Principal Component Analysis. In: Proceedings of the 3rd international conference on water resources and arid environments; 2008.
[54] Yang Z, Zhang XH Principal component method in analysis of water resources sustainability influence factors. Management and service science, MASS. In: IEEE International conference proceeding. Wuhan;2009. p. 1–4.
[55] Li T, Zhang H, Yuan C, Liu Z, Fan C. A PCA-based method for construction of composite sustainability indicators. Int J Life Cycle Assess 2012;17:593–603 (Springer publisher).
[56] Pearson K. On lines and planes of closest fit to systems of points in space. Philos Mag 1901;2:559–72.
[57] Helena B, Pardo R, Vega M, Barrado E, Fernańdez JM, Fernańdez L. Temporal evolution of groundwater composition in an alluvial aquifer (Pisuerga river, Spain) by principal component analysis. Water Res 2000;34:807–16.
[58] Jolliffe IT. Principal component analysis. New York: Springer Publishing; 2003.
[59] Mainali B, Pachauri S, Rao N, Silveira S. Assessing rural energy sustainability in developing countries. Energy SustainDev 2014;19:15–28.
[60] OECD. Towards a sustainable energy future. Paris. France: IEA; 2001.
[61] Mahat I. Implementation of alternative energy technologies in Nepal: towards the achievement of sustainable livelihoods. Energy Sustain Dev 2004;8:9–16.
[62] Vera I, Langlois L. Energy indicators for sustainable development. Energy 2007;32:875–82.
[63] Elkington J. Cannibals with forks: the triple bottom line of 21st century business. Oxford: Capstone; 1997.
[64] Brent AC, Rogers DE. Renewable rural electrification: sustainability assessment of mini-hybrid off-grid technological systems in the African context. Renew Energy 2010;35:257–65.
[65] Ilskog E. Indicators for assessment of rural electrification – an approach for the comparison of apples and pears. Energy Policy 2008;36:2665–73.
[66] Mainali B. Analysis of sustainability indicators for renewable energy based rural electrification. technologies for sustainable development: a way to reduce poverty?" May 2012 at Lausanne, Geneva organized by UNSCO chair for in Technologies for Development; 2012.
[67] Kemmler A, Spreng D. Energy indicators for tracking sustainability in developing countries. Energy Policy 2007;35:2466–80.
[68] Doukas HC, Andreas BM, Psarras JE. Multi-criteria decision aid for the formulation of sustainable technological energy priorities using linguistic variables. Eur J Oper Res 2007;182:844–55.
[69] Pilavachi PA, Stilianos DS, Pappas VA, Afgan NH. Multi-criteria evaluation of hydrogen and natural gas fuelled power plant technologies. Appl Therm Eng 2009;29:2228–34.
[70] Cavallaro F, Ciraolo L. A multi-criteria approach to evaluate wind energy plants on an Italian island. Energy Policy 2005;33:235–44.
[71] Mamlook R, Bilal AA, Salem N. Fuzzy sets programming to perform evaluation of solar systems in Jordan. Energy Convers Manag 2000;42:1717–26.
[72] Mamlook R, Bilal AA, Mousa SM. A neuro-fuzzy program approach for evaluating electric power generation systems. Energy 2001;26:619–32.
[73] Chatzimouratidis AI, Pilavachi PA. Multicriteria evaluation of power plants impact on the living standard using the analytic hierarchy process. Energy Policy 2008;36:1074–89.
[74] Chatzimouratidis AI, Pilavachi PA. Technological, economic and sustainability evaluation of power plants using the analytic hierarchy process. Energy Policy 2009;37:778–87.
[75] Dinca C, Badea A, Rousseaux P, Tiberiu Apostol. A multi-criteria approach to evaluate the natural gas energy systems. Energy Policy 2007;35:5754–65.
[76] Wang JJ, Jing YY, Zhang CF, Shi GH, Zhang XT. A fuzzy multi-criteria decision-making model for trigeneration system. Energy Policy 2008;36:3823–32.
[77] Afgan NH, Carvalho MG. Sustainability assessment of hydrogen energy systems. Int J Hydrog Energy 2004;29:1327–42.
[78] Afgan NH, Carvalho MG. Sustainability assessment of a hybrid energy system. Energy Policy 2008;36:2903–10.
[79] EEA.Greenhouse gas emission trends and projections in Europe. EEA environmental issue report no. 36. European Environment Agency, Copenhagen, Denmark; 2003.
[80] UNDP. Indicators for sustainable development. United Nations Division for Sustainable Development, 2007. CSD; 2007.
[81] Madlener R, Kowalski K, Stagl S. New ways for the integrated appraisal of national energy scenarios: the case of renewable energy use in Austria. Energy Policy 2007;35:6060–74.
[82] Balachandra P. Dynamics of rural energy access in India: An assessment. Energy 2011;36:5556–67.

[83] NREL. Indian renewable energy status report. national renewable energy laboratory. 1617 Cole Boulevard, Golden, Colorado 80401 USA; 2010.
[84] IWEO. Indian wind energy outlook 2011. Joint publication of global wind energy council, World Institute of Sustainable Energy and Indian Wind Turbine Manufacturers Association; 2011.
[85] Sukla AR. Policy development requirements for biogas upscaling in India. Ministry New Renew Energy 2010.
[86] ESMAP. Unleashing the potential of renewable energy in India. South Asia Energy Unit. Sustainable Development Department, The World Bank; 2010.
[87] Ramachandra TV, Shruthi BV. Spatial mapping of renewable energy potential. Renew Sustain Energy Rev 2007;11:1460–80.
[88] Rao RV, Baral SS, Dey R, Mutnuri S. Biogas generation potential by anaerobic digestion for sustainable energy development in India. Renew Sustain Energy Rev 2010;14:2086–94.
[89] ESMAP. Technical and economic assessment of off-grid, mini-grid and grid electrification technologies. Technical Paper, Energy, Transport and Water Department.The World Bank Group, NW; 2007.
[90] IRENA. Solar photovoltaics. Renewable energy technologies cost analysis series. Vol. 1: Power Sector Issue 4/5; 2012a.
[91] Pöschl M, Ward S, Owende P. Evaluation of energy efficiency of various biogas production and utilization pathways. Appl Energy 2010;87:3305–21.
[92] Kalina J. Integrated biomass gasification combined cycle distributed generation plant with reciprocating gas engine and ORC. Appl Therm Eng 2011;31:2829–40.
[93] Bansal RC, Bhatti TS, Kothari DP. On some of the design aspects of wind energyconversion systems. Energy Convers Manag 2002;43:2175–87.
[94] IRENA. Renewable energy jobs & access. International Renewable Energy Agency (IRENA); 2012b.
[95] Mahapatra S, Chanakya HN, Dasappa S. Evaluation of various energy devices for domestic lighting in India. Technology, economics and CO_2 emissions. Energy Sustain Dev 2009;13:271–9.
[96] Silva D, Nakata T. Multi-objective assessment of rural electrification in remote areas with poverty considerations. Energy Policy 2009;37:3096–108.
[97] Varun Prakash R, Bhat IK. Life cycle greenhouse gas emissions estimation for small hydropower schemes in India. Energy 2012;44:498–508.
[98] IOC. Indian Oil Corporation Ltd. Available online at: 〈http://www.iocl.com/Products/HighSpeedDiesel.aspx〉; 2012 [cited 15.01.13].
[99] MoLE. Wages rates in rural india. Ministry of Labour and Employment, Government of India; 2010.
[100] MoSPI. Prices and Wages in Rural India. Data Processing Division, Ministry of Statistics & Programme Implementation, Government of India;2012.
[101] Reuters. TABLE-India's petrol, diesel, kerosene and LPG prices. Available online at: 〈http://in.reuters.com/article/2010/02/04/india-fuel-prices-idINSGE6130E720100204〉; 2010 [cited on15.01.13].
[102] Pradhan N, Karki N. Probabilistic reliability evaluation of off-grid small hybrid solar pv-wind power system for the rural electrification in Nepal. In: IEEE North American Power Symposium (NAPS). IEEE: Champaign, IL: 2012. p. 1–6.
[103] Bagen. Reliability and cost/worth evaluation of generating systems utilizing wind and solar energy (Doctoral thesis), Department of Electrical Engineering, University of Saskatchewan Saskatoon; 2005.
[104] Billinton R, Bagen. Incorporating reliability index distributions in small isolated generating system reliability performance assessment. IEE Proc – Gener Transm, Distrib 2004;151(4):469–76.
[105] EIA. Renewable energy trends 2000: Issues and trends. Energy Information Administration, Office of Coal, Nuclear, Electric and Alternate Fuels, U.S. Department of Energy, USA; 2001.
[106] Susanto J, Smits M. Towards a locally adapted rural electrification assessment framework: a case study of the lao PDR. In: Proceedings of the international conference for a sustainable greater mekong subregion, GMSTEC 2010, 26–27 August 2010, Bangkok, Thailand; 2010.
[107] Lacayo AI. Off-grid energy in rural india: policy recommendations for effective UN projects. WWS Undergrad Task Force: Energy Sustain Dev. Working Paper: 2006. P. 1–31.
[108] Kishore, VVN, Dattakiran J. The quest for sustainable technology options for decentralized electrification using multi-criteria decision aids. Working paper. EPSRC/ DfID funded Research Grant Project; 2011.
[109] Jha R, Murthy K. An inverse global environmental Kuznets curve. J Compar Econ 2003;31:352–68.
[110] Mainali B, Silveira S. Alternative pathways for providing access to electricity in developing countries. Renew Energy 2013;57:299–310.
[111] El-Kordy MN, Badr MA, Abed KA, Ibrahim SMA. Economical evaluation of electricity generation considering externalities. Renew Energy 2002;25:317–28.