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Energy efficiency in the European Union: What can be learned from the joint application of directional distance functions and slacks-based measures?

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HIGHLIGHTS

- We analyze the efficiency of electricity and derived heat generation in the European Union (EU).
- We consider both desirable and undesirable outputs.
- In our specifications both directional distance functions and slacks-based measure models are used.
- Results show remarkable efficiency differences among EU countries.
- This would call for further intensification of harmonization environmental policies in the EU.

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ABSTRACT

Over the last few years concerns have increased about the energy mix in many countries. These concerns have been of greater magnitude for countries with a common energy regulation such as European Union (EU) member states. An important aspect to take into account when choosing a given energy mix is the efficiency involved in its generation. In this context, the present study analyzes the efficiency with which electricity and derived heat was produced in 25 EU member states over the last decade. This analysis considers not only the inputs and outputs involved but, more importantly, which undesirable by-products were generated during the production process, a relevant issue for EU climate policy. To this end, two nonparametric frontier models are applied: first, a Directional Distance Function (DDF), based on Briec's (1997) [16] proposal and, second, a modified version of Tone's (2001) [51] Slacks-Based Measure (SBM) model, both of which are especially appropriate in this particular context due to their treatment of undesirable outputs. Results are partly innovative since, with few exceptions, applications on this issue are relatively scarce. From a policy implications' point of view, our achievements are also interesting because they reveal remarkable efficiency differences among EU countries: those countries from the latest EU enlargements account for the lowest efficiencies, with large opportunities for improvement in CO_2 abatement and primary energy saving. Results also show stable efficiencies along the evaluated period and, therefore, highlighting the need to further intensify the initiatives designed to harmonize environmental policies and identifying drivers for efficiency improvement turn out to be still key objectives.

1. Introduction

The operation of power plants for electricity and derived heat production during the past decades provided the energy required for technological progress and economic development, leading to a rise in the living standards of many countries around the world. This type of operation has both positive and negative effects for society in general, as well as for the economy and the environment, in particular. For these and related reasons it is relevant to evaluate the electricity and derived heat generation process, bearing in mind not only the technical (and positive) aspects, but also the negative externalities that arise in the process.

This process involves consumption of resources, and is subject to several factors. Electricity is a secondary source of energy generated from other primary sources, the most important ones

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being: (i) coal; (ii) nuclear; (iii) natural gas; (iv) oil; and (v) renewable sources (mainly hydro power, wind and solar sources). As a consequence, the first decision a country should make is to choose from these available primary sources—ideally, those that provide a better fit for each country's energy strategy, or *mix* [1]. Some countries might opt to encourage the use of renewable sources, while others might either promote, or limit, the use of nuclear energy. This decision will ultimately be influenced by political, economic, technical and environmental factors. Many circumstances must be taken into consideration, such as, crucially, the availability of natural resources, and the lack of certain primary sources, which may be an important condition for the energy mix adopted. Whatever the primary energy involved, the final outcome will be generation of electricity power for the country.

Unfortunately, not all primary resources can be transformed into electricity, and a significant proportion is lost in the process, usually as unwanted heat—i.e. the process involves *inefficiency*. Hence, an important issue to evaluate is the balance between the primary resources actually consumed and the final output available. Although the positive aspects—the beneficial impact on both economic activity and economic growth—usually prevail, there are also harmful effects such as the release of greenhouse gases and other emissions or radioactivity, all of which are related to the rise in power plant operations that should also be considered.

In this particular respect, over the last two decades there has been an ongoing concern about (and, also, initiatives to address) the harmful effects of certain pollutants, such as carbon dioxide (CO_2), sulfur dioxide (SO_2), or nitrous oxide (NO_x). Pollutants like SO_2 have been controlled up to a certain level [2] and industrialized countries are trying to limit their amounts, while simultaneously attempting to convince developing nations about the importance of this issue.[1] In the particular case of Europe, in 1992 the former European Community reassessed its environmental policies for achieving the goal of sustainable development in the next century,[2] with a strategy of setting long-term objectives and focusing on a more global approach.[3]

In this context, the main goal of this study is to analyze efficiency in the electricity and derived heat generation process for 25 members of the European Union (EU25) during the early 2000s. On the issue of power generation, an effective climate change mitigation strategy for the short and medium term calls for the production of energy in the most *efficient* possible way [3]. The electricity generating capacity of all economies, be they emerging or developed countries, varies greatly and, in the case of the EU, there are remarkable differences in the standards of living of its member states. However, in order to benefit the global environment, the cleanest technology should be available to all countries. Efforts should therefore be directed to analyze energy consumption, CO_2 and other emissions, and development in different countries, in order to design and implement the best environmental policies, or to introduce disciplinary measures when necessary. The objective of this paper is to obtain a rank, index, or benchmark that will allow comparison of EU countries. This benchmark will not only be based on finding a balance between the electricity and derived heat produced and the total primary energy consumed in the process, but will also control for relevant environmental and economic issues involved in the production process. This will be done by explicitly comparing the different various methodologies considered to measure efficiency in this specific context, with a special focus on those with better abilities to model the (likely) negative effects that may arise in the electricity and derived heat generation process.

An extensive literature has analyzed this and related issues, although the body of work on the particular case of the EU is not especially large. Specifically, the literature on the aggregated measurement of environmental performance can provide condensed information for analysts and decision makers dealing with energy and environmental-related issues [4]. Within this field, two main approaches have been used to construct environmental performance indexes (EPIs) which, from the point of view of operations research, can be classified into *indirect* and *direct* approaches. Under the indirect approach, the key economic, energy and environmental sub-indicators are first identified, and then normalized and integrated into an overall index using a particular weighting scheme (see, for instance, [5]). In contrast, in the direct approach, which has gained importance over the last few years [6–11], the indicators are directly obtained after defining a set of inputs and outputs of the environmental study under analysis using frontier approaches such as Data Envelopment Analysis (DEA).

However, in the field of energy and environmental studies, following the survey by Zhou et al. [12], the assumption used by the traditional DEA models that all outputs should be maximized might be inappropriate when undesirable, or unwanted outputs are also generated as by-products in the production process [4].[4] As Scheel [15] notes, several approaches have been proposed to deal with this issue, most of which follow the concept of *radial* efficiency measures. These measures assume the reduction of inputs (and undesirable outputs), or the increase of desirable outputs, in the *same* proportion so as to become efficient; yet this assumption does not always match real production processes, where some variables may not have this proportional behavior.

An alternative taxonomy of DEA models is to choose between oriented and non-oriented models, where the orientation (or its absence) refers to the variable to be optimized—inputs, outputs, or undesirable outputs. If there is a clear attempt to look for inefficiencies among a certain set of variables, oriented models may be an appropriate option. However, if these concerns refer to more than one set of variables (which is usually the case in environmental performance analysis), then non-oriented models would represent the best alternative. In general, non-oriented efficiency measures provide more reasonable results for energy and environmental studies because of their enhanced ability to handle both desirable and undesirable outputs simultaneously. Because of these advantages, in recent years empirical research on efficiency measurement in this particular setting has focused more closely on non-oriented models, in what is known as *the full space of inputs and outputs* or, more briefly, the <input–output> space. In this field, one of the most prominent contributions is that of Briec [16], who introduced a graph measure of technical efficiency that is a special case of the Directional Distance Function (DDF).[5]

[1] For this reason, the United Nations Conference on Environment and Development (UNCED) held in Rio de Janeiro in 1992, highlighted two important sets of principles: (i) ''Precautionary Principles'' (15th Principle) and (ii) ''Internalization of Environmental Cost'' (16th Principle). The Kyoto Protocol (1997) and its most recent review (2010) have given prominence to climate change, increasing the number of countries that defend the goal of achieving ''stabilization of concentrations of greenhouse gases (GHG) in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system'' (United Nations Framework Convention on Climate Change, UNFCC, Article 2, 1992).

[2] The long term goals were stated in the 5th Environmental Action Program, ''Towards Sustainability''.

[3] One of the target sectors of the program was ''Energy'', and air quality is clearly linked to this sector. The Fourth Assessment Report (AR4) of the Intergovernmental Panel on Climate Change (IPCC) shows that warming of the climate system is unequivocal, and provides compelling evidence that climate change is very likely to be due to the observed increase in anthropogenic greenhouse gas concentrations.

[4] A review and systematic investigation on DEA model building with undesirable inputs and outputs can be found in Liu et al. [13]. The literature on undesirable outputs is evolving, and recent contributions [14, such as] consider that the traditional treatment of bad outputs suffers from serious weaknesses.

[5] See also a more recent contribution by Russell and Schworm [17].