# *TOTAL-FACTOR ENERGY EFFICIENCY WITH $CO_2$ EMISSION: A STUDY BASED ON POLLUTION GENERATION AND ABATEMENT PROCESS*

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## Overview

In literature, the modeling of production technologies in the presence of undesirable output is subject to ongoing academic debates (Dakpo et al., 2016). One of the hot debates relates to the weak disposability technology which could generate negative shadow price for the undesirable output. While Hailu and Veeman (2000) and Leleu (2013) pointed out that the negative shadow price is economically meaningless, Kuosmanen and Matin (2011) argued that the sign of the shadow price for undesirable output is free. Recently, Chen (2013) found that the weak disposability technology could result in non-monotonic eco-efficiency in undesirable outputs and lead to misleading implications for decision makers. Moreover, Murty et al. (2012) and Hampf and Rodseth (2015) respectively pointed out that the weak disposability technology violates the trade-off and material balance principle. To circumvent these weaknesses associated with weak disposability technology, a variety of new efficiency models are proposed. However, there is no consensus on the most reliable and practical one, leaving the issue of modelling undesirable output in the performance analysis far from being definitively settled.

This paper focuses on total-factor energy efficiency assessment in the presence of undesirable output (i.e. $CO_2$ emissions). In order to model undesirable output in a way consistent with the natural law and engineering relationship, we first examine the representation of the production technology based on the pollution generation and abatement technology. This discussion helps us clarify some arguements regarding the weak disposability technology, based on which we further propose a novel energy efficiency measure. This new measure contributes to the literature by providing a meaningful dual economical interpretation for the jointness of desirable output and undesirable output. It also provides economically meaningful shadow price for the undesirable output and therefore avoids non-monotonicity of energy efficiency in undesirable output. The new method is finally applied to a numerical example and a case of 117 countries.

This paper is organized as follows: Following the introduction the second section examines the representation of the production technology based on pollution generation and abatement technology. The third section proposes a novel total-factor energy efficiency measure which is meaningful from both physical and economical points of view. In section four the proposed measure is applied to a numerical example and a case of 117 worldwide countries. We make conclusions in the final section.

## Methods

Data envelopment analysis (DEA).

## Results

First, the undesirable output shows weak disposability in the joint prodution framework, indicating that the weakly disposable technology is capable to depict the real production frontier.

Second, the production area can be divided into two parts in which the underlying implications of energy inefficieny are different.

Third, the conventional energy efficiency models relying on weakly disposable technology fails to identify all the energy waste in production and abatement activities, and is only capable in identifying the energy waste in the abatement activity. Consequently, they are very likely to violate monotonicity and generate distorted and misleading energy efficiency scores.

Forth, our proposed total-factor energy efficiency measure can ensure the weak disposablity of undesirbale output and avoid above mentioned weakness. It is therefore expected to be a reliable enegry efficiency measure.

## Conclusions

Energy efficiency analysis is of vital importance for researchers, analyst and policy makers due to its advantages in conducting energy efficiency performance, evaluating policy effectiveness and promoting public communication. Among many others, DEA has been widely identified as a powerful tool for multi-input and multi-output energy efficiency evaluation as it can avoid using parametric/functional structure for the production technology.

Considering the ongoing debates in the field of modelling production technologies in the presence of undesirable output, in this paper, we examined the joint production technology based on pollution generation and abatement technology, and proposed a modified total-factor energy efficiency measure which is found to have meaningful interpretation for the jointness of desirabl output and undesirable output, and provide relistic enegry efficiency results by identifing energy waste in both abatement activity and production activity. It is also found that our proposed model can avoid the non-monotonicity of energy efficiency in desirable output.

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