Sustainable Energy Security for India:

An Assessment of the Energy Supply Sub-System

Kapil Narula [1*], B. Sudhakara Reddy [2], Shonali Pachauri [3], S Mahendra Dev [2]

[1] National Maritime Foundation, Varuna Complex, Airport Road,

NH - 8, New Delhi (India)

[2] Indira Gandhi Institute of Development Research,

Gen. A.K.Vaidya Marg,

Goregaon (E), Mumbai (India)

[3] International Institute for Applied Systems Analysis,

Laxenburg (Austria)

*Email (corresponding author): kapiln@igidr.ac.in

Abstract

This paper undertakes part of the assessment of the sustainable energy security (SES) for India. SES goes beyond 'energy supply' and is a function of the aggregate energy system of a country, including the 'energy demand' and 'conversion and distribution sub-system'. The supply sub-system which consists of eight primary energy sources viz. coal, oil, natural gas, biomass, hydro, solar, wind and nuclear has been evaluated for four dimensions of SES, viz., availability, affordability, efficiency and (environmental) acceptability using 16 selected metrics. The *dimensional indices are calculated for domestic and imported energy sources separately for the years 2002, 2007 and 2012. Results reveal that the SES index for oil has increased by 10% but it has decreased by 6% for gas from 2002 to 2012, while changes for other energy sources are marginal. The overall supply sub-system SES index is approximately 0.75(against an ideal value of 1.0) which reveal the shortfall from the desired value. A sensitivity analysis reveals that the SES index is relatively robust to variation in weights. The assessment provides a comprehensive way to track the performance of the energy supply sub-system and can be used to design policy interventions for improving the overall SES index for India.*

Keywords: Energy supply, Energy security, Energy sustainability, multidimensional, energy index

1. Introduction

Sustainable Energy Security (SES) is defined as "provisioning of uninterrupted energy services in an affordable, equitable, efficient and environmentally benign manner" (Narula, 2014) and has been proposed as an end goal of the energy policy for a developing country. Energy security is a property of the energy system (Mitchell and Watson, 2013) and the physical energy system of a country can be divided into three distinct sub-systems, 'energy supply' sub-system, 'energy conversion & distribution' sub-system and 'energy demand' sub-system. The energy supply sub-system deals with primary energy, either extracted as fossil fuels (coal, crude oil, natural gas); renewable energy (solar, wind, hydro) which is harnessed directly to generate electricity; biomass and; nuclear energy which is extracted as uranium and is then converted to electricity.

Energy security is often used synonymously with security of energy supply. This perception of energy security enhances the importance of the energy supply sub-system in the energy system. World Energy Outlook- 2015 (IEA, 2015) forecasts that India will move to the centre stage of the world energy system and the change in demand for energy for the period 2014-2040 will be the highest amongst all countries. Thus the energy supply sub-system will need to grow to meet this demand and there is likely to be a large increase in import of fossil fuels and renewable energy generation from domestic resources. Tracking of the performance of the energy supply sub-system of a country based on an assessment of various competing sources of energy is therefore essential. This paper attempts to contribute to the methodological advancement for undertaking a multidimensional assessment of an energy system for a country. The generic methodology is valid for any country or region and the paper applies it for undertaking a comprehensive analysis of the Indian energy supply sub-system.

There are a set of indices in literature which attempt to undertake the assessment of a country's energy security and sustainability. A few of them are: Energy Security Index (ESI_{price} and ESI_{volume}) by IEA (2007), 'willingness to pay function' for security of supply (Bollen, 2008), Oil Vulnerability Index (Gupta, 2008), Vulnerability Index (Gnansounou, 2008), geopolitical energy security measure (Blyth and Lefèvre, 2004), risky external supply index (Le Coq and Paltseva, 2009), economic and socio-political risk index under project Risk of Energy Availability: Common Corridors for Europe Supply Security (REACCESS, 2011), energy development index (IEA,2010), energy sustainability index (Doukas *et al.*, 2012), Aggregated Energy Security Performance Indicator (AESPI) (Martchamadol and Kumar, 2013), amongst others. Most of these indices focus on certain specific aspects of energy security; primarily on the economic dimension while neglecting environmental and social aspects; on specific fuels, such as oil and gas, while neglecting energy sources such as renewable energy, nuclear and coal. However, a couple of them such as S/D Index (Scheepers *et al.*, 2007), Model of Short-term Energy Security (MOSES)

(Jewell, 2011) and the index developed by Sreenivas and Iyer (2014), comprehensively attempted to measure major facets of the performance of the energy system. Yao and Chang (2014) have undertaken a quantitative analysis of energy security in China using the 4 A's framework. Using a similar approach Tongsopit et al. (2016) applied the 4-As framework to measure the status of energy security of ASEAN countries. The paper examines four quantitative indicators for each A's related to availability, applicability, affordability and acceptability and examines the trends from 2005 to 2010.

The aim of this paper is to assess the SES for the energy supply sub-system for India. Eight components of the supply sub-system (primary energy sources) are evaluated for 16 metrics and their dimensional indices are calculated for the years 2002, 2007 and 2012. These are aggregated into indices for domestic and imported energy sources and further into an SES index for the energy supply sub-system. An analysis of calculated indices is undertaken and the shortcomings in the performance of the energy supply sub-system are identified. A sensitivity analysis of various dimensional indices examines the robustness of the supply sub-system SES index. The paper highlights the applicability of the SES index for tracking the performance of the energy supply system for a country and concludes with certain policy implications for India based on the comprehensive analysis of its energy supply sub-system.

2. Methodology

The analytical framework for the assessment of SES of an energy system, the methodology for constructing an SES index and the metrics to calculate the SES index has been proposed earlier (Narula and Reddy, 2016). The paper describes in detail the overall framework of assessment of the energy subsystem, the methodology, the justification of selection of dimensions and the metrics and the relationship of the selected metrics with SES.

The energy system is divided into three parts to facilitate the assessment of its SES and the boundaries are shown on a representative Sankey diagram in Fig. 1 (Narula and Reddy, 2016). The supply sub-system consists of all domestic and imported primary energy sources. The impact of extraction of primary energy sources is also considered for the assessment of supply sub-system and is shown as an additional block in Fig. 1. Primary energy sources are converted into secondary energy such as electricity and refined petroleum products in the conversion and distribution sub-system. The demand sub-system consists of various energy consuming sectors. The end use devices which convert the final energy to useful energy are also considered in the assessment of the energy demand sub-system. The framework for the assessment of the energy supply sub-system which is evaluated in this paper is presented in Fig. 1a and the methodology is briefly described ahead.

Fig.1a here

The components of the supply sub-system are various primary energy sources which are assessed separately for domestic supply and imports. For hydro, solar, wind and biomass there are no sub-components as these energy sources are primarily domestic in nature. Renewable primary energy sources such as hydro, solar, and wind as well as nuclear (uranium), are assessed for their potential to supply electricity.

Four different dimensions — ‘Availability’ (related to adequacy and access), ‘Affordability’ (related to prices and paying ability), ‘Environmental Acceptability’ (related to resource extraction and waste production) and ‘Efficiency’ (related to productivity in the use of energy resources) are used for the assessment of SES of an energy system. These dimensions enshrine the principles of SES and are equally applicable to all sub-systems. However, they have different interpretations for different sub-systems. For the energy supply sub-system, 'availability' implies adequacy of domestic energy reserves, adequacy of primary energy supply and ease of energy imports. High availability lowers the risk of energy supply disruption. Lower cost of energy, lower volatility in the price of imported energy and a lower energy import bill for a country implies higher affordability of energy supply sub-system which increases the SES. 'Efficiency' dimension for the energy supply sub-system includes extraction efficiency of primary energy sources and a higher extraction efficiency (recovery factor) is desirable. Acceptability of a particular energy source is high if there is lower use of resources such as water and land and if there is reduced waste generation such as air emissions from primary energy extraction. Suitable metrics are then selected for each dimension for undertaking a comprehensive assessment of SES of the energy supply sub-system.

As shown in Fig. 1a, weights are allotted to metrics and dimensions. The shares of domestic (sh_{DOM}) and energy imports (sh_{IMP}) for various energy sources and their shares in the primary energy supply ($sh_{E(i)}$) are obtained from energy balances.

Measurement of SES can be undertaken through the use of 'metrics' which reflect the characteristics of the energy system. Following the hierarchical structure for assessment of SES for an energy system, energy indices can be evolved using a combination of 'weights' and 'scores' and a SES index for the energy supply sub-system can be aggregated. The model for creating an SES index consists of a scoring matrix and a weighting matrix, which are multiplied together to form a vector, elements of which can be considered as an 'index'. 'Scores' are used to measure the performance of specific characteristics of energy sources and are objective values which are obtained from statistical data and scoring rules for various metrics. On the other hand, 'weights' represent the subjective component and can be interpreted as a measure of relative importance of the metric. The generic model for constructing an index for the assessment is shown in Fig. 2.

Fig.2 here

Metrics are collated from various data sources (if directly available), or are calculated from its components. Data imputation and other approximations are undertaken to account for the missing data in certain cases. Various metrics have different units and these are normalized to make them dimensionless. The normalized metrics are then scaled appropriately/inverted to attain the scores which are elements of the scoring matrix.

Min-max normalization followed by scale inversion is used for the supply sub-system. Value (x) of each energy source for a particular metric is collected and is benchmarked against pragmatically (user) defined minimum and maximum values. The allotted score for a metric is 0, if the value of the metric is below the lower threshold (minimum), and is 1, if it is above the upper threshold (maximum), respectively. If the value of the metric for a country is within these two limits, the normalized score of the country is linearly interpolated. A similar methodology has also been used in calculating the S/D index (Scheepers *et al.*, 2007) and in MOSES (Jewell, 2011), where well defined scoring rules are formulated for each metric after defining the minimum and maximum values.

In order to calculate the normalized value, 'n', Eq. (1) is used, which transforms the values to a relative scale of 0-1.

$$n = \frac{x - \min(x)}{\max(x) - \min(x)} \qquad \ldots(1)$$

The selected metrics can be grouped into two categories, viz., metrics which have a positive impact and those which have a negative impact on SES. Positive impact metrics are those, where a high value of the metric contributes to high SES index; while for negative impact metric, a high value of the metric contributes to lowering of SES index. While the normalized values of the positive impact metrics are unchanged, the normalised values of negative impact metrics have to be inverted such that a low value of the metric contributes to increasing the index. Therefore, the normalised value is subtracted from 1 to obtain the score, i.e. the score will be (1-n), for negative impact metrics. As a result of this inversion, a high score for both, positive and negative metrics will contribute to increasing the SES index.

Weights are essentially value judgments and represent a tradeoff between various competing criteria. A pair-wise comparison is undertaken for determining the weights. This process is chosen as weights gathered from the stakeholders capture the perception of a cross-section of the society and therefore represents the concerns for energy security and sustainability of a country. Scores obtained by various metrics are evaluated and weights are allotted based on a survey of respondents.

This hierarchical structure allows us to undertake a comprehensive assessment of the SES of the energy supply sub-system for a country. High scores in all four dimensions for the supply sub-system contribute to a higher SES index for the energy supply sub-system.

3. Selected metrics and benchmarks

Different metrics are chosen to represent the four dimensions of SES for the supply sub-system. The selected metrics grouped under various dimensions, categories and sub-categories along with the variables, their units, benchmarks and desirable values for different sub-components are provided in Appendix A. A total of 7 metrics for availability dimensions and three metrics each for affordability, acceptability and efficiency dimensions are evaluated for eight primary energy sources.

3.1 Domestic energy sources

All eight domestic sources of primary energy, viz., coal, oil, gas, nuclear (uranium), hydro, solar, wind and biomass are assessed for the four selected dimensions.

3.1.1 Availability

Metrics for the assessment of availability dimension include both short term and long term aspects of physical energy security. Metrics are on 'per capita' basis, which ensures that the principle of (inter-country) equity is captured in the assessment.

'Estimate of per capita reserves (proven) of primary energy' for a country is chosen (AVL 1a) to characterize the geological availability of energy sources in the country. Adequacy of reserves of fossil fuels and uranium can be measured by comparing the 'estimate of per capita reserves (proven) of primary energy' for a country, against the world average. This metric conservatively uses 'proven', rather than 'inferred' or 'anticipated' reserves. Reserves are considered adequate if per capita domestic reserves are comparable to the world average and the value for the year 2012 has been selected as the benchmark for all energy sources for metric AVL1a.

Fossil fuel reserves are stocks, while renewable energy is a flow. Adequacy of renewable energy from a particular source can be measured by comparing the country's 'estimated potential for electricity generation/capita/year' against the world average. The estimated potential generally increases over the years as mapping of various areas is undertaken, but this is due to exploration efforts rather than a physical increase. The world average for the year 2012 has been selected as the benchmark for renewable energy sources. Resource potential would be considered adequate if per capita resource potential of energy in a country is comparable to this benchmark.

Per capita domestic supply of primary energy' in a year is used to measure the physical availability of energy. This is benchmarked to the per capita supply of primary energy in the world for the year 2012.

Primary energy reserves may be adequate but there might be technical limitations and poor capacity to extract and harness the available resources. There might be other constraints such as inadequate human and financial resources. Energy planning is an essential component for domestic supply of energy and targets are usually set for primary energy extraction and harnessing of renewable energy on a short, medium and long –term basis. In India, the process of energy planning is streamlined and five year plans decide the targets for production. 'Achievement in meeting planned target of domestic energy supply' is used as a metric to measure supply capability. The actual supply is compared against the planned target for the concerned time period (annual or five-year plan target). Ideally, the planned target should be met. However, targets are often not met due to various reasons, which reflect the inadequacy in capability of the country to extract or harness energy. If the planned target is met or exceeded, a score of 1 is allotted, while if the achievement in meeting the planned target is 50% or below, a score of 0 is allotted. A low score implies the presence of a large number of barriers, which is detrimental for attaining SES.

3.1.2 Affordability

Pricing of domestic energy sources is regulated in India and the process of price fixation is complex. Often there are cross subsidies, pooling of prices and complicated taxation regimes which include a host of levies. Taxes on basic extraction cost are an important source of revenue both for the state and for the central government. The domestic pricing of energy sources is therefore not contested and a score of 1 is allotted to all domestic energy sources for the affordability dimension.

3.1.3 Acceptability

Acceptability of a particular energy source is high if there is lower use of resources such as water and land and if there is reduced waste generation such as air emissions from primary energy extraction. Although international estimates of the environmental impact of extraction of primary energy sources are available, similar estimates in the Indian context are limited. Ideally, use of water, land and air emissions during the process of extraction of energy in a country should be benchmarked against the international standards, which is not possible due to lack of data on India. One way to overcome this limitation is to use common metrics for various primary energy sources and to measure the performance of different energy sources using minimum and maximum values. This method is adopted in this study for calculating the dimensional index for acceptability for different energy sources.

'Estimate of water consumed per unit of energy extracted' is used as metric ACP1. Water consumption is for extraction, pre-processing and other related processes and is measured in units of cu. mt. per GJ of energy extracted. Lower water consumption increases the SES index and is desirable. There are various estimates of water consumption for primary energy production and estimates by Gleick (1994) are used widely.

'Direct land use per unit of energy extracted' is used as metric ACP2. This includes mining and pre-processing for non-renewable energy sources and land required for electricity production for renewable sources. Common units of m^2/GWh are used for comparison. Land use for renewable energy sources (wind, solar and hydro) is assessed for its conversion to electricity but for fossil fuels, land use is considered for extraction only (land use for power plants is included in the C&D sub-system). Direct land use varies significantly for different primary energy sources due to large differences in their energy densities. To account for such large variations, 'log (direct land use)' is used as a metric for ACP2. This narrows the range for undertaking min-max normalization for calculating scores. Lower value of ACP2 increases the SES index and is desirable. There are various estimates of land use for primary energy extraction and values for this study are based on the estimates by Fthenakis and Kim (2009).

'Average emission of GHG (methane) per unit of energy extracted' (Kg methane/PJ) is selected as the metric ACP3. The emission factors used for primary energy extraction are shown in Table 1.

Table 1here

Emissions from other GHG are neglected as they are small in comparison with methane gas emissions. PM, SO_2 and NOx are air pollutants, which accompany extraction of energy. However, these are not included in the assessment of acceptability as they have a local impact.

3.1.4 Efficiency

'Efficiency' for the supply sub-system implies extraction efficiency of primary energy sources (recovery factor) and technical efficiency of conversion of RE to electricity. High score in the efficiency dimension implies that maximum amount of energy (which is technically feasible) is extracted and converted, resulting a higher SES index.

'Estimate of recoverable energy/energy in place' (EFF1a) is the selected metric for fossil fuels and for biomass. Internationally obtained recovery factors are used to define the range for this metric and the actual values for India are compared with these benchmarks. Higher extraction efficiency implies better utilization of existing reserves and contributes to increasing the total domestic supply of energy with the same resources.

In the case of renewable energy, estimates of 'Electric energy output/primary energy input' (EFF1b) is used as a metric for the efficiency dimension. An increase in this metric leads to better utilization of the existing renewable energy resource. Specifically, for the case of solar and wind, a larger amount of electricity can be generated from the same area by using better materials and technology. Higher efficiency therefore contributes to a higher SES index.

3.2 Imported energy sources

A country may be a net importer or exporter of energy. Resource rich countries are exporters of energy sources such as crude oil and may import refined oil products such as gasoline or petrol, while other countries which have a strong refinery sector, maybe importers of crude oil but exporters of refined products. This assessment considers the net imports (imports-exports) of various energy sources and all variables used for calculation of imports are on a 'net' basis, thereby circumventing the need of considering energy exports separately.

3.2.1 Availability

For energy imports, lower risk and higher resilience to possible energy supply disruption leads to higher energy security. 'Herfindahl Hirschman Index (HHI) corrected for political risk of country' is used to measure the concentration of energy supplying countries. Diversification of energy suppliers is one of the strategies of reducing the risk of disruption of energy imports. While diversification, as a strategy for increasing energy security, can be extended to diversification of modes of supply (pipeline, ships), diversification of energy routes by ships supplying energy (avoiding major choke points) and geographic diversification (concentrated imports from countries in a specific area such as Middle East), this study uses metric AVL 4 $(\sum(S_i)^2 \times (100-r_i)/100$, refer to appendix A for details) for measuring the diversification of energy imports. The value of $(S_i)^2$ varies between 10000 to 0 signifying minimum and maximum possible diversification respectively. The value of $(100\text{-}r_i)/100$ varies between 0 and 100 for a country with minimum and maximum risk respectively. A low value of AVL4 implies lower risk of disruption and is desirable.

Risk of short term supply disruption can be lowered by maintaining emergency energy reserves or ready use stocks of energy. 'Number of days of stocks as a % of net imports' is used as the metric AVL5 for energy imports. Larger stocks need to be maintained for energy sources having higher import dependency to guard against possible supply disruptions. IEA mandates that 90 days of emergency reserves are to be maintained by member countries and this value is selected as the benchmark for crude oil. The import dependency of nuclear fuel (uranium) for India is also high and a similar value is selected for uranium. Import dependency of natural gas and coal is in the range of 25-30% and a value of 45 days is selected as a benchmark. The values of various energy sources are compared to these benchmarks and a higher score for metric AVL5 is desirable.

For the specific energy commodity, 'percentage of excess port capacity for import of energy' is calculated by comparing the port capacity with the actual port traffic for a particular year. 20% excess port capacity is selected as the benchmark and the value of metric AVL6 is compared with this benchmark. Higher spare capacity implies adequate port infrastructure which allows for a possible increase in imports (in both short and long– term) and contributes to a higher SES index.

3.2.2 Affordability

Affordability of energy imports implies macroeconomic affordability for a country. Energy imports can be considered affordable if the price of energy imports is comparable to the cost of domestic extraction of energy. Lower price volatility (than historic volatility) lowers the uncertainty in budgeting for a country and contributes to a higher SES index.

‘Average per unit import cost of primary energy’ (without taxes, duties and levies) is used as a metric for affordability of energy imports (AFF1). This value for different fossil fuels is compared to the average per unit extraction cost of domestic energy (without taxes duties and levies). The domestic cost is the maximum value and the minimum value is taken as 0. It is found that the imported cost of energy is often greater than domestic cost of energy which gives a value greater than 1. This metric is therefore inverted (new score = 1/original score) to fall in the range of 0-1. A linear scale ensures that if the imported price of energy is equal or lower than domestic price, a score of 1 is obtained and if the imported price is twice that of domestic price, a score of 0.5 is obtained.

‘Coefficient of Variation (CV) in international spot price’ of primary energy is used as metric AFF 2. CV is a measure of volatility and is calculated by dividing the standard deviation with the mean value. The CV of monthly prices over a financial year is averaged over a period of five years (historical CV) and is used as a benchmark for comparison with CV for that year. This historical CV is designated as the maximum value while the minimum value is 0. A lower value of metric AFF2 is desirable and if the obtained value of AFF2 is greater than or equal to the historical CV, a value of 0 is allotted.

‘Energy import bill as a % of GDP’ (AFF3) is selected as the metric for macroeconomic affordability of energy imports. This is a function of unit price of imported energy, quantity of energy imports and GDP of a country. Considering that energy imports are essential for India, a benchmark of 1% has been selected for coal, gas and uranium imports. A value of 10% has been designated as the maximum value for crude oil and the minimum value of metric AFF3 for all energy sources is selected as 0%. A low value of metric AFF3 implies higher macroeconomic affordability of energy imports and is desirable.

3.2.3 Acceptability

Acceptability is not measured for imported energy as the environmental impact of extraction of energy is on the supplier county. Hence it is assumed that the all forms of energy imports have nil environmental impact (environmental impact of transportation of imported primary energy is neglected) and a score of 1 is allotted to this dimension for imported sources of energy.

3.2.4 Efficiency

'Supply efficiency of primary energy imports' is used as a metric (EFF1c) for the efficiency dimension. Neglecting the minimal losses during transportation of imported energy, it is assumed that the value of metric EFF1c is 100% for all forms of imported primary energy.

4. Calculation of scores

Scores are calculated from the actual values of metrics for different years and the benchmarks using the adopted scoring rules and the scores for different energy sources are compiled in tables 4-17 at the end of this section.

4.1 Scores for acceptability metrics

Metrics for the acceptability dimension are case specific, vary considerably across different locations, and are long term averages. One set of values are therefore used for calculation of scores, which are then allotted to all years. The range of values, median estimates (values used) and the calculated scores for all primary energy sources are shown in Table 2 and 3 for metric ACP1 and ACP2 respectively.

Table 2 and 3 here

The median estimates of water use in energy extraction for different energy sources range from 0 to 0.111 m^3/GJ. The score for metric ACP1 is the lowest for mining of uranium and is highest for renewable sources of energy. The average value of land used per unit energy extracted is spread over a wide range. The log of the average value is therefore used to narrow this range within 2.06 (min.) to 5.73 (max.). The score for the metric ACP2 is the highest for biomass and is lowest for uranium mining. GHG emissions during energy extraction are maximum for natural gas extraction and hence it obtains a score of 0.0 while there are nil emissions for renewable energy sources such as wind and solar which obtain a score of 1.0. These values and scores for acceptability metrics are allotted to various energy sources and are shown along with other metrics for different primary energy sources in Tables 4-17.

4.2 Coal

Refer Table 4. The average per capita coal reserves in the world (2012) was 122 tonnes and is chosen as the benchmark value. Although India has the world's third largest coal reserves, its per capita value is quite low (49 tonnes) as compared to the world average. Similarly, despite India being the third largest producer of coal, the value for the metric AVL2 (per capita coal production) is low as compared to the world average. The score for the metric AVL3 is high for the years 2002 and 2007, but has decreased during 2012, which indicates hurdles in meeting the planned target of coal production. Value of metric EFF1, is calculated as the weighted average of open pit and underground mining. The average efficiency of open pit mining in India is 85% and its share is predominant (90%) in India, while the average efficiency of underground coal mining is 50%. The weighted average is therefore calculated as 81.5%.

Refer Table 5. In the case of coal imports, the score of the metric AVL 4 is decreasing while that of AVL5 is 1.0 as there are enough ready to use stocks of coal. Security of coal imports is therefore not an immediate cause of concern. Value of the metric AVL 6 for the year 2012 is quite low which may impact the capability to import coal. Score for metric AFF1 of imported coal is low which indicates that domestic sources of coal are much cheaper than imported coal but the score for metric AFF2 and AFF3 is high implying that coal imports are still affordable for the country on the selected scale.

4.3 Crude Oil

Refer Table 6. The average per capita crude oil reserve in the world (2012) was 238 barrels and is chosen as the benchmark value. The score for metric AVL1a is very low as India has low quantity of oil reserves. The score for the metric AVL2 is also low as compared to the world average. The score for the metric AVL3 is high which indicates that the planned targets have been met. Value of metric EFF1a, is 30% for India which is lower than the world average of 35%. Considering that the highest efficiency (after including secondary recovery methods) for extraction of crude oil from oil fields is 70%, the scores for India are relatively low.

Refer Table 7. In the case of crude oil imports, the value of the metric AVL4 is almost constant over the years and there is not much variation in the scores of metric AVL5. The score for AVL6 has however increased from 2007 to 2012 which is a positive development. Score for AFF1 of imported crude oil is high which indicates that imported sources of crude oil are priced approximately equal to domestic sources and therefore it makes economic sense to import crude oil. While score of AFF2 has increased from 0.07 in 2007 to 0.75 in 2012, volatility of crude oil continues to remain a source of financial risk. The decreasing score of metric AFF3 is also a major cause for concern.

4.4 Natural gas

Refer Table 8. The average natural gas reserves for the world in 2012 was 26,173 cu. mt./capita, and is chosen as the benchmark value. The score for metric AVL1a is very low as India has low quantity of natural gas reserves. The score for AVL2 is also low as compared to the world average. The score for AVL3 for the year 2012 is lower than that of 2007, which indicates that the planned targets have not been met. Value of metric EFF1a is 75% which is lower than the world average.

In the case of natural gas imports, (Table 9) the value of the metric AVL4 has increased from 2007 to 2012 indicating an increase in the diversification and security of supply of natural gas. Emergency stocks of natural gas are however low and inadequate port infrastructure for import of natural gas is a cause for concern. The score for metric AFF1 for natural gas close to 0 as the average per unit import cost is much higher than that for domestic gas. The score for metric AFF2 is low, implying that international prices of natural gas are relatively stable. The score of metric AFF3 has decreased from 0.84 in 2007 to 0.61 in 2012 and this is a cause for concern.

4.5 Nuclear (Uranium)

Refer Table 10. The average per capita reserves for uranium in India are significantly lower than the world average. The score of the metric AVL2 is also low but is on an increasing trend. The scores for the metric AVL3 for the years 2002 and 2012 are low due to low achievement of planned targets. As data on the efficiency of nuclear power plants in India is not available, the score for the metric EFF1a is assumed to be 1.

In case of uranium imports, (Table 11) data for 2012 is only available and the scores attained for various metrics are allotted to earlier years. Diversity of uranium suppliers is fairly high (AVL4), stocks are adequate (AVL5) and port capacity is not a constraint for uranium imports (AVL6). Import of uranium is cheaper than domestic extraction and hence the score of metric AFF1 is equal to 1.0. Scores for AFF2 and AFF3 are high indicating a high score in the affordability dimension for uranium imports.

4.6 Hydro

Refer Table 12. The per capita estimated resource potential for hydro for the world in 2012 was 0.24 kW, and is chosen as the benchmark value. The score for metric AVL1a is relatively higher than fossil fuel availability. The score of the metric AVL2 also shows an increasing trend. The score for the metric AVL3 for the year 2012 is close to 0 as the targets for hydro power plant projects have regularly not been met for the past decade. This may be indicative of problems in execution of large hydro power plant projects in the country. Value of metric EFF1b, is considered at par with the world average.

4.7 Solar

Refer Table 13. The estimated resource potential for solar power for the world in 2012 was 0.08 kW/capita and is chosen as the benchmark value. The score for metric AVL1a is close to 1.0 indicating high solar potential in the country. The score for AVL2 shows an increasing trend due to high capacity addition in the past few years. The score for AVL3 for the year 2012 is 1.0 as the targets for setting up of solar plants have been exceeded. Value of metric EFF1b is considered at par with the world average.

4.8 Wind

Refer Table 14. The estimated resource potential for hydro for the world in 2012 was 0.16 kW/capita, and is chosen as the benchmark value. The score for metric AVL1a is close to 0.5 indicating moderate wind potential in the country as compared to world average. The score for AVL2 shows an increasing trend due to high capacity addition in the past few years. The score for the metric AVL3 for the year 2012 is 1.0 as the targets for setting up of wind plants have been exceeded. Value of metric EFF1b is considered at par with the world average.

4.9 Biomass

Refer Table 15

Table 15.. The scores for metrics AVL 1b, AVL3 and EFF1b are considered as 1.0. For metric AVL2 the average per capita supply of biomass for the world in 2012 was 0.19 toe and the scores for India show a decreasing trend. The scoring matrices are populated using the obtained scores and are used for the calculation of various indices.

5. Stakeholder Responses and Weights

The responses of seven stakeholders were captured in interviews and weights for different metrics and dimensions are derived. The consolidated matrix and the (n x n) judgment matrix, [*A*], for seven different participants (P1-P7) for evaluating the metrics for availability of domestic supply (AVL1, 2, 3) are shown at Appendix B. Using Eq. (2), each element of the consolidated matrix (b_{ij}) is obtained as a geometric mean of the elements (a_{ij}) of the seven judgment matrices.

$$b_{ij} = (a_{1ij} \cdot a_{2ij} \cdots a_{kij})^{\frac{1}{k}}, \qquad \ldots(2)$$

where, k = number of respondents (=7).

The iterations for calculation of the normalized principal eigenvector [W] are shown in Appendix C and weights are allotted to the metrics AVL1-AVL3. Weights for other metrics are calculated in a similar way. As respondents have different perceptions of the relative importance of weights, they allocate different values for the pair-wise comparison, which results in different normalized principal eigenvectors [W]. This diversity in the perception of the stakeholders is used to generalize the weights of different metrics across the entire population. The consolidated weights which are used to form the weighting matrices for calculation of various indices are shown in Table 16. The minimum and the maximum weights for different metrics are also presented and are used for undertaking a sensitivity analysis. Respondents were also interviewed for evaluating their perceptions on the relative importance of various dimensions. The weights obtained for different dimensions are summarized in Table 17.

Table 16 and 17 here

The range of weights varied from 5 to 57% for various dimensions but the consolidated weights of the seven respondents showed almost equal weights for all four dimensions for the supply sub-system. These consolidated weights are used to fill the weighting matrix and the range of obtained weights is used for undertaking the sensitivity analysis.

6. Results and Discussions

The scoring matrix is multiplied by the weighting matrix to obtain various indices. The SES indices calculated for different energy sources for different years are shown in Fig. 3 for domestic sources and in Fig. 4 for imported sources.

Fig. 3 and 4 here

SES indices for domestic energy sources reveal that the index for fossil fuels is relatively lower than other sources. Results reveal that (domestic) renewable energy sources have a higher SES index than domestic fossil fuels. Therefore, a transition to renewable energy sources should be encouraged for increasing the overall SES index. However, large scale deployment of renewable energy, cost, grid integration, variability and intermittency (both seasonal and daily) are some of the challenges which need to be overcome.

Fig. 4 shows that SES index for imported gas has decreased considerably in 2012 (from 2007) and is a cause for concern. The SES index for imported coal has marginally decreased from 2007 to 2012 while that for oil has increased during the same period. SES index for imported uranium is significantly higher than that of domestic uranium. It is also observed that the SES index for import of coal, oil and nuclear sources are higher than the corresponding SES index for domestic fossil fuels. This implies that a shift to imported sources of energy would lead to an increase in the overall SES index. This would also lead to an increase in the acceptability dimension as there would be no environmental impacts associated with extraction of energy on the importing country. It can therefore be concluded that energy imports are good for the country in the short term to meet the shortage in energy demand. Hence investment in import infrastructure for oil, gas and coal is paramount for India However, in the long term, developing domestic sources of energy and minimizing dependence on energy imports would ensure higher availability and affordability of energy sources.

Fig. 5 here

The SES indices for different energy sources and for the entire supply sub-system are shown in Fig. 5. Results reveal that there was not much change in the SES index for the supply sub-system from 2002 to 2012, and it was around 0.75. A closer look reveals that the index for oil increased by 10% while that for gas decreased by 6%. The SES index for nuclear, coal and biomass have shown a marginal decrease while hydro, solar and wind have shown a marginal increase from 2002 to 2012. The limited range of SES index for the supply sub-system over a ten-year period, implies a ‘lock-in’ of infrastructure and technologies and the slow dynamics of the system. The value of the index which is around 0.75 during the entire period, quantifies the large gap between the current and the ideal desired state (SES index of 1.0). This gap may widen as the demand for energy grows, unless simultaneous actions are taken to build infrastructure and to increase the supply of sustainable energy sources.

A sensitivity analysis of indices to variation in weights is also undertaken. For measuring the availability dimension for domestic energy sources, three metrics are used. Six scenarios are developed by allotting different weights to the three metrics (AVL1-3). Scenarios are created by allocating minimum weight to one metrics, maximum weight to the second metric and the balance is allotted to the third metric. The availability index for coal is calculated by multiplying the scores with different weights for different scenarios (Table D.1-D.4).

Fig. 6-9 here

Figs. 6-9 shows the sensitivity of the availability index, affordability index and acceptability index to different weights allotted to the metrics of the respective dimensions (for selected energy sources for 2012). The range of weights for various scenarios, consolidated weights and the corresponding availability index obtained are also shown.

Fig. 10,11 here

Fig. 10 shows the percentage variation in weights (shown as deviation from the consolidated weights) allotted to different metrics by the respondents. Fig. 11 shows the sensitivity of dimensional indices to variation in weights (from the dimensional index obtained by using corresponding consolidated weights). 12 scenarios (Table D.5) are developed by allotting different weights to the four dimensions. Scenarios are created by allocating minimum weights to two metrics, maximum weight to one metric and the balance is allotted to the fourth metric. Fig. 12Figure 12. shows the range of weights and the variation in SES index for the supply sub-system for domestic coal and imported oil for the year 2012.

Fig. 12 here

Assessment of sensitivity analysis shows that although there is a large range of weights which are allotted to the metrics, the variation in dimensional indices is relatively small. Further, despite large variations in dimensional weights (-80% to +123% from the consolidated weights) the percentage change (from the index which is obtained when consolidated weights are used) in the supply sub-system SES index is within +/- 20 % in the case of domestic coal and within +/- 15 % for the case of imported oil. This implies that the supply sub-system SES index is relatively robust to variation in weights allotted to different dimensions and the index is suitable for monitoring the performance of India in attaining the goal of SES over time.

7. Conclusion and Policy Implications

This paper has undertaken an assessment of India's energy supply sub-system. The dimensional indices and SES index for various energy sources have been calculated for different years. The SES index for the supply sub-system has also been obtained and this quantitative assessment reveals key characteristics of the performance of the energy supply sub-system over time. Results show that although there are minor variations in the SES indices for various sources, the SES index for the supply sub-system is close to 0.75 during the considered period (2002 to 2012) and there is still a large scope for improvement. Sensitivity analysis reveals that the dimensional indices and the supply sub-system SES index are robust to variation in weights and the results of this assessment can be used with reasonable confidence.

Following are recommended based on the analysis of the obtained results:

(a) Increase share of renewable energy in the overall energy mix as the SES index of these sources is higher than domestic fossil fuel sources.

(b) SES index for import of nuclear fuel is much higher (0.9) than that of domestic nuclear fuel (0.4). Hence, continued efforts for procurement of imported nuclear fuel need to be undertaken.

(c) SES index for imported and domestic coal are almost similar and in the light of large coal reserves available in India, long term plans for increasing the supply of domestic coal need to be implemented. Policies for lowering the environmental impact from coal extraction and increasing the efficiency of coal extraction also needs to be formulated simultaneously.

(d) SES index for import of crude oil (0.8) is higher than that of domestic crude oil (0.5). Considering the poor endowment of crude oil resources, continued focus on procurement of imported crude needs to be maintained.

(e) Inadequate infrastructure, limited storage capacity and lower affordability of imported natural gas hints at moving away from imported sources. Appropriate policies for mapping, exploration and production of domestic sources of natural gas therefore need to be fast tracked and implemented aggressively.

The assessment of perceptions of interviewed experts gives insights into the relative importance of metrics and dimensions of SES which are perceived by the respondents. Affordability dimension emerges as the most important and acceptability dimension is perceived as least important. This explains the focus of the Indian government on providing affordable sources of energy even at the cost of the degradation of the environment.

The methodology used and the analysis provides a comprehensive assessment of the energy supply sub-system across all energy sources. A comparative assessment of domestic and imported energy sources gives new insights into the suitability of energy imports for different energy sources. The paper therefore builds a strong case for formulating appropriate policies to increase energy trade rather than following a one track approach of energy independence.

The simultaneous increase in SES index of some energy sources and decrease in other hint at the need for coordinated planning of energy policy using this index. Lack of targets was also apparent during the assessment and energy planners can set indicative targets to meet SES based objectives. The slow pace of change is apparent from the assessment and appropriate policy interventions such as accelerated transition mechanisms need to be adopted by policy makers if India has to meet its goal of SES in the near term.

Use of this index to evaluate the supply sub-system at a future point in time can also be undertaken by using the outputs of different energy models. Such an assessment might lead to results which require a reconsideration of the existing or forthcoming energy policies. Finally, regular use of the multidimensional SES index by policy makers in energy planning and monitoring activities may lead to increase in validity and impact of the index.

Acknowledgements

The authors wish to acknowledge the time and effort of the following participants of the survey who have contributed immensely by sharing their perceptions with the authors: Andrew H. Jeffries, Energy Head (India), Energy Division, Asian Development Bank, South Asia

Department; Dr Arunabha Ghosh, CEO, Council on Energy, Environment and Water (CEEW); Padma Bhushan Ambassador C Dasgupta, Distinguished Fellow, TERI; Padma Bhushan Dr. Kirit S. Parikh, Chairman, Integrated Research and Action for Development (IRADe); Ms. Madura Joshi, Associate Fellow and area convener at the 'Centre for Research on Energy Security', TERI; Dr. Navroz Dubash, Senior Fellow, Centre for Policy Research and; Dr. Ritu Mathur, Associate Director, Modelling & Economic Analysis Division, TERI.

References

- Blyth, W., Lefevre-Marton, N., 2005. Energy Security and Climate Change Policy Interactions-An Assessment Framework. Oil, Gas & Energy Law Journal (OGEL), 3(1).
- Bollen, J., 2008. Energy security, air pollution, and climate change: an integrated cost-benefit approach. MNP, Bilthoven.
- Doukas, H., Papadopoulou, A., Savvakis, N., Tsoutsos, T., Psarras, J., 2012. Assessing energy sustainability of rural communities using Principal Component Analysis. Renewable and Sustainable Energy Reviews, 16(4), 1949-1957.
- Fthenakis, V., Kim, H. C., 2009. Land use and electricity generation: A life-cycle analysis. Renewable and Sustainable Energy Reviews, 13, 1465-1474.
- Gerbens-Leenes, P. W., Hoekstra, A.Y., Meer, Th. H., 2008. Water footprint of bio-energy and other primary energy carriers, UNESCO-IHE Institute for Water Education.
- Gleick, P.H., 1994. Water and Energy, Annual Reviews, Annu. Rev. Energy Environ., 1994, 19:267-99.
- Gnansounou, E., 2008. Assessing the energy vulnerability: Case of industrialised countries. Energy Policy, 36(10), 3734-3744.

- IEA (International Energy Agency), 2007. Energy security and climate change-Assessing interactions. Paris: OECD/IEA.
- IEA (International Energy Agency), 2010. World Energy Outlook, 2010. Paris: OECD/IEA.
- IEA (International Energy Agency), 2015. World Energy Outlook 2015. Paris: OECD/IEA.
- IPCC Emission Factor data base, 2006. Retrieved from http://www.ipcc-nggip.iges.or.jp/EFDB/main.php
- Jewell, J., 2011. The IEA model of short-term energy security (MOSES).
- Le Coq, C., Paltseva, E., 2009. Measuring the security of external energy supply in the European Union. Energy Policy, 37(11), 4474-4481.
- Martchamadol, J., Kumar, S., 2013. An aggregated energy security performance indicator. Applied Energy, 103, 653-670.
- Mitchell, C., Watson, J., 2013. New Challenges in Energy Security, in: Mitchell, C., Watson, J., Whiting, J. (Eds.), New Challenges in Energy Security. Basingstoke: Palgrave Macmillan, New York, pp.238–257.
- Narula, K., 2014. Is sustainable energy security of India increasing or decreasing? International Journal of Sustainable Energy, 33(6), 1054-1075.
- Narula, K., Reddy, B. S., 2016. A SES (sustainable energy security) index for developing countries. Energy, 94, 326-343.
- REACCESS (Risk of Energy Availability: Common Corridors For European Security of Supply), 2011. Quantification of Socioeconomic Risk & Proposal for an Index of Security of Energy Supply. Madrid: Universidad Nacional de Educación a Distancia.

- Scheepers, M., Seebregts, A., de Jong, J., Maters, H., 2007. EU standards for energy security of supply. Gas, 52, 67-5.
- Sreenivas, A., Iyer, R. K., 2014. A comprehensive, multi-dimensional energy index for India. Prayas Energy Group, Pune.
- Tongsopit, S., Kittner, N., Chang, Y., Aksornkij, A., Wangjiraniran, W., 2016. Energy security in ASEAN: A quantitative approach for sustainable energy policy. Energy Policy, 90, 60-72.
- Yao, L., Chang, Y., 2014. Energy security in China: A quantitative analysis and policy implications. Energy Policy 67, 595–604.

List of figures

List of tables

Table D.1. Scenarios for weights to metrics and AVL Index

Table D.2. Scenarios for weights to metrics and AVL Index (Oil, 2012)

Table D.3. Scenarios for weights to metrics and AFF Index (Oil, 2012)

Table D.4. Scenarios for weights to metrics and ACP Index (Coal, 2012)

Table D.5. Scenarios for weights to dimensions

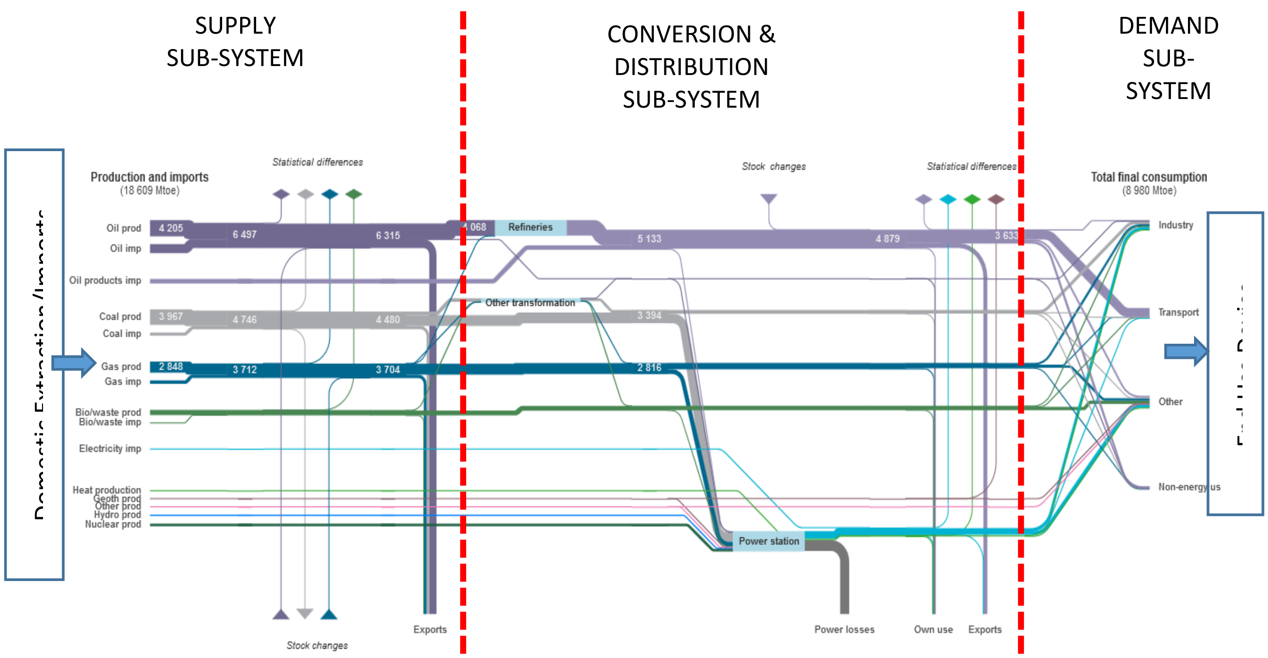

Figure 1. Boundaries of energy system for assessment of SES

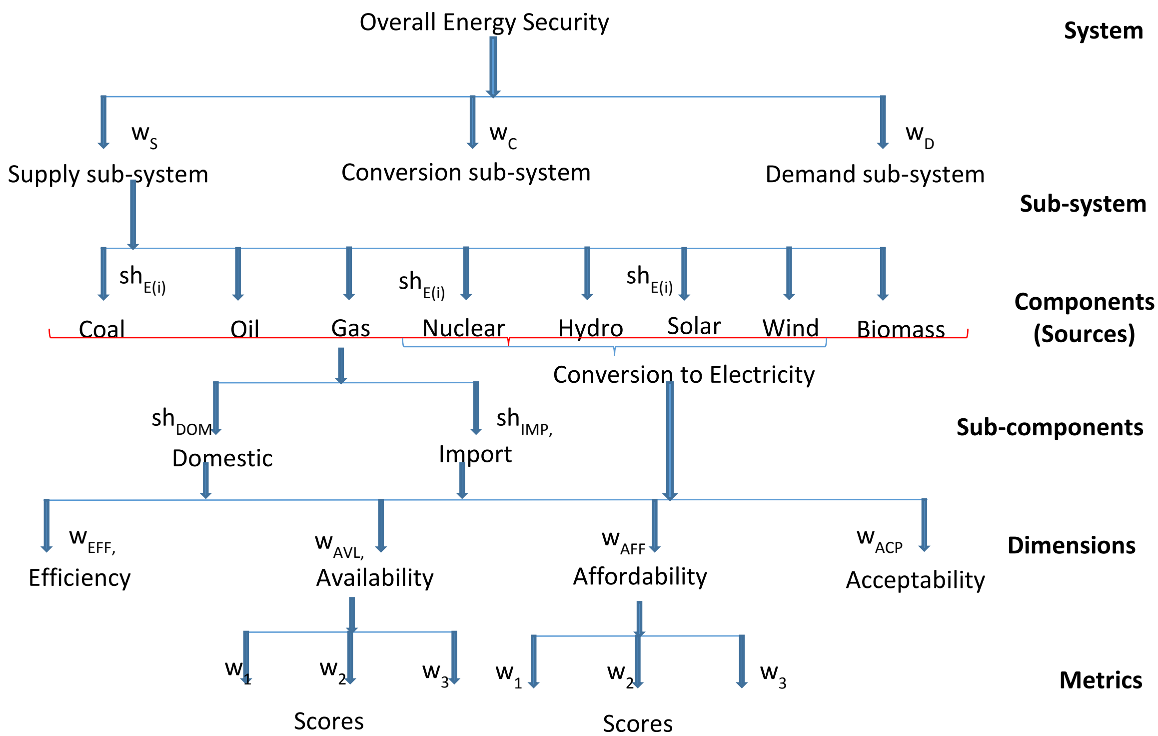

Figure 2a. Framework for assessment of SES

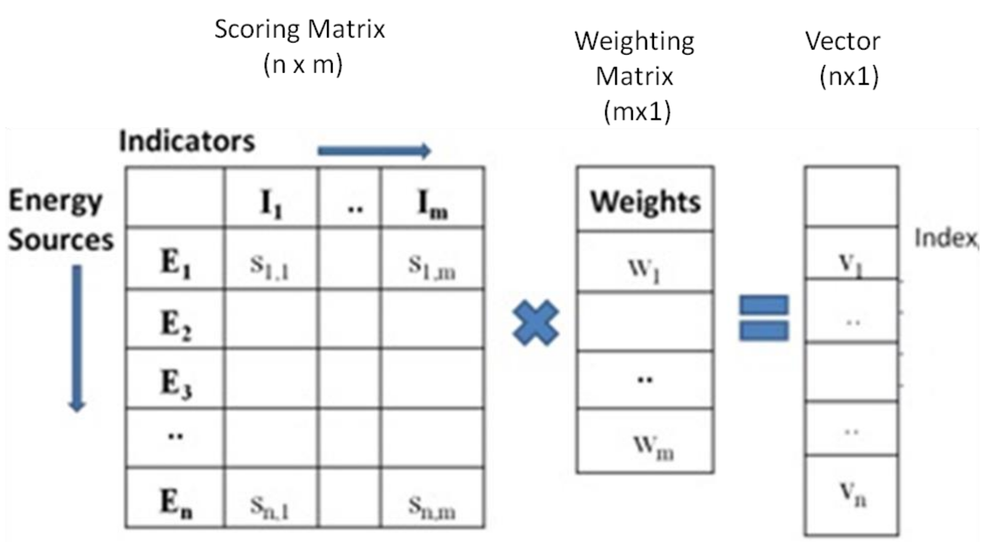

Figure 2. Model for constructing an index

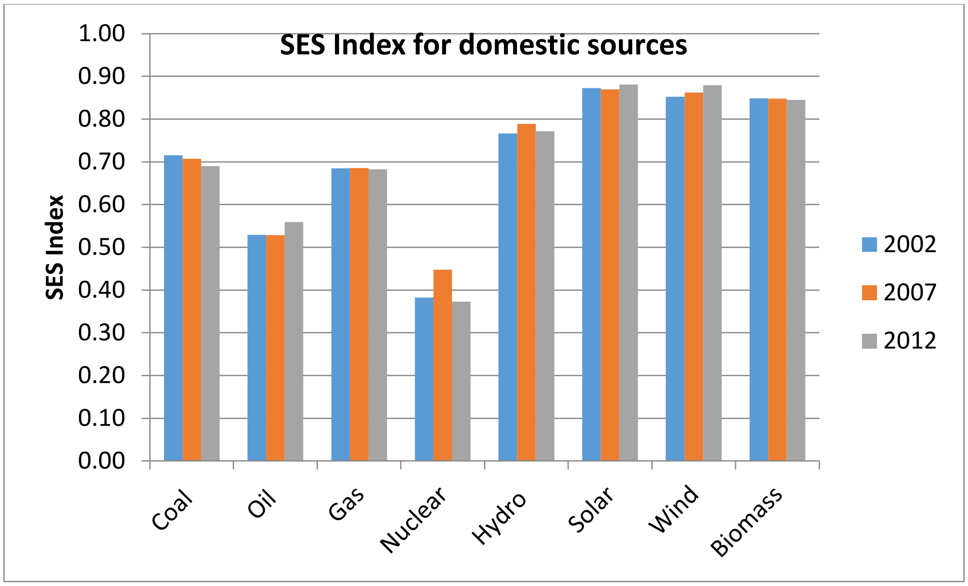

Figure 3 SES index for domestic sources

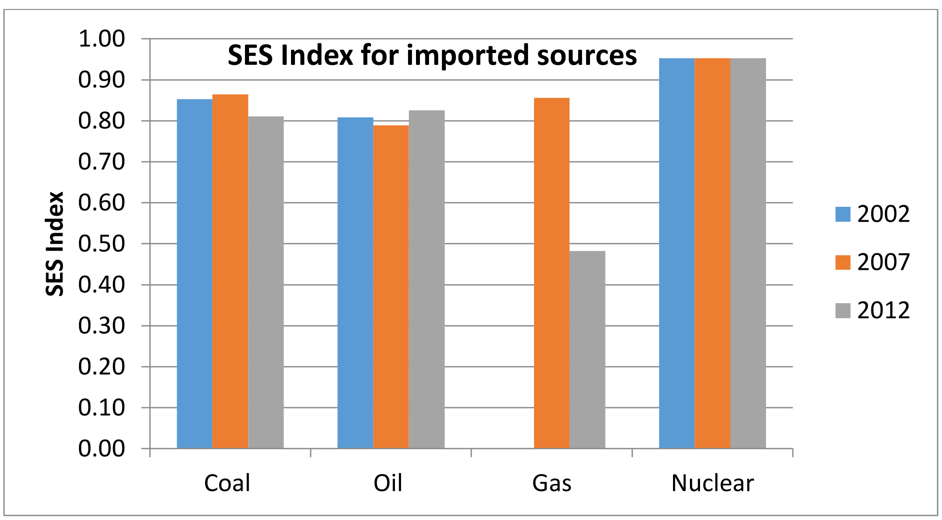

Figure 4. SES index for imported sources

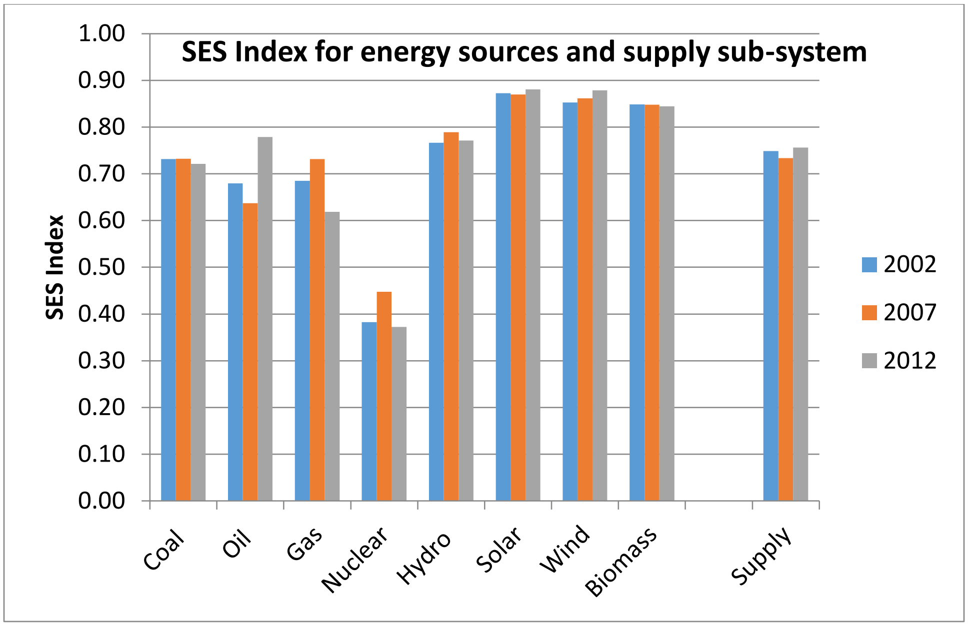

Figure 5. SES index for energy sources and supply sub-system index

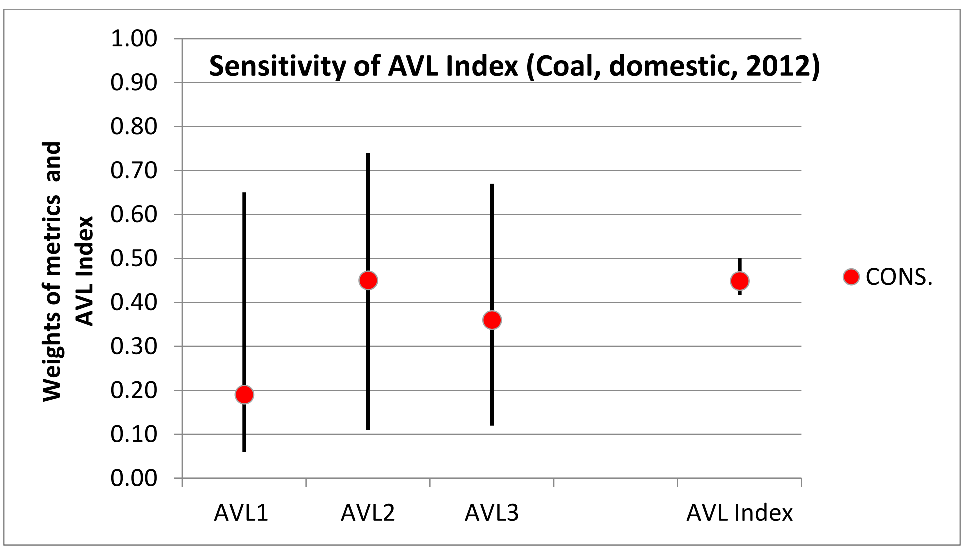

Figure 6. Sensitivity of availability index (domestic)

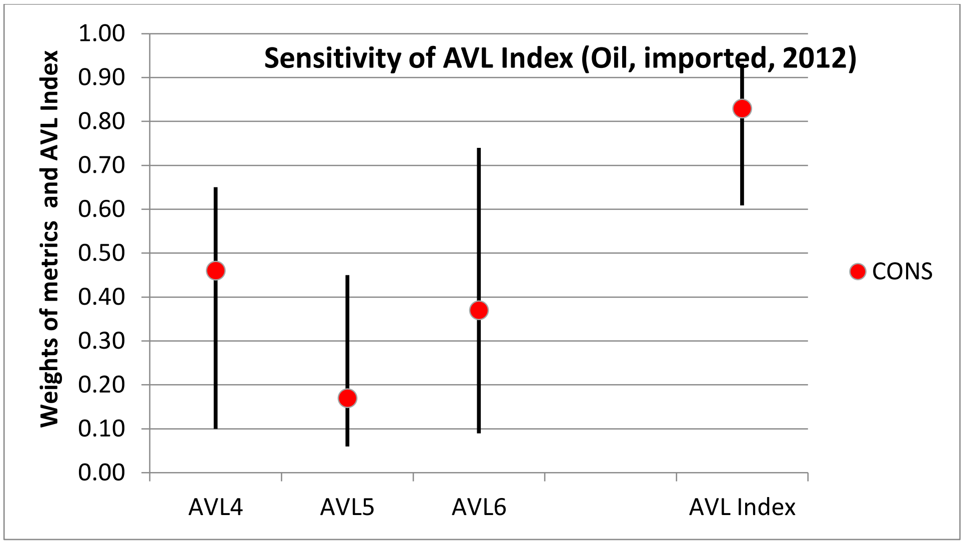

Figure 7. Sensitivity of availability index (imports)

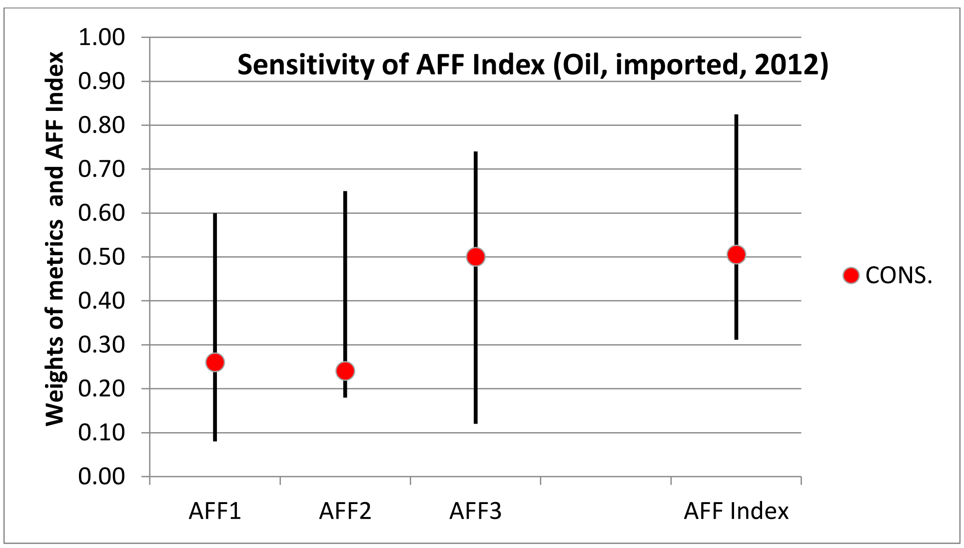

Figure 8. Sensitivity of affordability index

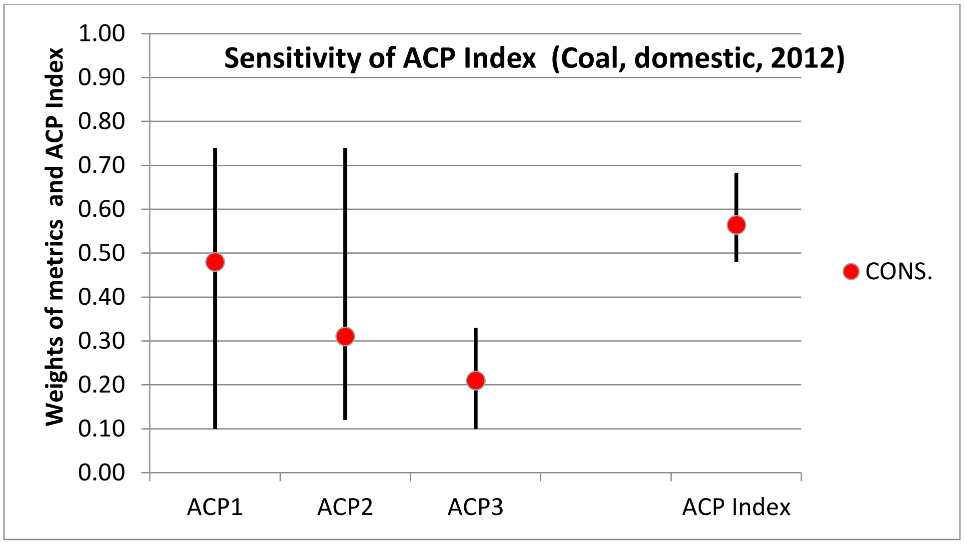

Figure 9. Sensitivity of acceptability index

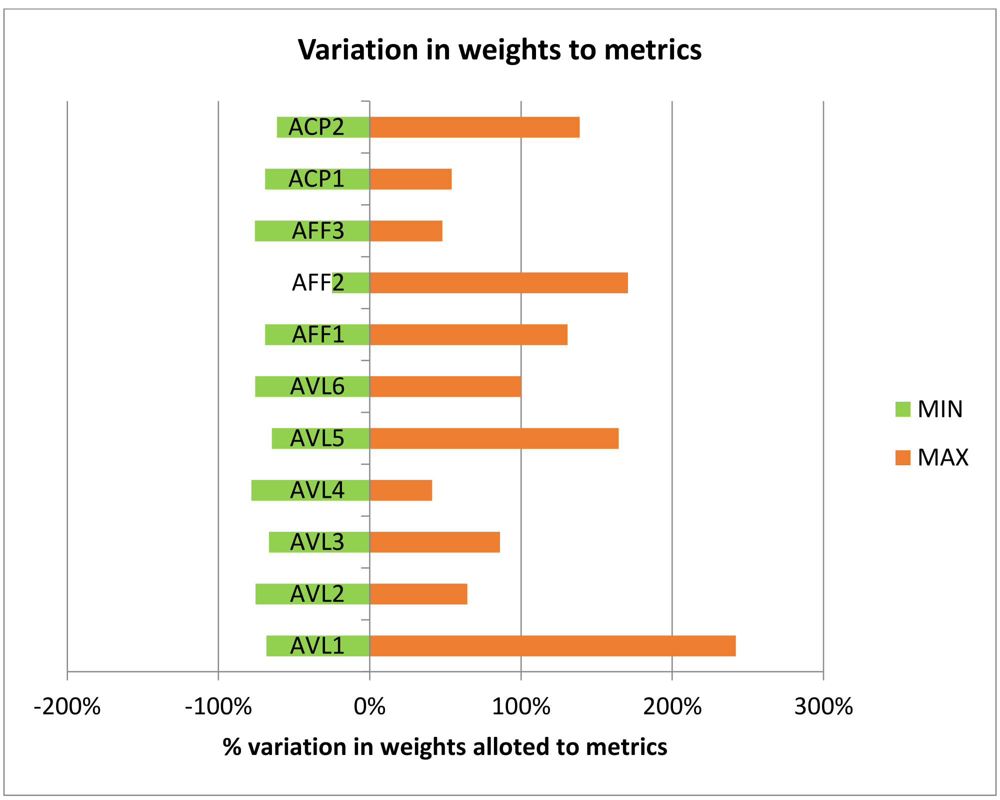

Figure 10. Variation in weights allotted to different metrics

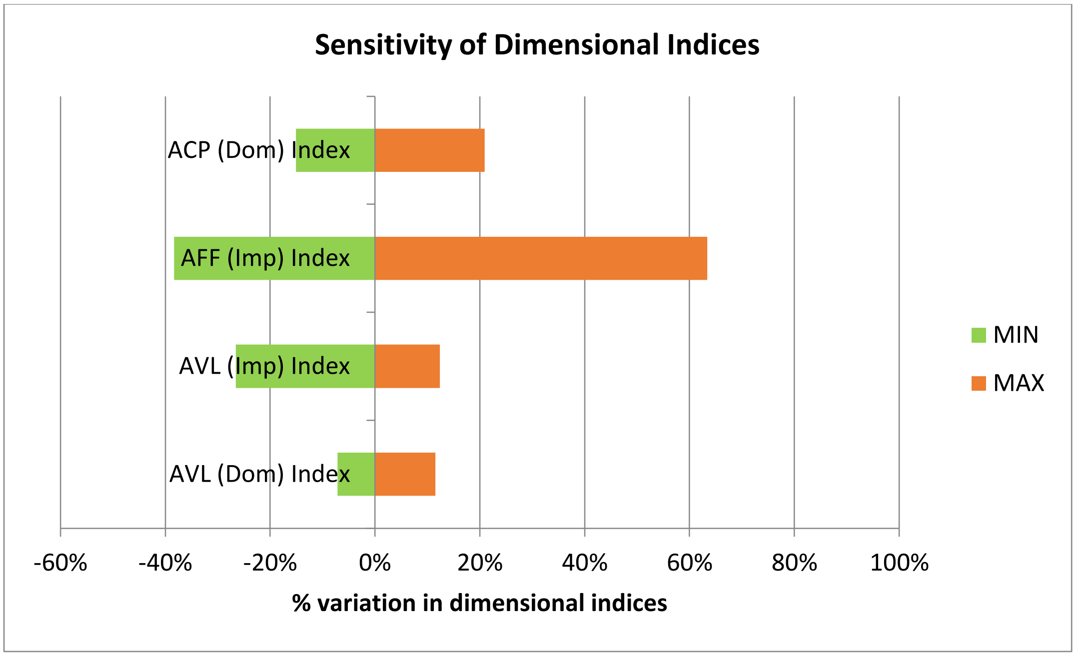

Figure 11. Sensitivity of dimensional indices to variation in metric weights

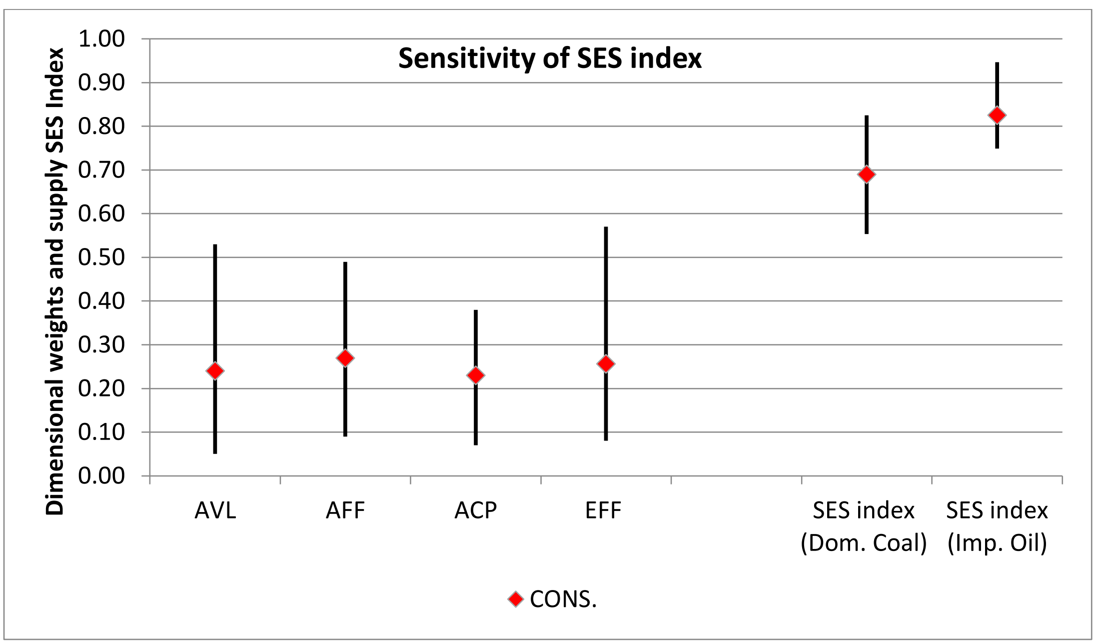

Figure 12. Variation in dimensional weights and SES index

Table 1. Emission factors during energy extraction

GHG emissions during extraction of	Kg/PJ
Coal	57477
Natural gas	67795
Crude oil	2480
Uranium	12000
Harnessing of solar, wind, hydro	0
Biomass*	0
*Biomass absorbs CO_2 during the growth stage and releases embodied CO_2 when used as an energy source. Hence it can be considered as a net zero emitter	

Source: IPCC database (2006)

Table 2. Scores for metric ACP1 for various sources

	Range	Median estimate	Score
Primary energy	m^3/GJ	m^3/GJ	
Coal	0.006 - 0.242	0.043	0.61
Conventional oil	0.036- 0.14	0.081	0.27
Conventional gas	0.001-0.027	0.004	0.96
Uranium[a]	0.049 - 0.345	0.111	0.00
Biomass	156-844	0[b]	1.00
Wind	0.001	0	1.00
Solar PV	0.027	0.006	0.95
Hydro	5-26 $m^3/10^3$ kWh(electric)	0[c]	1.00
Min		0	
Max		0.111	

[a]: Including mining, milling, conversion, fuel enrichment, fuel fabrication and fuel reprocessing

[b]: It is assumed that biomass does not require any special watering as it is not cultivated for use as fuel

[c]: It is assumed that there are other benefits of dams such as flood control and water used for irrigation. Hence water loss from storage is not attributed to electricity generated from hydro power

Source: Gerbens-Leenes *et al.*, (2008)

Table 3. Scores for metric ACP2 for various sources

	Avg. values	Log (Avg. value)	Score
Primary energy type	m^2/GWh		
Coal	800[a]	2.9	0.77
Conventional oil	200[b]	2.3	0.93
Conventional gas	195	2.29	0.94
Uranium	114	2.06	0.00
Biomass	5,41,516[c]	5.73	1.00
Wind	2000	3.3	0.85
Solar PV	400	2.60	0.66
Hydro	3000	3.48	0.61
Min		2.06	
Max		5.73	

[a]: Average assumed on the basis of seam thickness and share of surface mining.
[b]: Value for oil is NA. A value close to natural gas value is taken
[c]: Value corresponds to an average of 150m^2/GJ

Source: Fthenakis and Kim (2009)

Table 4. Benchmarks, values and scores for domestic coal

Metric	Unit	Benchmark			Value			Score		
		High	Low	Range	2002	2007	2012	2002	2007	2012
AVL 1a	tonnes/capita	122	0	122	78[a]	49	49	0.64[b]	0.40	0.40
AVL 2	toe/capita	0.55	0	0.55	0.15	0.18	0.21	0.27	0.33	0.39
AVL 3	%	100	50	50	93.53	91.05	77.58	0.87	0.82	0.55
ACP 1	m^3/GJ	0.11	0.00	0.11	0.04	0.04	0.04	0.61	0.61	0.61
ACP 2	m^2/GWh	5.73	2.06	3.68	2.90	2.90	2.90	0.77	0.77	0.77
ACP 3	kg/PJ	67795	0	67795	57477	57477	57477	0.15	0.15	0.15
EFF1a	%	95	50	45	81.50	81.50	81.50	0.81	0.81	0.81

[a]: This value is inconsistent with later years
[b]: This score is higher as the value is inconsistent with later years and may be interpreted in that light
[c]: Value corresponds to an average of 150m^2/GJ

Table 5. Benchmarks, values and scores for imported coal

Metric	Unit	Benchmark			Value			Score		
		High	Low	Range	2002	2007	2012	2002	2007	2012
AVL 4	-	10000	0	10000	896	2046	2408	0.91	0.80	0.76
AVL 5	days	45	0	45	335	388	270	1.00	1.00	1.00
AVL 6	%	20%	0%	20%	No data	15.11%	1.70%	0.76[a]	0.76	0.09
AFF1	Rs./MT	2002: No data 2007: 1170.71 2012: 2411.20	0	2002: No data 2007: 1170.71 2012: 2411.20	2207.32	3873.77	7665.08	0.30[b]	0.30	0.31
AFF2	-	2002: 0.06 2007: 0.11 2012: 0.19	0.00	2002: 0.06 2007: 0.11 2012: 0.19	0.09	0.06	0.04	0.00	0.45	0.80
AFF3	%	1%	0%	1%	0.02%	0.05%	0.15%	0.98	0.95	0.85

[a]: No data is available for 2002 for this metric. Hence score obtained for 2007 is allotted
[b]: No data is available for 2002 for this metric. Hence score obtained for 2007 is allotted

Table 6. Benchmarks, values and scores for domestic crude oil

Metric	Unit	Benchmark			Value			Score		
		High	Low	Range	2002	2007	2012	2002	2007	2012
AVL 1a	barrels/capita	238	0	238	5.18	4.71	4.61	0.02	0.02	0.02
AVL 2	tonnes/capita	581.55	0	581.55	35.66	34.08	35.01	0.06	0.06	0.06
AVL 3	%	100	50	50	No Data	82.65	109.59	0.65[a]	0.65	1.00
ACP 1	m^3/GJ	0.11	0.00	0.11	0.08	0.08	0.08	0.27	0.27	0.27
ACP 2	m^2/GWh	5.73	2.06	3.68	2.30	2.30	2.30	0.93	0.93	0.93
ACP 3	kg/PJ	67795	0	67795	2480.00	2480.00	2480.00	0.96	0.96	0.96
EFF1a	%	70.00	20.00	50	30.00	30.00	30.00	0.20	0.20	0.20

[a]: No data is available for 2002 for this metric. Hence score obtained for 2007 is allotted

Table 7. Benchmarks, values and scores for imported crude oil

Metric	Unit	Benchmarks			Value			Score		
		High	Low	Range	2002	2007	2012	2002	2007	2012
AVL 4	-	10000	0	10000	717	853	707	0.93	0.91	0.93
AVL 5	days	90	0	90	15	28	18	0.17	0.31	0.20
AVL 6	%	20	0	20	No data	12.81	19.82	0.64[a]	0.64	0.99
AFF1	Rs./MT	2002: 5570 2007: 16725 2012: 42293	0	2002: 5570 2007: 16725 2012: 42293	7881	20726	39302	0.71	0.81	1.00
AFF2	-	2002: 0.12 2007: 0.10 2012: 0.18	0.00	2002: 0.12 2007: 0.10 2012: 0.18	0.14	0.09	0.05	0	0.07	0.75
AFF3	%	10	0	10	2.40	5.02	8.69	0.76	0.50	0.13

[a]: No data is available for 2002 for this metric. Hence score obtained for 2007 is allotted

Table 8. Benchmarks, values and scores for domestic natural gas

Metric	Unit	Benchmark			Value			Score		
		High	Low	Range	2002	2007	2012	2002	2007	2012
AVL 1a	cu.mt./capita	26173	0	26173	697.23	910.19	1075.65	0.03	0.03	0.04
AVL 2	kgoe/capita	426.08	0	426.08	23.40	22.52	26.93	0.05	0.05	0.06
AVL 3	%	100	50	50	No imports	89.09	86.53	NA	0.78	0.73
ACP 1	m^3/GJ	0.11	0.00	0.11	0.00	0.00	0.00	0.96	0.96	0.96
ACP 2	m^2/GWh	5.73	2.06	3.68	2.29	2.29	2.29	0.94	0.94	0.94
ACP 3	kg/PJ	67795	0	67795	67795	67795	67795	0.00	0.00	0.00
EFF1a	%	100	30	70	75	75	75	0.64	0.64	0.64

Table 9. Benchmarks, values and scores for imported natural gas

Metric	Unit	Benchmark			Value			Score		
		High	Low	Range	2002	2007	2012	2002	2007	2012
AVL 4	-	10000	0	10000	No imports	1250	615	NA	0.87	0.94
AVL 5	days	45	0	45	No imports	No data	17.83	NA	0.40[a]	0.40
AVL 6	%	20	0	20	No imports	No data	-0.03[c]	NA	0.0[b]	0.0
AFF1[d]	Rs./ ‘000 cu.mt.	2002: No imports 2007: 3200 2012: 8387	0	2002: No imports 2007: 3200 2012: 8387	NA	61004	176495	NA	0.05	0.0
AFF2	-	2002: 0.07 2007: 0.05 2012: 0.10	0.00	2002: 0.07 2007: 0.05 2012: 0.10	NA	0.03	0.08	NA	0.35	0.21
AFF3	%	1	0	1	NA	0.16	0.39	NA	0.84	0.61

[a]: No data is available for 2007 for this metric. Hence score obtained for 2012 is allotted
[b]: No data is available for 2007 for this metric. Hence score obtained for 2012 is allotted
[c]: Quantity of imports was higher than the capacity
[d]: There is a large differential in price as the domestic prices are for natural gas, while import prices are for LNG

Table 10. Benchmarks, values and scores for domestic nuclear

Metric	Unit	Benchmark			Value			Score		
		High	Low	Range	2002	2007	2012	2002	2007	2012
AVL 1a	kW/cap	1	0	1	0.10	0.09	0.08	0.10	0.09	0.08
AVL 2	kWh/cap	349.49	0	349.49	18.01	14.63	26.58	0.05	0.04	0.08
AVL 3	%	100	50	50	56.25	90.77	27.85	0.13	0.82	0.00
ACP 1	m^3/GJ	0.11	0.00	0.11	0.11	0.11	0.11	0.0	0.0	0.0
ACP 2	m^2/GWh	5.73	2.06	3.68	2.06	2.06	2.06	1.00	1.00	1.00
ACP 3	kg/PJ	67795	0	67795	12000	12000	12000	0.82	0.82	0.82
EFF1a	%	2.00	0.00	2	0.06	0.06	0.06	0.03	0.03	0.03
EFF1b*	%	36	33	3	No data	No data	No data	1.00	1.00	1.00

*: Values for thermal efficiency of nuclear power plants are not available. These are assumed to be at par with the world and a score of 1 is assumed

Table 11. Benchmarks, values and scores for imported nuclear

Metric	Unit	Benchmark			Value			Score[a]		
		High	Low	Range	2002	2007	2012	2002	2007	2012
AVL 4	-	10000	0	10000	No data	No data	2225	0.78	0.78	0.78
AVL 5	days	90	0	90	No data	No data	483.34	1.00	1.00	1.00
AVL 6	%	20	0	20	20	20	20	1.00	1.00	1.00
AFF1	US$/ kg	2002: No data 2007: No data 2012: 156	0	2002: No data 2007: No data 2012: 156	No data	No data	130.00	1.00	1.00	1.00
AFF2	-	2002: No data 2007: No data 2012: 0.10	0.00	2002: No data 2007: No data 2012: 0.10	No data	No data	0.04	0.65	0.65	0.65
AFF3[b]	%	1%	0	1	No data	No data	0.00	1.00	1.00	1.00

[a]: Scores for 2012 are allotted to 2007 and 2002 due to lack of data
[b]: Although no data is available for 2002 and 2007, the value of imports will be negligible as compared to the GDP and a score of 1 is assumed for those years

Table 12. Benchmarks, values and scores for hydro

Metric	Unit	Benchmark			Value			Score		
		High	Low	Range	2002	2007	2012	2002	2007	2012
AVL 1b	kW/ capita	0.24	0	0.24	0.11	0.10	0.09	0.45	0.42	0.39
AVL 2	kWh/ capita	0.52	0	0.52	0.06	0.11	0.10	0.12	0.21	0.20
AVL 3	%	100	50	50	46.95	58.26	27.83	0.00	0.17	0.00
ACP 1	m^3/GJ	0.11	0.00	0.11	0.00	0.00	0.00	1.00	1.00	1.00
ACP 2	m^2/GWh	5.73	2.06	3.68	3.48	3.48	3.48	0.61	0.61	0.61
ACP 3	kg/PJ	67795	0	67795	0.00	0.00	0.00	1.00	1.00	1.00
EFF1b	%	95	90	5	-	-	-	1.00	1.00	1.00

Table 13. Benchmarks, values and scores for solar

Metric	Unit	Benchmark			Value			Score		
		High	Low	Range	2002	2007	2012	2002	2007	2012
AVL 1b	kW/ capita	0.08	0	0.08	0.08	0.07	0.07	0.93	0.87	0.81
AVL 2	kWh/ capita	13.29	0	13.29	0.00	0.05	1.70	0.00	0.00	0.13
AVL 3	%	100	50	50	NA	NA	112.29	NA	NA	1.00
ACP 1	m^3/GJ	0.11	0.00	0.11	0.01	0.01	0.01	0.95	0.95	0.95
ACP 2	m^2/GWh	5.73	2.06	3.68	2.60	2.60	2.60	0.85	0.85	0.85
ACP 3	kg/PJ	67795	0	67795	0.00	0.00	0.00	1.00	1.00	1.00
EFF1b	%	20.00	15.00	5	-	-	-	1.00	1.00	1.00

Table 14. Benchmarks, values and scores for wind

Metric	Unit	Benchmark			Value			Score		
		High	Low	Range	2002	2007	2012	2002	2007	2012
AVL 1b	kW/ capita	0.16	0	0.16	0.09	0.08	0.08	0.58	0.54	0.51
AVL 2	kWh/ capita	73.75	0	73.75	2.50	10.18	22.87	0.03	0.14	0.31
AVL 3[a]	%	100	50	50	No data	No data	105.12	1.00	1.00	1.00
ACP 1	m^3/GJ	0.11	0.00	0.11	0.00	0.00	0.00	1.00	1.00	1.00
ACP 2	m^2/GWh	5.73	2.06	3.68	3.30	3.30	3.30	0.66	0.66	0.66
ACP 3	kg/PJ	67795	0	67795	0.00	0.00	0.00	1.00	1.00	1.00
EFF1b	%	40.00	35.00	5	-	-	-	1.00	1.00	1.00

[a]: No data is available for 2002 and 2007. Considering that the growth of the wind sector has been robust the score of 2012 is allotted to these years

Table 15. Benchmarks, values and scores for biomass

Metric	Unit	Benchmark			Value			Score		
		High	Low	Range	2002	2007	2012	2002	2007	2012
AVL 1b*	GJ/capita	-	-	-	-	-	-	1.00	1.00	1.00
AVL 2	toe/capita	0.19	0	0.19	0.14	0.14	0.15	0.26	0.25	0.22
AVL 3	100%	50%	50%	%	100%	100%	100%	1.00	1.00	1.00
ACP 1	m^3/GJ	0.11	0.00	0.11	0.00	0.00	0.00	1.00	1.00	1.00
ACP 2	m^2/GWh	5.73	2.06	3.68	5.73	5.73	5.73	0.00	0.00	0.00
ACP 3	kg/PJ	67795	0	67795	0.00	0.00	0.00	1.00	1.00	1.00
EFF1b	%	100.00%	90.00%	10%	-	-	-	1.00	1.00	1.00

[*]: Resource potential of biomass for the world and for India for direct energy use is not estimated. However, it is assumed that India has sufficient biomass which is comparable to the world average and a score of 1 is allotted to the metric for all years

Table 16. Weights obtained for different metrics

Dimension	Metric	Min weight	Max weight	Consolidated Weight
Availability (Domestic)	AVL1	0.06	0.65	0.19
	AVL2	0.11	0.74	0.45
	AVL3	0.12	0.67	0.36
Availability (Imports)	AVL4	0.10	0.65	0.46
	AVL5	0.06	0.45	0.17
	AVL6	0.09	0.74	0.37
Affordability (Imports)	AFF1	0.08	0.6	0.26
	AFF2	0.18	0.65	0.24
	AFF3	0.12	0.74	0.50
Acceptability (Domestic)	ACP1	0.10	0.74	0.48
	ACP2	0.12	0.74	0.31
	ACP3	0.10	0.33	0.21

Table 17. Weights obtained for different dimensions

Dimension	Min weight (%)	Max weight (%)	Consolidated Weight (%)
Availability	5	53	24
Affordability	9	49	27
Acceptability	7	38	23
Efficiency	8	57	26

Appendix A. Metrics for energy supply sub-system system

Sub-compnts/ Dimen.	Category/ Sub-category	Name	Metric	Variables	Unit	Benchmark	Desirable Values
Domestic/ AVL	Geological availability in country	AVL 1a	Per Capita Domestic reserves	Estimate of (proven) reserves of primary energy available in country/Population	Energy unit /cap	Estimate of (proven) reserves of primary energy available in the world/ world population	High
		AVL 1b	Per Capita estimated resource potential of (renewable) energy	Estimated potential for electricity generation per year /Population	kWh/cap/ yr	Estimated potential for electricity generation per year in the world/ world population	High
	Production	AVL 2	Per capita domestic supply of primary energy	Primary energy supply/total population	Energy unit/ cap	Supply of primary energy in the world/ world population	High
	Supply capability	AVL 3	Achievement in meeting planned target of domestic energy supply (OR) installed electricity capacity	Actual domestic energy supply (annual/five-year plan)	%	Planned target (annual/five-year plan) 100% :1 50% tgt met : 0	High
Imports/ AVL	Lower risk of energy import disruption	AVL 4	Herfindahl Hirschman Index (HHI) for diversification of energy supplying countries[a] corrected for political risk of country	$\sum(S_i)^2$ x $(100-r_i)/100$; Where S_i is share of each supplier country in total imports of a particular energy source; 'r_i' is the political risk rating of the country [b]	-	10,000 (1 country): Min value 0 0 (many countries, tending to infinite): Max value 1	Low
	Resilience to supply disruption	AVL 5	Number of days of stocks as a % of net imports	(Storage capacity [c]/ annual imports) x 365	days	Coal: 45 Crude oil, Uranium:90 Natural Gas:45	High
	Adequate port infrastructure for import	AVL 6	% of excess port capacity for import of energy	(Total port capacity- actual port traffic)/ Actual port traffic (for a year)	%	20% excess: Max 0% excess: Min	High
Imports/ AFF	Cost of primary energy	AFF 1[d]	Average per unit import cost of primary energy (without taxes, duties and levies)	(Value of energy import/ Qty of energy imports)	-	Average per unit extraction cost of domestic energy	High

						(without taxes, duties and levies) Domestic cost: Max 0 cost : Min	
	Volatility in price	AFF 2	Coefficient of Variation (CV) in international spot price of primary energy	(Standard Deviation / Mean) of international spot price of energy	-	Average coefficient of Variation (CV) in international spot price for last five years Historical CV: Max 0 CV : Min	Low
	Macro-Economic Affordability	AFF 3	Energy import bill as a percentage of GDP	Value of energy imports/GDP	%	1% for coal, gas and nuclear; 10% for crude oil: Max 0%: Min	Low
ACP	Resource use/ Water use	AC P1	Water consumption[e] for energy production	Estimate of water consumed per unit energy extracted (extraction and pre-processing)	m^3/GJ	Relative among sources Max. among various sources: Max 0: Min	Low
	Resource use/ Land use	ACP2	Land used for energy extraction	Direct land use per unit energy extracted (incl. pre-processing)	m^2/GWh	Relative among sources Log (Max. among various sources): Max Log (Min. among various sources): Min	Low
	Waste generation/ Air emissions	ACP 3	GHG[f] (methane) emission factors for primary energy extraction	Average emission of GHG (methane) per unit energy extracted	Kg methane /PJ	Relative among sources Max. among various sources: Max 0: Min	Low
Domestic / EFF	Extraction efficiency	EFF 1a	Recovery factor of primary energy	Estimate of recoverable energy/Estimate of energy in place	%	Range: (Min-Max) Coal: 50-95% Crude oil: 20-70% N Gas:30-100% Uranium: 0-2% Biomass: 90-100%	High
	Resource efficiency	EFF 1b	Technical efficiency of conversion to electricity	Estimate of electric energy output/primary energy input	%	Range: Min-Max Hydro:90-95% Solar: 15-20% Wind: 35-40%	High

Imports/ EFF	Supply efficiency	EFF 1c	Supply efficiency of primary energy imports	Assumed as 100% for imported fossil fuels as all energy is usable	%	100%	High

[a]: No. of countries taken are such that they account for more than 85% of total imports
[b]: 'r_i' represents the political risk of the country. The percentile rank obtained by various countries in 'political stability and absence of violence' dimension is used as a proxy variable. It is one of the six dimensions of governance used in the Worldwide Governance Indicators (WGI) project.
[c]: It is assumed that storage capacity is full at all times.
[d]: As imported cost of energy is often greater than domestic cost of energy, this metric is inverted to fall in the range of 0-1.
[e]: Water consumption implies water which is removed from the immediate water environment
[f]: Other GHG such as CO_2 etc. are neglected

Appendix B.

Table B.1. Judgment matrix [A] for different participants

Consolidated				P1			
	AVL1	AVL2	AVL3		AVL1	AVL2	AVL3
AVL1	1	0.4	0.5	AVL1	1	3	5
AVL2	2 1/3	1	1.3	AVL2	1/3	1	3
AVL3	2	7/9	1	AVL3	1/5	1/3	1
P2				P3			
	AVL1	AVL2	AVL3		AVL1	AVL2	AVL3
AVL1	1	5	3	AVL1	1	1/5	1/7
AVL2	1/5	1	1/5	AVL2	5	1	1/3
AVL3	1/3	5	1	AVL3	7	3	1
P4				P5			
	AVL1	AVL2	AVL3		AVL1	AVL2	AVL3
AVL1	1	1/7	1/3	AVL1	1	1/7	1/9
AVL2	7	1	5	AVL2	7	1	1
AVL3	3	1/5	1	AVL3	9	1	1
P6				P7			
	AVL1	AVL2	AVL3		AVL1	AVL2	AVL3
AVL1	1	1/5	1/4	AVL1	1	1/5	1/3
AVL2	5	1	2	AVL2	5	1	3
AVL3	4	1/2	1	AVL3	3	1/3	1
P1-P7: Participant 1 to 7 (Individual responses by name have not been indicated) AVL 1-3: Refer Table A.1 for specific metrics							

Appendix C.

Table C.1. Normalised matrix and iterations

Normalization	Normalized matrix			Normalized principal Eigenvector	
				1st iteration	3rd iteration
R1	0.18	0.19	0.18	18%	19%
R2	0.44	0.45	0.46	45%	45%
R3	0.38	0.35	0.36	36%	36%
				EV	Difference (between successive EVs)
1st iteration	0.185	0.185	0.185	18.51%	6.5E-04
	0.455	0.455	0.455	45.51%	3.1E-03
	0.36	0.36	0.36	35.98%	-3.7E-03
2nd iteration	0.185	0.185	0.185	18.51%	5.8E-05
	0.455	0.455	0.455	45.50%	-4.9E-05
	0.36	0.36	0.36	35.98%	-9.0E-06
3rd iteration	0.185	0.185	0.185	18.51%	-2.3E-08
	0.455	0.455	0.455	45.50%	2.0E-08
	0.36	0.36	0.36	35.98%	3.0E-09

The final allotted weights for AVL1, AVL2, AVL3 are 19, 45, and 36% respectively.

Appendix D

Table D.1. Scenarios for weights to metrics and AVL Index

	Scenarios for weights to metrics			Actual weights to metrics			AVL Index (Coal, domestic,2012)
Scenario	AVL1	AVL2	AVL3	AVL1	AVL2	AVL3	
Sc 1	Min	Max		6	74	20	0.4202
Sc 2	Min		Max	6	27	67	0.4980
Sc 3	Max	Min		65	11	24	0.4368
Sc 4		Min	Max	22	11	67	0.5006
Sc 5		Max	Min	14	74	12	0.4083
Sc 6	Max		Min	65	23	12	0.4169
Cons. Value				19	45	36	0.4489

Table D.2. Scenarios for weights to metrics and AVL Index (Oil, 2012)

	Scenarios for weights to metrics			Actual weights to metrics			AVL Index
Scenario	AVL1	AVL2	AVL3	AVL1	AVL2	AVL3	(Oil, imported, 2012)
Sc 1	Min	Max		10	45	45	0.6311
Sc 2	Min		Max	10	16	74	0.8590
Sc 3	Max	Min		65	6	29	0.9037
Sc 4		Min	Max	20	6	74	0.9315
Sc 5		Max	Min	46	45	9	0.6089
Sc 6	Max		Min	65	26	9	0.7466
Cons. Value				46	17	37	0.8290

Table D.3. Scenarios for weights to metrics and AFF Index (Oil, 2012)

	Scenarios for weights to metrics			Actual weights to metrics			AFF Index (Oil, imported, 2012)
Scenarios	AFF1	AFF2	AFF3	AFF1	AFF2	AFF3	
Sc 1	Min	Max		8	65	27	0.6011
Sc 2	Min		Max	8	18	74	0.3115
Sc 3	Max	Min		60	18	22	0.7633
Sc 4		Min	Max	8	18	74	0.3115
Sc 5		Max	Min	23	65	12	0.7315
Sc 6	Max		Min	60	28	12	0.8250
Cons. Value				26	24	50	0.5049

Table D.4. Scenarios for weights to metrics and ACP Index (Coal, 2012)

	Scenarios for weights to metrics			Actual weights to metrics			ACP Index (Coal, domestic, 2012)
Scenarios	AFF1	AFF2	AFF3	AFF1	AFF2	AFF3	
Sc 1	Min	Max		10	74	16	0.6553
Sc 2	Min		Max	10	57	33	0.5503
Sc 3	Max	Min		74	12	14	0.5670
Sc 4		Min	Max	55	12	33	0.4795
Sc 5		Max	Min	16	74	10	0.6829
Sc 6	Max		Min	74	16	10	0.5917
Cons. Value				48	31	21	0.5647

Table D.5. Scenarios for weights to dimensions

	Scenarios for weights to dimensions				Actual weights to dimensions				SES Index (domestic coal, 2012)
Scenarios	AVL	AFF	ACP	EFF	AVL	AFF	ACP	EFF	
Sc 1	Min	Min	Max		5	9	38	48	0.6630
Sc 2	Min	Min		Max	5	9	29	57	0.6752
Sc 3	Min	Max	Min		5	49	7	39	0.8250
Sc 4	Min		Min	Max	5	31	7	57	0.7710
Sc 5	Min	Max		Min	5	49	38	8	0.7830
Sc 6	Min		Max	Min	5	49	38	8	0.7830
Sc 7	Max	Min	Min		53	9	7	31	0.5844
Sc 8	Max		Min	Min	53	32	7	8	0.6534
Sc 9	Max	Min		Min	53	9	30	8	0.5533
Sc 10		Min	Min	Max	27	9	7	57	0.6497
Sc 11		Min	Max	Min	45	9	38	8	0.5626
Sc 12		Max	Min	Min	36	49	7	8	0.7471
Cons. Value					24	27	23	26	0.6896