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Comparative assessment of energy sources for attaining Sustainable Energy Security (SES):

The case of India's residential sector

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ABSTRACT

Attaining 'Sustainable Energy Security' (SES) is a valid end goal of an energy policy. However, SES is a multidimensional concept which is difficult to evaluate. The aim of this paper is to undertake a comparative assessment of SES of various energy sources for the residential sector in India. The paper also intends to construct a SES Index and rank the energy sources by assessing their performance in different dimensions. The end goal is to identify the energy sources which are relatively more secure and sustainable for India. The paper uses a scoring matrix and a weighting matrix to develop a SES Index. This multidimensional index is constructed as a weighted sum of four indices representing various dimensions, viz. Availability, Affordability, Efficiency and Environmental Acceptability. A comparative assessment of six energy sources for the residential sector for urban India reveals that, firewood has the highest rank followed by LPG and electricity while kerosene has the lowest rank. However in rural India, firewood has the highest rank followed by dung cakes while LPG has the lowest rank. Sensitivity of the SES Index to variation in weights reveals that the results are mostly insensitive to +/– 10% variation in allotted weights. It is therefore important that energy policy in India should be designed in a manner, so as to promote the use of firewood and dung cakes which are relatively more 'Available' and 'Affordable' in rural areas. Along with this, emphasis should be given on design of better technologies to increase the 'Efficiency' and 'Acceptability' of these energy sources.

Keywords:

Sustainable Energy Security, Indicators, Multi-criteria analysis

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1. Introduction

Energy is now widely recognized as a prerequisite for human development, as it has a multiplier effect on health, education, transport, water supply, agriculture, industry and other tertiary sectors of the economy [1,2]. Hence, developing countries need to eradicate energy deprivation for its citizens. However, fossil fuel-induced climate change has thrown a unique challenge to developing countries. On one hand, these countries have to ensure adequate energy supplies for meeting the needs and aspirations of the growing population, and on the other, have to reduce conventional energy use to limit emissions. Hence, these countries should have sufficient supply of clean energy to meet the demand, at a cost which is affordable for its people. Therefore energy security as well as sustainable energy is the need for the future.

Sustainable Energy Security (SES) can be defined as "provisioning of uninterrupted energy services in an affordable, equitable, efficient and environmentally benign manner [3]. Traditionally the concept of energy security is related to 'Security of Supply' of energy.

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However, security of energy supply is a one-sided approach where the implicit assumption is, that any energy demand can be met by increasing the supply of energy. However, SES acknowledges the 'demand-side' aspect of energy security. Demand-side aspect of energy security implies universal provision of modern energy services, which is affordable and accessible to consumers [4]. Apart from supply and demand side aspects of energy security, energy sustainability is equally important and the entire 'energy system' needs to be sustainable in the long run. Keeping in view this need for attaining both, 'sustainability' and 'security' of energy, the concept of Sustainable Energy Security (SES) was defined and targeted.

The residential sector in India with an energy consumption of 182 million tonnes oil equivalent (mtoe) (7.6EJ) accounted for approximately 37% of Total Final Energy Consumption (TFEC) (512 mtoe) (21.4EJ) in 2012 [5]. The final energy used in the residential sector (including lighting and cooking) is shown in Figure 1 (in mtoe) and the predominant share (75%) of biomass which includes firewood, chips, dung cakes and agricultural waste is clearly evident.

However, with a per capita Total Primary Energy Supply (TPES) of only 0.59 toe (ton oil equivalent) (24.7GJ) India still lags behind the world per capita average of 1.86 toe (77.8GJ) [6]. Further, India has 289 million people who lack access to electricity and 836 million people who rely on traditional biomass for cooking [7]. This concern for lack of energy security from the household consumer's perspective is evident in the Indian governments' approach to Energy Security, which is summarized as "The country is energy secure when we can supply lifeline energy to all our citizens as well as meet their effective demand for safe and convenient energy to satisfy various needs at affordable costs at all times with a prescribed confidence level considering shocks and disruptions that can be reasonably expected" [8]. In the light of the above background, there is a need to evaluate and compare various energy sources for the residential sector, which can contribute to increasing the SES for India.

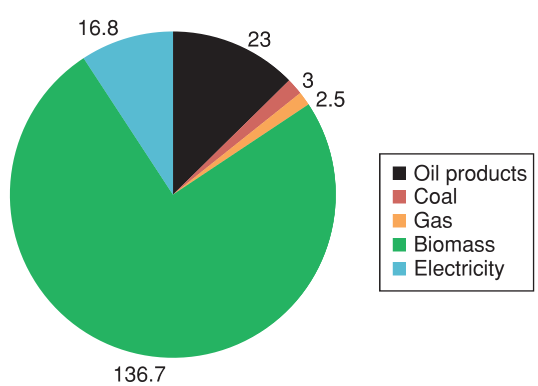

Figure 1: Final energy consumption in the residential sector in 2012 (mtoe).

Energy poverty and energy security issues at household level have been analysed in the Indian context [9, 10]. Cooking fuel use patterns and energy options for cooking have also been discussed in detail for India [11, 12]. A comparative and descriptive analysis of the household energy transitions in India has been undertaken to derive aggregate trends for identifying the key factors driving the household energy transition [11, 13, 14]. However, a comparative assessment and ranking of various energy sources for the residential sector in the Indian context has not been undertaken till date. While the 'energy ladder' principle and 'fuel stacking' approaches have been observed in the Indian context, it is acknowledged that there are variations in the way household consumers choose their energy sources [15]. While consumer preferences will always play a part, a country should endeavour to design policies to promote energy sources which enhance the SES of the country.

Multi criterion analysis and Analytical Hierarchy Process (AHP) has been earlier used for sustainability evaluation of power plants [16]. The methodology is well defined and has been accepted as it aids the decision making process and has been used to evaluate the renewable energy resources in India [17]. In order to undertake such an assessment, various technologies are evaluated on some selected criteria. The choice of indicators can be made from a set of indicators and some of the indicators quantifying the physical and financial threats have been examined for evaluating household energy security [10]. Different sustainability indicators can be used for evaluating the performance of the technologies and a few of them have been effectively used as an instrument to support decision making for renewable energy technologies [18] and for sustainable expansion of the electricity sector [19].

The aim of this paper is to undertake a comparative assessment of SES of various energy sources for the residential sector in India. The paper also intends to construct a SES Index and rank the energy sources by assessing their performance in different dimensions. The end goal is to identify the energy sources which are relatively more secure and sustainable so that policy measures can be adopted to enhance the SES for India.

2. Methodology

Creating energy security indexes with decision matrices and quantitative criteria was proposed and an adapted version of this methodology has been applied to evaluate the energy security of Sweden [20, 21, 22]. This paper follows a modified approach and this section presents the methodology to construct a SES Index.

2.1. Assessment Framework

This study chooses an indicator based approach for the assessment and allows evaluation of SES in any sector of the economy. This framework is applied to the residential sector in this paper to undertake a comparative assessment of energy sources commonly used in the urban and rural households in India. Different indicators are chosen to represent each dimension of SES and the performance of various energy sources are evaluated for these parameters.

2.2. Model for constructing a SES Index

Figure 2 shows the model which has been developed for formulating a SES Index and subsequent ranking of energy sources. The model consists of a decision matrix, a weighting matrix and a ranking vector.

A decision matrix is a 2-D matrix and consists of 'n' rows, for different energy sources to be evaluated, and 'm' columns, having different indicators representing the selected dimensions. The model used for constructing the decision matrix is shown in Figure 3.

Each Dimension (*D*) is represented by various Indicators *I*(*j*). Different types of energy sources *E*(*i*), which are used by the Indian households, are evaluated

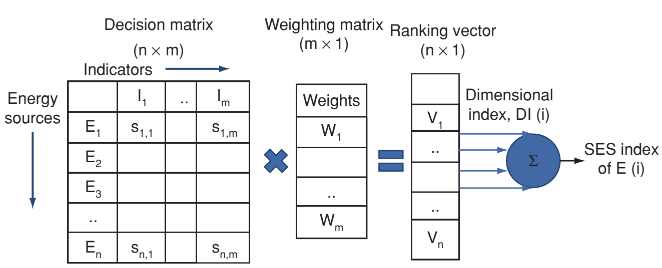

Figure 2: Model for constructing a SES Index for various energy sources.

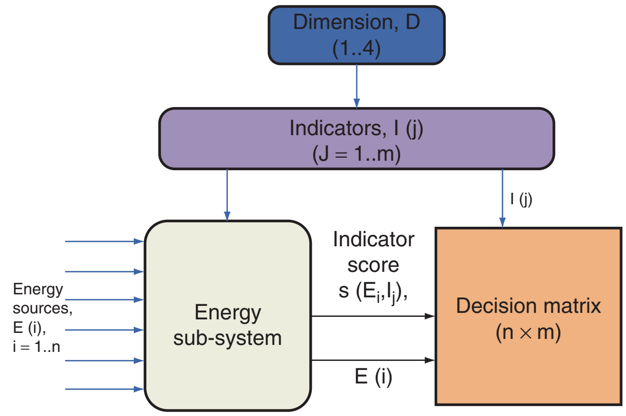

Figure 3: Model for constructing a Decision Matrix.

for undertaking a comparative assessment. Each element of the matrix has the 'score', $s(E_i, I_j)$, which is the value for the indicator I_j, for the particular energy source E_i. The elements of the ($n \times m$) decision matrix (shown in Figure 2) are filled using these scores.

As shown in Figure 2, the weighting matrix, which is a column matrix, having 'm' rows, is assigned the values w_j. The weights represent the contribution of each individual indicator to the overall index. There are various methods to allocate weights (w_1 to w_m) to indicators. Some of these are equal weights, weights evaluated by applying multiple linear regression models, weights based on statistical models such as Principal Component Analysis (PCA), Factor Analysis (FA), budget allocation method etc. However, in this paper, weights have been appropriated to each indicator using an Analytical Hierarchy Process (AHP) as explained further in section 2.5.

The decision matrix and the weighting matrix are multiplied to obtain a ($n \times 1$) ranking vector. The component, v_i, of the ranking vector *V*, is an index and indicates the SES associated with the energy source *E*(*i*). The components of this ranking vector can be calculated as shown in Eq. (1).

$$V_1 = W_1 \times S_{1,1} + \ldots.. + W_m \times S_{1,m}$$
$$V_n = W_1 \times S_{n,1} + \ldots.. + W_m \times S_{n,m} \quad (1)$$

A larger value of the index implies higher SES and the energy source *E*(*i*), having the highest value (v_i) is allotted the highest rank as it indicates the most sustainable and secure energy source. The weighted scores for a particular energy source *E*(*i*) can also be summed up under different dimensions to arrive at a Dimensional Index (*DI*) as shown in Eq. (2).

$$DI\left(\text{Dimension }(p), E(i)\right) = \text{s}(\text{i},1)\times \text{w}(1) + .. + s(i,k)\times w(k) \quad (2)$$

Here, '*p*' is the particular dimension which has '*k*' indicators representing it and the *DI* indicates the performance of the energy source *E*(*i*) in that dimension.

2.3. Dimensions and Indicators

The dimensions of SES, which have been carefully selected after an extensive literature review, are Availability (AVL), Affordability (AFF), Efficiency (EFF) and Environmental Acceptability (ACP). These dimensions closely follow the four A's of energy security advocated by the Asia Pacific Energy Research Centre [23]. The chosen dimensions have different interpretations, when applied to the residential sector and the indicators are suitably chosen to reflect these concerns. 'Availability' dimension for the residential sector implies physical access of various energy sources and its quantity consumed by the household. 'Affordability' for the residential sector refers to the ability of a household to pay for a unit of energy for a particular energy service and how important the cost of energy is, to the users. Affordability is a function of retail price of energy and consumer's income (or expenditure) and per capita consumption of energy has a direct correspondence with affordability. 'Efficiency' dimension is one of the important pillars of SES and improvement in end use efficiency of appliances substantially increases the SES of a country. (Environmental) 'Acceptability' dimension for the residential sector relates to emissions produced from cooking when various energy sources are used. Selection of indicators for each dimension is based on data availability and the indicators are carefully chosen to represent the respective dimension. Further, the paper limits the number of indictors so that the relative comparison of indicators using the AHP is easier.

2.4. Scores

The decision matrix has to be populated with 'scores', *s*(*I*, *E*) for each energy source. The paper uses min-max normalisation and scale inversion to derive the scores from the raw values, as explained in the next sub-sections.

2.4.1. Min-Max normalisation of raw values

Raw value (*x*) of each energy source for the particular indicator is gathered from various data sources and the minimum and maximum value of the indicator for various energy sources are identified as min(*x*) and max (*x*) respectively. In order to calculate the normalized value, norm (*x*), Eq (3) is used. This transforms the values to a relative scale of 0–1, where 0 represents a relative minimum and 1, a relative maximum value.

$$\text{norm }(x) = \frac{x - \min(x)}{\max(x) - \min(x)} \quad (3)$$

2.4.2. Scale Inversion

The selected indicators can be grouped in two categories, those having a positive impact and those having a negative impact. Positive impact indicators are those, where a high value contributes to high SES; while in negative impact indicators, a high value of the indicator will contribute to a low SES. While the normalized values of the positive impact indicators are unchanged and are transcribed as scores, the normalised values of negative impact indicators have to be inverted such that a low value of the indicator should contribute to a high value in the SES Index. Hence, the scale for this indicator is inverted by subtracting the normalised value from 1, i.e. its score will be (1– norm (*x*)). Therefore the final score of a negative impact indicator with normalized score of 1 (norm (*x*) = 1) will be 0 (1–1 = 0); and a normalized score of 0 (norm (*x*) = 0) will be 1 (1 – 0 = 1). With this inversion, the scores can now be linearly added to create a SES Index.

2.5. AHP Approach for selection of weights

2.5.1. Theoretical basis

AHP which belongs to the family of multi criterion analysis techniques is used for deriving weights, which are allotted to various indicators. Weights represent the trade-off across indicators and they measure the willingness to forego a given indicator in exchange for another. The core of AHP is an ordinal pair wise comparison of attributes. In the AHP process, comparisons are made between pairs of individual indicators, and decision-makers have to decide on how important one particular indicator is, relative to another. The preference is expressed on a semantic scale, and the paper uses the nine-point ratio measurement scale for making the comparisons as shown in Table 1. Table 2 lists the corresponding Random Index (RI) for various values of 'm' (where 'm' is the number of indicators) and is used to check the consistency of the judgment.

Table 1: Preference scale for pair wise comparison [24].

Value	Definition	Value	Definition
1	Equally Important	7	Very strongly more important
3	Moderately more important	9	Extremely more important
5	Strongly more important	2,4,6,8	Intermediate values

Table 2: Scale for Random Index [24].

m	RI	m	RI
2	0.00	5	1.12
3	0.58	6	1.24
4	0.9	7	1.32

The results are represented in a (m × m) pair wise comparison matrix [A], where 'm' is the number of indicators. In the pair wise comparison matrix all the diagonal elements are unity (a factor when compared with itself will be equally important) i.e A_{ii} = 1. The upper matrix entries need to be filled as per the given scale in Table 1 and the lower matrix entries will be its inverse i.e $A_{ij} = 1 / A_{ji}$ and are determined automatically. The elements of the matrix [A] are therefore on a ratio scale as shown in Eq (4) and the paper uses this formulation of the problem [24] to derive the weights.

$$[A] \times [W] = k \times [W],$$

$$\begin{pmatrix} \frac{w1}{w1} & \frac{w1}{w2} \cdots & \frac{w1}{wn} \\ \frac{w2}{w1} & \frac{w2}{w2} \cdots & \frac{w2}{wn} \\ \vdots & \vdots & \vdots \\ \frac{wn}{w1} & \frac{wn}{w2} \cdots & \frac{wn}{wn} \end{pmatrix} \times \begin{pmatrix} w1 \\ w2 \\ . \\ . \\ wn \end{pmatrix} = k \times \begin{pmatrix} w1 \\ w2 \\ . \\ . \\ wn \end{pmatrix} \qquad (4)$$

Here, [A] is a pair wise comparison matrix which is a square and a reciprocal matrix and [W] is a column vector which is to be derived. Now, if 'k' is an eigen value of A, then W is the eigenvector associated with it. It has been shown that the solution of Eq. (4), called the principal right eigenvector of A, consists of positive entries and is unique to within a multiplicative constant. In a general decision-making environment, where a respondent undertakes a qualitative assessment, one cannot give the precise values to the ratio associated with the comparison, but can only estimate its value. Hence, while undertaking pair wise assessment of a large number of values, the assessment may deviate from being consistent. Saaty (1990) has as shown that the formulation of the problem as shown in equation (4) leads to an eigen value problem of the form $[A] \times [W] = \lambda_{\max} [W]$, where $\lambda_{\max}$ is the principal eigen value of A and Consistency Ratio (CR) can be used to check the consistency of the judgment [24]. This is the theoretical basis of the procedure for calculation of weights and is listed below.

2.5.2. Procedure for calculation of weights and checking the consistency of judgment

(a) To calculate the weights, the following procedure is adopted.
   - (i) Perform pair wise comparison of indicators and fill the (m × m) judgment matrix, [A].
   - (ii) Square the obtained matrix to calculate $[A]^2$.
   - (iii) Divide each entry of the column by the column total and then average the rows to obtain the first eigen vector (EV_1).
   - (iv) Calculate $[A]^4$ and keep squaring the obtained matrix to give $[A]^8$, $[A]^{16}$ and subsequently obtain their respective Eigen Vectors (EV_2, EV_3 and so on) for each iteration as explained in (iii).
   - (v) Stop the iterations when the difference between the successive calculated EV's is less than 0.0001 (e.g. ($EV_4 - EV_3$) < 0.0001)).
   - (vi) The obtained EV_n after the last iteration is the weighting matrix [W].

(b) To check the consistency of the judgment, the paper uses the following procedure.
   (i) Calculation of $(\lambda_{max})_{average}$ by solving Eq. (5)

$$[A] \times [W] = [X],$$

$$[X] = \lambda_{max} \times [W]. \quad (5)$$

   (ii) Using this obtained value of λ_{max}, calculate the Consistency Index (CI) by using Eq (6)

$$CI = (l_{max} - m) / (m - 1), \quad (6)$$

   Where, λ_{max} is the principal eigen value and 'm' is the number of indicators.
   (iii) Calculate the Consistency Ratio (CR) by using the Eq (7)

$$CR = CI/RI, \quad (7)$$

   Where, RI is the Random Index and is read out from Table 2.
   (iv) The obtained value of CR should be less than 0.1 (thumb rule). If CR is greater than 0.1 (10 %), the assessment is inconsistent and the pair wise comparison process is repeated [24].

3. Application of the framework

The proposed methodology is applied in this paper to undertake a comparative assessment of SES of various energy sources for the residential sector in India. Six different types of energy sources which are most commonly used in Indian households ('n' = 6) have been selected. These are Firewood (including chips and biomass), dung cake, Liquefied Petroleum Gas (LPG), kerosene, electricity and coal (including coke and charcoal). A total of seven indicators ('m' = 7) have been selected (I_1 to I_7), two each for AVL, AFF and ACP dimensions while one indicator has been selected for EFF dimension. The selected indicators along with their components which are considered in this paper are shown in Table A. 1 at Appendix 1. While three indicators have a positive impact, there are four negative impact indicators viz. AFF1, AFF2, ACP1, and ACP2 for which scale inversion is undertaken. The decision matrix is thereafter filled with scores as per the adopted procedure and is discussed below.

3.1. Filling the decision matrix

Energy security issues for the residential sector in India have been analyzed and it has been found that there is a large difference in patterns of energy consumption in rural and urban India [14]. Hence this paper undertakes the comparison of various energy sources for the residential sector in India separately for rural and urban areas.

3.1.1. Raw values of indicators

Table 3 shows the raw values of various indicators for different energy sources for Rural (R) and Urban (U) India. However, as the indicators of ACP1, ACP 2 and EFF are same for rural and urban India, only one value is shown. Raw values of indicators have been calculated using data derived from various publications and secondary data sources (Refer to Table A. 1 for details of calculations).

3.1.2. Calculating scores

Normalisation of raw values is undertaken and Table 4 shows the scores after inversion of scale for negative impact indicators.

3.2. Calculation of weights from AHP

The basic theory and method of deriving weights from AHP has been outlined in section 2.5. This paper uses the AHP macro designed by Goepl, which calculates the weights and also checks the consistency of the judgment [26]. This makes the process of comparison and calculation of weights much simpler and faster as it automates all calculations.

3.2.1. Weights derived from AHP

It is anticipated that if a household survey is conducted, each respondent will have a different response. This is because each household has a different perception of the relative importance of the dimensions. Further, the choices are also dependent on the income levels, location, education levels and other such parameters. In terms of weights, it would imply the entire spectrum of weights from 0-100% for the selected indicators as well as for dimensions. However, if we take an average of the responses of various households, it is expected that the weights would converge to equal weights as the number of respondents' increases.

This paper therefore demonstrates the methodology by undertaking a pair wise comparison of the selected indicators according to author's own assessment (from a policy maker's perspective) and the filled matrix is shown in Table 5. This process can also be administered to consumers and other stakeholders to gather their perceptions, for undertaking an exhaustive assessment.

The above pair wise comparison matrix is then used to calculate the weights as explained in section 2.5.2 and the calculated weights after the sixth iteration are 0.132, 0.338, 0.072, 0.338, 0.044, 0.044 and 0.031 for indicators I_1 to I_7 respectively. The aggregated weights for AVL, AFF, ACP and EFF dimensions are 0.47, 0.41, 0.088 and 0.031 respectively. Results of the AHP indicate that 'Availability' and 'Affordability' of energy sources emerge as dominant dimensions from a policy maker's perspective who has an obligation to provide cooking and lighting energy services to the people.

3.2.2. Checking the consistency of judgements

Eq. (6) – (7) is used to calculate the CI and CR and the calculations are shown in Eq. (8) – (9).

Table 3: Raw value of indicators for different energy sources for rural and urban India.

	AVL 1		AVL 2		AFF 1	AFF 2		ACP 1	ACP 2	EFF
	R	U	R	U	C	R	U	C	C	C
C	0.64%	1.92%	3.92	8.12	8.33	147.83	180.06	42	0.02	23.2%
FW	61.04%	14.00%	318.09	78.03	0.00	63.75	197.96	23	1.8	15.7%
DC	5.04%	1.04%	87.36	19.08	0.00	41.82	140.74	21	13	11.1%
LPG	9.20%	51.60%	13.75	83.63	12.50	276.09	273.03	4	0.01	60.4%
K	7.32%	6.14%	19.54	15.31	9.72	193.32	247.26	8	0.02	50.4%
L	13.22%	19.04%	28.53	87.36	16.67	249.56	302.21	0	0	71.3%

R: Rural; U: Urban; C: Common for U & R

Energy Sources; C:Coal; FW: Firewood; DC: Dung Cake; K: Kerosene; L: Electricity

Table 4: Scores for different energy sources for rural and urban India.

	AVL 1		AVL 2		AFF 1	AFF 2		ACP 1	ACP 2	EFF
	R	U	R	U	C	R	U	C	C	C
C	0.00	0.02	0.00	0.00	0.50	0.55	0.76	0.00	1.00	0.25
FW	1.00	0.26	1.00	0.88	1.00	0.91	0.65	0.45	0.86	0.00
DC	0.07	0.00	0.27	0.14	1.00	1.00	1.00	0.50	0.00	0.22
LPG	0.14	1.00	0.03	0.95	0.25	0.00	0.18	0.90	1.00	0.61
K	0.11	0.10	0.05	0.09	0.42	0.35	0.34	0.81	1.00	0.48
L	0.21	0.36	0.08	1.00	0.00	0.11	0.00	1.00	1.00	1.00

R: Rural; U: Urban; C: Common for U & R

Energy Sources; C:Coal; FW: Firewood; DC: Dung Cake; K: Kerosene; L: Electricity

Table 5: Pair wise comparison matrix.

		1	2	3	4	5	6	7
		Access to fuel	Energy Consumption	Capital Cost	Monthly fuel Cost	CO emissions	PM emissions	Efficiency of end use
1	Access to fuel	1	1/3	3	1/3	5	5	7
2	Energy Consumption	3	1	5	1	7	7	9
3	Capital Cost	1/3	1/5	1	1/5	3	3	5
4	Monthly fuel Cost	3	1	5	1	7	7	9
5	CO emissions	0.2	0.14	0.33	0.14	1	1	3
6	PM emissions	0.2	0.14	0.33	0.14	1	1	3
7	Efficiency of end use	0.14	0.11	0.20	0.11	0.33	0.33	1

$$\lambda_{max} = 7.387;\ m = 7\ ;$$

$$CI = (\lambda_{max} - m)/(m - 1),\ CI = 0.064 \qquad (8)$$

$$CI = 0.064;\ RI = 1.32 \text{ (from Table 2)};$$

$$CR = CI/RI,\ CR = 4.9\%. \qquad (9)$$

As *CR* is less than 10%, the decision is consistent.

4. Results

'Scores' when multiplied by 'weights' (as per Eq. (1) – (2)), give us the *DI* and the overall SES Index, which are shown for rural and urban India respectively in Figure 4.

Results of the assessment as shown in Figure 4 reveal that firewood (in rural areas) and LPG (in urban areas) ranks the highest in the 'Availability' dimension. In the 'Affordability' dimension dung cake is ranked the highest in both rural and urban areas, while LPG in rural and electricity in urban areas is ranked lowest. Electricity followed by LPG as an energy source is most 'Environmentally Acceptable' while dung cake has the lowest rank. In the 'Efficiency' dimension electricity has the highest rank while firewood is ranked as the lowest. The overall rank obtained by the energy sources in rural India is as follows: Firewood, dung cake, kerosene, coal, electricity, LPG while for urban India it is in the following order: Firewood, LPG, electricity, dung cake, coal, kerosene.

5. Discussions

Although firewood obtains the highest SES Index in rural and urban areas, the paper does not implicitly assume and support the view that it is the most sustainable and secure energy source. The results present the comparative ranking of energy sources based on the actual consumption patterns, cost and technical data. This result is obtained, as a large weight is allotted to AVL and AFF dimension, on which firewood obtains a high score. Therefore, despite firewood being inefficient and having highest CO emissions, it still obtains the highest SES Index for the residential sector. The results therefore merely establish that households 'perceive' firewood to be sustainable and secure, due to its easy availability and low affordability (relatively). It is evident that the results are in contradiction to the 'desirability' of energy source from the perspective of the energy policy planner who may want consumers to shift to cleaner fuels such as electricity and LPG rather than rely on dung cake and firewood.

Actually the choice of the energy source by a household is made according to the following hierarchy: AVL, AFF, ACP and EFF. This implies that if all sources of energy are available, households make their choice of energy source based on the affordability of energy. If the available energy sources are similarly priced, households make their choices based on acceptability and convenience of use. It is only at the very end that a choice of the energy source is made based on efficiency dimension. This hierarchy in dimensions is also reflected in the weights which emerge from the pair wise comparison process.

Notwithstanding the weights which have been used for this assessment, this paper has presented the framework and has demonstrated the methodology for ranking of energy sources. Allocation of weights is always a 'subjective' criterion which depends on the perception of different stakeholders and therefore different results will be obtained when the process is

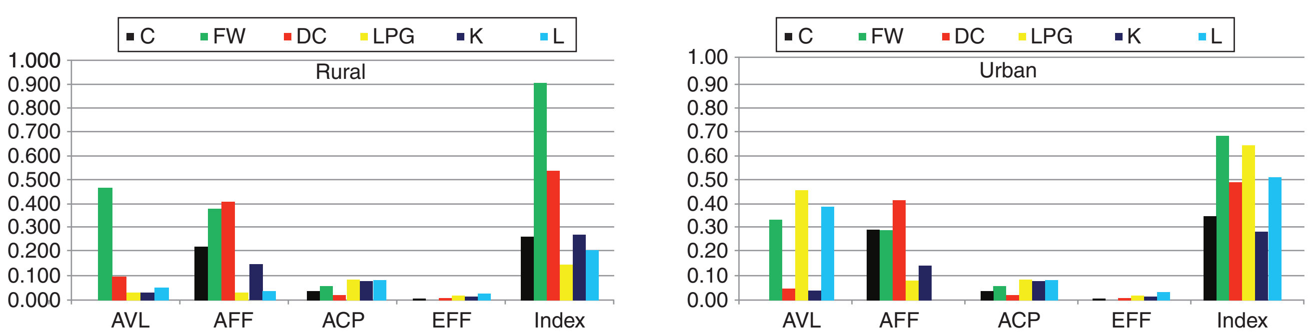

Figure 4: Dimensional and SES Index for various energy sources for rural and urban India.

repeated using different weights. SES Index is a function of 'weights' and 'scores'. A participatory approach to gather the weights from a wider representation of the households may change the final results to an extent but that effect has been simulated by undertaking a sensitivity analysis of the SES Index to a variation in weights allotted to different indicators.

5.1. Sensitivity of SES Index to variation in weights

Six scenarios, SC 1-6 have been simulated to evaluate the sensitivity of SES Index to variation in weights. As the weights allotted to ACP1, ACP 2 and EFF (from the AHP) are small, these are kept fixed at 4.5, 4.5 and 3 percent respectively. Original (ORG) weights have been rounded off to the nearest whole number to obtain reference (REF) weights. The weights for other indicators are varied +/– 5 percent from the reference. Various scenarios have thereafter been worked out by varying the weights allotted to AVL and AFF dimensions (aggregate variation +/– 10 percent), so as to generate a range of weights, which are shown in Table 6.

The SES Index obtained for these scenarios are shown in Figure 5 for rural and urban India respectively. As observed from Figure 5, firewood is still the highest ranked energy source in rural India while LPG has the lowest rank in all scenarios. The ranking of sources for urban India are also similar to those obtained for the original run except in scenario 6, (when AFF dimension is given less weight) where LPG emerges at the first rank. Hence it can be concluded that the ranking of various energy sources for both rural and urban India is mostly insensitive (but may change in a few cases) to variation (+/– 10%) in weights for AFF and AVL dimension.

5.2. Sensitivity of SES Index to variation in indicator scores

Values of the selected indicators of ACP and EFF are dependent on the end use device for cooking (and lighting) and are unlikely to change significantly in the near future. On the other hand, AVL of clean energy sources will increase steadily over the next few years as they become more AFF. It is observed that there is a large variation in the score of the indicator AFF 2 (i.e. cost of energy purchased per month) by different households, which varies from a minimum value of 0 (when firewood and dung cake are collected, with no cash payout for the household) to a maximum value (when these are bought at market price). It has been reported that only 27% of households buy firewood in rural areas while 69 % buy it in urban areas [11]. The corresponding values for dung cake are 21 % and 58% in rural and urban areas respectively [11]. The unit price of firewood and dung cake used in the paper for calculating the value of AFF 2 is the weighted average price which has been calculated as: 0.27 × market price + 0.73 × 0 (no cash payout for collection of firewood) for rural areas and similarly for urban areas. In order to analyze the effect of different cash outflows on the overall ranking of energy sources, a scenario was simulated to calculate the value of indicator AFF 2 using the minimum (0) and maximum (market price) unit price of firewood and dung cake. The minimum price assumed was zero (when they are collected) and the maximum unit price of firewood was assumed to be Rs 1.86 per Kg (3.1 cents/kg) in rural areas and Rs 2.26 (3.76 cents/kg) in urban areas. For dung cake it was assumed to be Rs 1.12 per Kg (1.86 cents/kg) and Rs 1.36 per Kg (2.26 cents/kg) in rural and urban areas respectively. Results using minimum prices for firewood and dung cake revealed that there is no change in the ranking of energy sources in the case of rural and

Table 6: Weights allotted under different scenarios (in percentage).

Scenarios	ORG	REF	SC1	SC2	SC3	SC4	SC5	SC6
AVL 1	13.23%	13	8	13	13	8	18	18
AVL 2	33.84%	34	29	34	34	39	29	39
AFF 1	7.17%	7	12	12	2	7	7	2
AFF 2	33.84%	34	39	29	39	34	34	29
ACP 1	4.41%	4.5	4.5	4.5	4.5	4.5	4.5	4.5
ACP 2	4.41%	4.5	4.5	4.5	4.5	4.5	4.5	4.5
EFF	3.11%	3	3	3	3	3	3	3

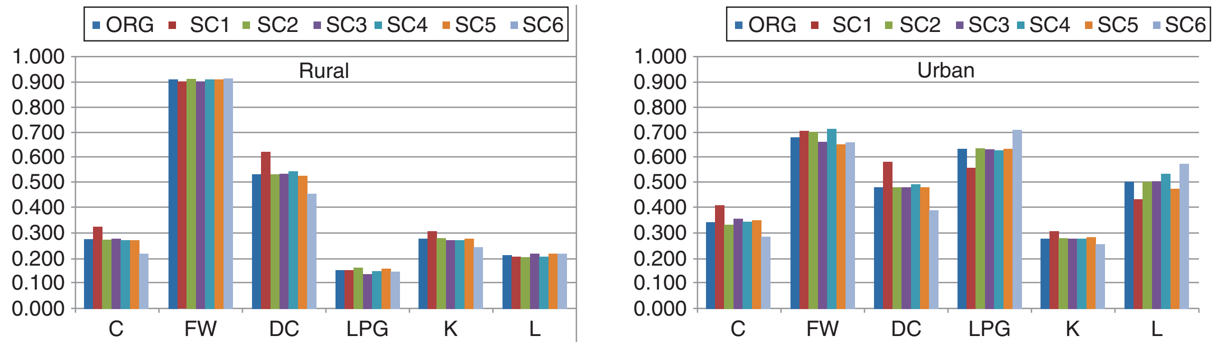

Figure 5: SES Index of energy sources for different scenarios for rural and urban India.

urban India. However, when the maximum unit price of firewood and dung cake are used, LPG emerges as the highest ranked energy source in urban India and dung cake is ranked below coal. Hence, it can be concluded that LPG may have a higher SES Index than firewood in urban India, as firewood may have to be purchased at market price by many consumers. Further, as affordability is a function of both, energy prices and household income, high income households both in rural and urban areas may prefer LPG which is more convenient, over other energy sources.

5.3. Strategy to achieve SES for India

In order to promote cleaner energy sources which rank high on EFF and ACP dimensions such as LPG and electricity, India needs to make them more AFF. Higher AFF will result in more households switching to cleaner and efficient forms of cooking sources. Additionally, in case of energy sources which rank high on AFF and AVL dimensions, such as firewood and dung cake, there should be a thrust on the adoption of newer technologies which may increase its EFF and ACP. These technologies can be in the form of clean cook stoves and decentralized electricity generation from biomass and also in the form of increased deployment of biogas (from dung) plants. Careful attention therefore needs to be given to energy policy design which needs to promote the use of biomass and dung cakes in rural areas instead of pushing LPG as a cooking source.

6. Conclusion

The paper has undertaken a comparative assessment of various energy sources for attaining SES for India's residential sector. The generic framework has been applied to evaluate the SES Index for ranking of energy sources commonly used in rural and urban India. Results reveal that firewood has the highest rank followed by dung cake and kerosene in rural areas, while LPG has the lowest rank. It is therefore important that the energy policy should be designed in a manner, so as to promote the use of firewood and dung cakes which are relatively more 'Available' and 'Affordable' in rural areas. However, emphasis should be given on design of better technologies to increase the 'Efficiency' and 'Acceptability' of these energy sources. In urban area, the ranking of energy sources is in the following order: firewood, LPG, electricity, dung cake, coal and kerosene. However if firewood has to be purchased at the market price and is not collected, LPG displaces firewood to obtain the first rank. Based on the sensitivity analysis it can be concluded that these rankings are mostly insensitive to (+/– 10%) variation in the weights allotted to different dimensions. Lastly, this study has presented the results of a quantitative assessment of various energy sources for the residential sector which will be helpful for energy planners in designing appropriate policies for attaining SES for India.

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Abbreviations:

SES: Sustainable Energy Security
AHP: Analytical Hierarchy Process

DI: Dimensional Index
LPG: Liquefied Petroleum Gas
AVL: Availability
AFF: Affordability
EFF: Efficiency
ACP: Acceptability
AFF: Affordability
AHP: Analytical Hierarchy Process
AVL: Availability
CI: Consistency Index
CR: Consistency Ratio
DI: Dimensional Index
EFF: Efficiency
FA: Factor Analysis
HH: Household
LPG: Liquefied Petroleum Gas
mtoe: million tonne oil equivalent
ORG: Original
PCA: Principal Component Analysis
REF: Reference
RI: Random Index
SC: Scenario
SES: Sustainable Energy Security
SFC: Specific Fuel Consumption
TFEC: Total Final Energy Consumption
toe: tonnes oil equivalent
TPES: Total Primary Energy Supply

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Appendix 1

Table A.1: List of selected dimensions, indicators and components.

Dimension	Name	Indicator	Components	Unit
Physical Availability (Access and consumption)	AVL1	% of HH using ___as primary energy source[1]	80 % weight: cook/water heating 20 % weight: lighting	%
	AVL2	Average qty of energy (includes cooking and lighting) consumed per month per capita	Qty of energy[1] × energy content per unit of energy source[2]	Unit × (MJ/unit) =MJ
Affordability	AFF1	Monthly capital cost of end use device for cooking *	Capital cost of cook stove/Life of stove [3]	Rs/month
	AFF2	Cost of fuel purchase per month for meeting requirement of cooking **[4]	Average unit price of energy consumed per month [1] × Specific fuel consumption[5] × cooking work reqd per HH per month[6]	Rs per HH per month
Environmental Acceptability	ACP1	CO emissions from end use device for cooking	CO emissions from cook stove using ___ energy source[7]	mg/m^3
	ACP2	PM emissions from end use device for cooking	PM emissions from cook stove using ___ energy source[7]	mg/mg^3
Efficiency	EFF	Efficiency of end use device for cooking	(Energy output/energy input)[8] × 100	%

*Capital cost of end use device for lighting has not been accounted for as cost will be incurred only if there is access to electricity connection. Discount rate has not been considered.

**Efficiency of end use device for lighting has not been accounted for as it is not applicable to all energy sources and use of electricity for lighting is dependent on access to electricity connection

[1] Data Source: [27]

[2] Assumed energy content per unit of energy source:

Source	Coal	Firewood	Dung Cake	LPG	Kerosene	Electricity
Unit	Kg	Kg	Kg	Kg	lt	kWh
Energy content (MJ/unit)	18	15	12	46	33	3.6

[3] Assumptions for cost and life of cook stove

	Coal	Firewood	Dung Cake	LPG	Kerosene	Electricity
Capital Cost (Rs) (Lower limit)	150	0	0	1200	250	790
Capital Cost (Rs) (Upper limit)	300	0	0	2500	500	3000
Capital Cost (Rs) (Estimated)	200	0	0	1500	350	2000
Life of stove (Months)	24	12	12	120	36	120
Monthly capital cost (Calculated) (Rs/month)	8.33	0	0	12.5	9.72	16.67

Data Source: Author's own assessment based on market survey

[4]Cost of fuel purchase per month (Rs) = Monthly fuel consumption per HH × Average unit price of energy (Rs/unit);

Where Monthly fuel consumption per HH (g) = SFC (g fuel/Kg cooked food) × Cooking work required per HH per month

[5]Specific fuel consumption is the fuel used per unit of product produced. The unit of product produced for cooking is Kg of cooked food.

SFC values in units of (g fuel/Kg cooked food) which are used for various energy sources are as follows:

Source	Coal	Firewood	Dung Cake	LPG	Kerosene	Electricity
Unit	Kg	Kg	Kg	Kg	lt	kWh
SFC	95	217	305	20.1	26.5	0.18

Data Source: [28]

[6]Cooking work required per HH per month (Kg cooked food) = (1.3 Kg per capita per meal)x(3 meals per day)x (5 members per HH)

[7] Data Source: Author estimates based on [29]

[8] Efficiency of cook stove (in %)

Data Source: [28]

Energy Source	Coal	Firewood	Dung Cake	LPG	Kerosene	Electricity
Stove	Traditional	3 stone fire	Traditional 3 pan	Superflame double burner	Nutan /Perfect	Hotplate
Per cent heat utilization	23.2	15.7	11.1	60.4	50(40.4-60.4)	71.3

Data Source: [28]