Journal of Cleaner Production 116 (2016) 13–22

Contents lists available at ScienceDirect

Journal of Cleaner Production

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

Assessment of the environmental efficiency of the electricity mix of the top European economies via data envelopment analysis

A. Ewertowska [a], A. Galán-Martín [a], G. Guillén-Gosálbez [a, b, *], J. Gavaldá [a], L. Jiménez [a]

[a] Departament d'Enginyeria Química, Universitat Rovira i Virgili, Av. Països Catalans 26, 43007 Tarragona, Spain
[b] Centre for Process Systems Engineering (CPSE), Imperial College London, SW7 2AZ, United Kingdom

ARTICLE INFO

Article history:
Received 8 May 2015
Received in revised form
14 August 2015
Accepted 28 November 2015
Available online 17 December 2015

Keywords:
Eco-efficiency
Energy assessment
Data envelopment analysis
Life cycle assessment

ABSTRACT

Moving towards a more sustainable energy system is a major goal of modern societies that aim to minimize the dependence on fossil fuels and the associated anthropogenic impacts. In this article, the combined use of Life Cycle Assessment (LCA) and Data Envelopment Analysis (DEA) is applied to analyse the environmental performance (eco-efficiency) of the electricity mix of the top European economies. This approach allows identifying environmentally efficient and inefficient countries considering as undesirable inputs several environmental impacts associated with the production of 1 kWh (regarded as output). The method provides as well targets for the inefficient countries that (if attained) would make them efficient. Our results provide valuable insight for governments and policy makers that aim to satisfy the electricity demand while minimizing the associated environmental impact.

1. Introduction

Energy transition has recently received increasing public attention because of the role it plays in sustainability (Kern and Smith, 2008). In the last decade, renewable energy sources (e.g. wind energy, biomass, hydropower, solar power, geothermal, and ocean power) have become promising alternatives to reduce the dependence on fossil fuels, as they could lead to significant environmental and economic benefits, including energy security enhancement.

In Europe, several environmental strategies and policies have been recently developed, which highlight the necessity for a clean and efficient energy supply. These policies aim to transform the current energy system into a sustainable and low-carbon system, which will have far-reaching implications on how to produce energy. Due to the increased awareness of the role played by energy in our society, it is imperative to find effective ways for assessing the environmental impact of the technologies available for electricity generation in order to move towards an environmentally friendly electricity mix (i.e., eco-friendly mix).

Intensive research efforts are presently being undertaken to seek sustainable alternatives for satisfying the growing electricity demand at minimum environmental impact. In practice, it is unlikely that a single technology will show the best performance in every environmental impact category of interest. As an example, nuclear energy contributes marginally to global warming, but shows high impact in ionising radiation (Frischknecht et al., 2000), whereas with coal the opposite situation occurs. Understanding that electricity production technologies may perform well in some environmental categories and poorly in others, the question that arises is how to identify the best ones (i.e., environmentally efficient ones) and, for the worst, specify targets that (if achieved) would make them efficient. This valuable insight could facilitate the transition towards a cleaner electricity generation system.

The concept of eco-efficiency offers an appealing framework to carry out this task. The Eco-efficiency concept was originally introduced in the Earth Summit and later defined as a general management philosophy (Schmidheiny, 1992) during the World Business Council for Sustainable Development. Eco-efficiency is a general instrument for sustainability analysis of products or processes of different nature. It is usually expressed as the ratio between the product value and its environmental burden, thereby indicating the economic creation for a given ecological destruction. This ratio was also called environmental productivity or incremental eco-efficiency by Huppes and Ishikawa (2005).

The eco-efficiency concept has so far been used in many disciplines. According to Michelsen et al. (2006), the concept of eco-efficiency can be used for measuring the system progress and for communicating the economic and environmental performance of a

* Corresponding author. Departament d'Enginyeria Química, Universitat Rovira i Virgili, Av. Països Catalans 26, 43007 Tarragona, Spain.
E-mail address: gonzalo.guillen@urv.cat (G. Guillén-Gosálbez).

http://dx.doi.org/10.1016/j.jclepro.2015.11.100
0959-6526/

product or process. The main drawback when constructing eco-efficiency indicators is that there are no agreed rules or standards for the measurement, recognition, and disclosure of environmental information (UNCTAD, 2003).

Hence, a key point in eco-efficiency assessment concerns the manner in which the economic and environmental performance values are defined. Kuosmanen and Kortelainen quantified the environmental performance using pressure indicators (calculated by weighting the contribution of different pollutants to several damage categories), and the economic performance through the profit (which measures the economic value added) (Kuosmanen and Kortelainen, 2005). On the other hand, Dyckhoff and Allen (2001) proposed to quantify the environmental performance using life cycle assessment (LCA), a well-established environmental engineering technique. LCA is a methodology that quantifies the impact caused in all of the stages in the life cycle of a product (i.e., cradle to grave analysis), including raw materials acquisition, processing, manufacturing, end-use, disposal and waste management (SETAC, 1993). LCA focuses on environmental impacts. Indeed, ISO documentation restricts LCA's purview to environmental effects (ISO, 2006a; ISO, 2006b). The ISO 14040 standards (ISO, 2006b) describes LCA as the “compilation and evaluation of the inputs, outputs and potential environmental impacts of a product system throughout its life cycle”. Due to the holistic approach it applies (Finnveden et al., 2009), in recent years LCA has expanded rapidly in both industry and academia.

In the context of energy systems analysis, LCA considers all aspects associated with energy generation over the entire energy supply chain, that is, throughout the entire life cycle of the production of energy. These lifecycle stages include the extraction and combustion of the corresponding fuels (e.g. coal, oil, biomass, natural gas, etc.) the transportation tasks associated with these fuels, the distribution of energy and the impact associated with the construction and maintenance of the facilities that produce energy (e.g. nuclear plants, wind turbines, coal plants, etc.). The main advantage of using LCA in the assessment of energy systems is that it provides a holistic view of each technology, thereby informing on the extent to which it contributes to decrease the impact globally. This comes at the cost of requiring large amounts of data, some of which might be difficult to collect in practice. Applications of LCA to electricity production include the assessment of different renewable energy sources (Bhat and Prakash, 2009) and of several emissions associated with electricity production from coal and natural gas in Canada (Zhang et al., 2010), among others.

Eco-efficiency is typically assessed via data envelopment analysis (DEA) (Cooper et al., 2007). DEA is a non-parametric linear programming (LP) based technique that objectively assesses the relative efficiency of a set of units (i.e., products/services). Each of these units is formally defined as an entity that consumes certain amounts of inputs to manufacture certain amounts of outputs. DEA identifies non-dominated (i.e., efficient) (Hongye, 2010) units and for the ones found to be inefficient, it provides both an efficiency score and a set of target values (for its inputs and outputs) that (if attained) would make the unit efficient.

DEA is a very useful analytical tool that can be employed to assess the efficiency and guide retrofit efforts towards an effective enhancement of the environmental performance. Unfortunately, DEA shows some limitations as the results it provides are very sensitive to the number of inputs and outputs considered as well as the size of the sample (Bhagavath, 2009).

In the last decade, the combined use of LCA and DEA has developed significantly (Vázquez-Rowe and Iribarren, 2015) as a tool to benchmark the operational and environmental performance of resembling entities (Vázquez-Rowe et al., 2010; Avadíet al., 2014). Despite being general enough to be applied to any product, the combined use of LCA and DEA have been primarily used to assess specific systems (Iribarren et al., 2010). For instance, (Iribarren et al., 2013) have recently carried out an integrated LCA + DEA study of wind farms, showing that this methodology can be useful for the benchmarking of energy conversion systems. This approach has also been applied to assess thermal plants (Liu et al., 2010; Sarıca and Or, 2007; Sözen et al., 2010), electric and electronic appliances (Barba-Gutiérrez et al., 2008), U.S manufacturing sectors (Egilmez et al., 2013), building components (Iribarren et al., 2015) and also to evaluate the environmental efficiency of the Chinese industry (Wu et al., 2014), among others.

The combined approach that integrates LCA and DEA proposed by Vázquez-Rowe et al. (2010) has been applied in this work to assess the environmental efficiency of the electricity mix of the 27 wealthiest economies in Europe. We discuss in this paper which countries are efficient and for those found to be inefficient, environmental targets are provided to make them efficient. Note that we have focused here on analyzing the environmental performance of the electricity generation mixes of the top European countries, which display similar levels of development. Note also that, as it will be discussed in more detail later in the article, economic, social, technological and political aspects have been left out of the analysis. The main reason for this is that there is a lack of quantitative indicators for describing the performance of a technology in these dimensions (except for the economic case, for which several indicators are available, but they seldom reflect the true cost of the system due to external regulations).

The article is organized as follows. The results of applying LCA to the electricity mix of the top economies are first presented. We next describe the DEA methodology, which is employed to quantify the environmental efficiency of the electricity mix of each country. The results of the DEA study are presented afterwards, while the conclusions of the work are drawn in the last section.

2. Environmental impact assessment of energy production

The environmental performance of the electricity mix of the top economies in Europe (see Table 1) is analyzed first following LCA principles. Particularly, this environmental performance is quantified through the CML 2001 (Guinée, 2001; Van Oers, 2004), an LCA-based methodology that considers 15 damage scores (which are quantified over the entire life cycle of the energy supply chain).

The impacts analysed and the corresponding units are given in Table 2. The results of this LCA analysis have been retrieved from the environmental database EcoInvent v3.1 (Weidema et al., 2013), which contains LCA data of the main technological processes implemented worldwide.

Fig. 1 shows the normalized environmental impacts associated with the generation of 1 kWh in the different damage categories. The interval within which the impact values fall is very large, which leads to numerical problems during the application of the DEA approach. Hence, to enhance the numerical robustness of the models solved by DEA, we first normalize the data prior to its application. The goal of normalization is to refer the impact scores to a common interval (e.g., [0,1], where 0 is the minimum value and 1 is the maximum). This facilitates the comparison of different environmental impacts and their visual analysis (see Fig. 1), while at the same time avoiding the numerical difficulties that may arise when solving the LP models of the DEA approach using the original raw data.

In Fig. 1, the average of each impact is depicted by a vertical line (note that the values of the average of impact 9, 10 and 11 are very similar; 0.2235, 0.2227 and 0.2240, respectively, and cannot be properly distinguished in the figure). As seen, there are countries that perform poorly in one impact and well in others. As an