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Incorporating life cycle external cost in optimization of the electricity generation mix

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HIGHLIGHTS

- The Life Cycle Assessment concept has been integrated in a Linear Programming model.
- Externalities change the ranking order of cost-competitiveness of the energy sources.
- The electricity generation cost for the years 2012-2050 is minimized.
- Most of the new generating capacity should be renewable (mainly wind and biomass).
- Natural gas is the only conventional fuel source used in most scenarios.

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ABSTRACT

The present work aims to examine the strategic decision of future electricity generation mix considering, together with all other factors, the effect of the external cost associated with the available power generation technology options, not only during their operation but also during their whole life cycle. The analysis has been performed by integrating the Life Cycle Assessment concept into a linear programming model for the yearly decisions on which option should be used to minimize the electricity generation cost. The model has been applied for the case of Greece for the years 2012–2050 and has led to several interesting results. Firstly, most of the new generating capacity should be renewable (mostly biomass and wind), while natural gas is usually the only conventional fuel technology chosen. If externalities are considered, wind energy increases its share and hydro-power replaces significant amounts of biomass-generated energy. Furthermore, a sensitivity analysis has been performed. One of the most important findings is that natural gas increases its contribution when externalities are increased. Summing-up, external cost has been found to be a significant percentage of the total electricity generation cost for some energy sources, therefore significantly changing the ranking order of cost-competitiveness for the energy sources examined.

1. Introduction

When comparing environmental issues of different options fulfilling a similar function, it is important to consider the complete life cycle and not only one phase, e.g. production or use. This is because environmental impacts and benefits may occur at different phases of the life cycle. The most important phases may not be the same when two options are compared (Moberg et al., 2005). Thus, a life cycle approach is needed and, more precisely, the Life Cycle Assessment (LCA) methodology should be used. LCA is a method for evaluating the environmental impact associated with a product, process or an activity during its life cycle by identifying and describing, both quantitatively and qualitatively, its requirement for energy and materials, as well as the emissions and waste released to the environment (Madival et al., 2009; Liu et al., 2010).

Nowadays, many companies have been practicing environmentally conscious design and manufacturing to tackle environmental issues by LCA (Zutshi and Sohal, 2004; Nakano and Hirao, 2011). Moreover, the use of LCA in environmental management and sustainability has grown in recent years as evidenced by the steadily increasing number of published papers and case studies on LCA methodology (Notarnicola et al., 2012). As a result, life cycle management is quickly becoming a well-known and often used approach for environmental management in the energy sector as well. Thus, LCA studies of different energy products (Von Blottnitz and Curran, 2007), fuels (Dinca et al., 2007; Tsoutsos et al., 2010), power generation systems (Babbitt and Lindner, 2005; Georgakellos, 2012) and relevant technologies′ appraisals (Nguyen and Gheewala, 2008) are very common.

On the other hand, the LCA framework seems to be, to some extent, ignored in electricity demand forecasting and in power

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generation technologies' mix projections. Specifically, there is a noteworthy number of such studies in the literature attempting to investigate future electricity generation of particular countries, such as India (Grover and Chandra, 2006), Kazakhstan (Atakhanova and Howie, 2007) and Turkey (Kucukali and Baris, 2010). Similarly, Lady (2010) demonstrated the basic feasibility of approximating some portions of the US National Energy Modeling System projections for the amounts of electricity and natural gas consumed by the residential and commercial sectors with linear regression results. Among these studies, only few consider in their projection the environmental impact of the examined scenarios, primarily focusing on the climate change as a result of CO_2 emissions. For example, Rachmatullah et al. (2007) presented a scenario planning for the electricity generation in Indonesia, Dilaver and Hunt (2011) modeled and forecasted the Turkish residential electricity demand and Simshauser et al. (2007) analyzed the economic and environmental impact of various future electricity generation technology options in Australia. In addition, Rentizelas et al. (2012) investigated the effect that various scenarios for emission allowance price evolution may have on the future electricity generation mix of Greece. Only Liu et al. (2011) include the carbon dioxide life cycle emissions in their analysis, which concerns a preliminary prediction of the development of renewable energy in China for the future decades.

Thus, the present work is, to the best of our knowledge, the first research attempting to investigate whether and how the strategic decision of future electricity generation mix may be affected by the external cost associated with the available electricity production technology options, not only regarding their operation but also considering their whole life cycle. This is based on an appropriate mathematical framework developed for this purpose by adapting a linear programming model for the yearly decisions on which electricity generation source should be used to minimize the electricity generation cost. The model has been applied for the case of Greece. It should be noted that the life cycle approach seems to be vital in such analyses in order to improve the reliability of decision making. This is because there is a number of power generation technologies (mostly those based on renewable energy sources) which have almost zero externalities linked with the electricity generation phase, but the other stages of their life cycle may have noteworthy effects on the environment.

The present paper is organized as follows: Section 2 concerns the literature review associated with this research. Section 3 presents the methodology used, analyzing the LCA external cost estimation as well as the mathematical model. Results' presentation and discussion is the subject of Section 4, while Section 5 is about the sensitivity analysis performed in order to assess the reliability of the results. Finally, Section 6 highlights the main conclusions of the work.

2. Literature review

2.1. Life Cycle Assessment

Life Cycle Assessment was originally developed to form a decision-making tool which is aimed at a systematic assessment of the environmental performance of production systems (Huybrechts et al., 1996; Steen, 2005). During the evolution of LCA, a number of related applications emerged, such as decision-making support, choice of environmental performance indicators, and product design and market claims (Guinée et al., 2001; Vinodh and Rathod, 2009). It also provides a consistent basis for comparison between alternatives based on the environmental consequences associated with them (Georgakellos, 2012). However, results from an LCA can mainly be used for the identification of parts and aspects of a life cycle where improvements in the environmental performance are important (Höjer et al., 2008; Graedel and Allenby, 2010).

The philosophy adopted by LCA is that the true extent of the environmental burden can only be understood if all the steps in the delivery, use, and eventual disposal of the product or service are accounted for in the final analysis.

The LCA methodology is described by four phases: (1) goal and scope definitions, (2) inventory analysis, (3) impact assessment, and (4) interpretation (Curran, 2006; Georgakellos, 2006). The foundation of a product's LCA is the inventory component where energy, raw materials and environmental releases are measured (Hassan, 2003; Ison and Miller, 2000). Specifically, the task in the inventory stage is to trace (ideally) all inputs to and outputs from every stage in the life cycle back to the associated terminal inputs to and outputs from nature (the environment). The flows may be segregated into inputs of materials and outputs of waste to air, land and water. In practice, it may not be possible to follow all the input flows all the way back to the extraction of resources from the environment. However, this must be acknowledged in the study report and the consequences (for the use of the report) should be assessed (Georgakellos, 2005).

In the present work, the life cycle inventory concept is being used in order to quantify the atmospheric emissions associated with each power generation technology under examination. It is process oriented, involving consideration of the individual technologies of interest. All energy systems are described on a "cradle to grave" basis, from the stage of extracting raw materials from the environment through downstream processes, with each stage in the chain being decomposed into construction, operation and dismantling phases (Dones et al., 1999). In the power sector, the assessment should include extraction, processing and transportation of fuels, building of power plants, production of electricity and waste disposal (Gagnon et al., 2002).

2.2. External cost of power generation systems

Almost every electricity generation option, aside from its beneficial consequences to society, causes undesirable effects, such as environmental degradation. Electricity production can influence a wide set of end points including soil, noise, visibility, global climate, human health, and visual amenity (Georgakellos, 2010). Common air pollutants that draw intense concerns include particulate matter (PM), ozone (O3), carbon monoxide (CO), sulfur dioxide (SO2), nitrogen dioxide (NO2), lead (Pb), volatile organic compounds (VOCs), and polycyclic aromatic hydrocarbons (PAHs) (Han and Naeher, 2006).

Fossil fuel-fired power plants cause the biggest environmental pollution problem. Air pollution is caused by the high content of aliphatic hydrocarbons with impurities such as sulfur, water and other chemicals, the combustion of which results in the formation of effluents such as sulfur dioxide and oxides of nitrogen as well as carbon dioxide and particulate matters (PM) (Chaaban et al., 2004; Lora and Salomon, 2005). Moreover, other harmful constituents in the combustion gases are heavy metals, dioxins, etc., which affect the life of humans, animals and plants (National Observatory of Athens, 2005).

In order to appraise the environmental impacts of various electricity production technologies, one of the most widely accepted approaches today relies on external costs of electricity production, i.e. monetary value of damages. External costs are imposed on society (e.g. human health) and the environment (e.g. built environment, crops, forests and ecosystems) and are not accounted for by the producers or the consumers of electricity (Montanari, 2004). Generally, monetary estimates of both market and non-market damages are ideally expressed in the form of willingness to pay, or willingness to accept compensation (Fankhauser and Tol, 1996). Estimates of future economic damages resulting from atmospheric pollution have an important impact on policy decisions being made today. Reducing airborne emissions and protecting humanity from those impacts will be costly, but a