Applied Energy xxx (2016) xxx–xxx

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Sustainable Energy Security for India: An assessment of energy demand sub-system

Kapil Narula [a,b,*], B. Sudhakara Reddy [b], Shonali Pachauri [c]

[a] National Maritime Foundation, Varuna Complex, Airport Road, NH - 8, New Delhi, India
[b] Indira Gandhi Institute of Development Research, Gen. A.K. Vaidya Marg, Goregaon (E), Mumbai, India
[c] International Institute for Applied Systems Analysis, Laxenburg, Austria

HIGHLIGHTS

- A multidimensional Sustainable Energy Security (SES) index is developed.
- The SES index evaluates the performance of the energy demand sub-system using 23 metrics.
- Dimensional indices are calculated for 2002, 2007 and 2012 for various sectors for India.
- The aggregate demand sub-system SES index shows an increase by 10% from 2002 to 2012.
- The index is 30% short of the target implying a large scope for improvement.

ARTICLE INFO

Article history:
Received 8 September 2015
Received in revised form 10 February 2016
Accepted 29 February 2016
Available online xxxx

Keywords:
Energy assessment modeling
Energy security
Energy sustainability
Urban residential sector
Multidimensional energy index

ABSTRACT

This paper presents a quantitative assessment of Sustainable Energy Security (SES) of the energy demand sub-system for India by calculating a multidimensional SES index. The demand sub-system has been evaluated for four dimensions of SES, viz., Availability, Affordability, Efficiency and (Environmental) Acceptability using 23 selected metrics. A hierarchical structure has been used to construct indices using 'scores' (objective values of selected metrics), and 'weights' (subjective values, representing importance of each metric) which are then aggregated, to obtain a SES index. Various sectors of the energy demand sub-system are evaluated and dimensional and sectoral indices are calculated for the years 2002, 2007 and 2012. Assessment of the obtained energy indices is undertaken (separately for rural and urban residential sector) and results reveal that all (except one) sectoral indices have shown an increase during the period of assessment. The results show that from 2002 to 2012, the aggregate SES index has increased by approximately 10% which indicates a gradual improvement in the sustainability and security of the energy demand sub-system. However, the SES index is approximately 0.7 (against a desired target of 1.0), which implies that there is still a large scope for improvement in the performance of the India's energy demand sub-system. A sensitivity analysis of various indices reveals that the SES index is relatively robust to variation in weights allotted to different dimensions and hence provides a reliable assessment of the energy demand sub-system.

1. Introduction

Sustainable Energy Security (SES) has been defined as "provisioning of uninterrupted energy services in an affordable, equitable, efficient and environmentally benign manner" and is proposed as an end goal of the energy policy for a developing country [1]. Energy security is a property of the energy system [2] and a structured analysis has been proposed by Hughes [3] and a SES index for developing countries has been developed by Narula and Reddy [4].

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 includes domestic extraction of primary energy and energy imports in the form of coal, crude oil, natural gas etc. Primary energy is then converted to different forms of energy carriers such as electricity and oil products which is distributed to the end users and this forms a part of the

* Corresponding author at: National Maritime Foundation, Varuna Complex, Airport Road, NH - 8, New Delhi, India.
E-mail address: kapiln@igidr.ac.in (K. Narula).

http://dx.doi.org/10.1016/j.apenergy.2016.02.142
0306-2619/

energy conversion & distribution sub-system. The energy demand sub-system consists of various sectors of the economy such as industrial, residential, and transport and final energy is consumed in various sectors.

The demand of energy services from various sectors of the economy triggers the supply of energy in an energy system. The energy supply sub-system responds to this demand and fulfils it to the extent feasible. Hence the demand sub-system is the driver and is critical for attaining SES for a country. The importance of the demand sub-system is also evident in India's 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*" [5]. However, the concept of SES goes beyond providing 'lifeline' of energy and beyond 'citizens' to include all sectors of the economy.

While increase in per capita energy consumption is inevitable and even desirable, it can be reduced as compared to the Business As Usual (BAU) scenario by adopting Demand Side Management (DSM) programs, and by reducing wastage (such as by utilizing waste heat). In case of electricity, peak demand management and dynamic demand reduction do not contribute directly to reduction in aggregate energy consumption, but it avoids the setting up of additional conversion, transmission and distribution infrastructure, thereby contributing to SES.

There are a large number of indices in literature, for evaluating energy security and sustainability. Narula and Reddy [6] have evaluated three indices, 'Energy Sustainability Index', 'International Index of Energy Security Risk' and 'Energy Architecture Performance Index', in detail and have concluded that these indices do not give reliable information for developing countries and further work is required for assessing the energy system of these countries. Coude [7] provides a good starting point for a literature review on energy security. Most of the studies on energy security such as Gupta [8], Cabalu [9], Cohen et al. [10], Le Coq and Paltseva [11] are limited to security of energy supply and deal with mostly oil and gas, while neglecting the demand side of the energy system. Although Jewell [12] extends the assessment to other energy sources using the Model of Short-term Energy Security (MOSES), it falls short of undertaking a detailed assessment of the energy demand sub-system. Hence the most prevalent view of energy security is from the supply side perspective as studies often overlook the assessment of the demand sub-system while evaluating the country's energy security and sustainability.

More recently, energy security for Singapore was evaluated using a framework with 22 indicators, three sub-indexes and a composite index. This assessment helped in quick identification of deficiencies within the Singapore's energy supply chain and pinpointed the main weaknesses in the energy system [13]. Energy security assessment for Thailand was also undertaken using energy security indicators and the paper recommended that Thailand needs to develop specific policy measures to enhance energy security by paying attention to energy markets, national energy efficiency and lower CO_2 emissions [14]. Energy security for the Association of Southeast Asian Nations (ASEAN) was analysed using the 4-A's framework and the importance of energy efficient technologies for achieving energy security and sustainable energy policy goals were highlighted [15]. A broader approach using a complex systems perspective in conceptualizing the energy system and a policy-oriented approach for identifying risks, threats and vulnerabilities for assessment of energy security was also undertaken [16]. While there are different approaches to analyse the energy system, this paper focuses on comprehensively and systematically assessing the performance of the demand sub-system, thereby highlighting its role towards attaining SES for India.

The aim of this paper is to assess the SES for the energy demand sub-system for India. The paper presents the methodology for calculating the SES index in the next section briefly. Scoring matrices are derived for various sectors and scores are calculated in Section 3 followed by calculation of weighting matrices. Results are presented in Section 4, followed by a discussion on sensitivity of the derived SES index for the demand sub-system, prior to concluding the paper.

2. Material and methodology

The framework for assessment and the methodology to calculate the SES index is presented briefly in this section.

2.1. Hierarchical structure for assessment of energy system

The hierarchical structure for the aggregation of SES index for an energy system of a country is shown in Fig. 1. The SES of an energy system is a function of the SES of the three sub-systems: supply, conversion & distribution and demand. Each sub-system has various components. The energy supply sub-system is assessed for eight primary energy sources: coal, oil, natural gas, biomass, nuclear, wind, solar and hydro. The energy conversion & distribution sub-system is assessed for five energy carriers: coal, gas, oil products, biomass and electricity and the energy demand sub-system is assessed for five main sectors of the economy: Residential, Industrial, Commercial (Services), Agriculture and Transport. These components are further divided into sub-components for a detailed assessment. SES of domestic and imported energy for various energy sources are assessed separately in the energy supply sub-system and SES of rural and urban consumers are assessed in detail for the residential sector in the demand sub-system. The structure for assessment of SES is similar to the S/D (Supply/Demand) index proposed by Scheepers et al. [17,18], but differs in many details. This hierarchical structure allows us to undertake a complete assessment of the SES of an energy system for a country or a region.

SES is a multidimensional concept and there are various dimensions and indicators which can be chosen to assess the energy system. Four different dimensions—Availability (related to adequacy and access), Affordability (related to prices and consumer's ability to pay for energy), Environmental Acceptability (related to resource extraction and waste production) and Efficiency (related to energy productivity) are selected for undertaking an assessment of SES of an energy system. These dimensions are distinct and selected indicators can be grouped under respective dimensions for assessing the SES. The dimensions are further divided into various categories and sub-categories which help in easy comprehension.

2.2. Constructing a SES index

In this paper, measurement of SES is undertaken through the use of 'indicators'. Quantitative indicators are based on data and can be used for measurement without any subjectivity and are known as 'metrics'. Following the hierarchical structure for assessment of SES for an energy system, a hierarchy of energy indices can be evolved using a combination of 'weights' and 'scores' and a composite SES index can be aggregated. Working level details are given in the following sub-sections but more details on the methodology can be found in [4].

Please cite this article in press as: Narula K et al. Sustainable Energy Security for India: An assessment of energy demand sub-system. Appl Energy (2016), http://dx.doi.org/10.1016/j.apenergy.2016.02.142