Ilmenau University of Technology
Institute of Economics

Ilmenau Economics Discussion Papers, Vol. 19, No. 90

Assessment of the Environmental Performance of European Countries over Time: Addressing the Role of Carbon Leakage and Nuclear Waste

Thomas Grebel & Michael Stuetzer

September 2014

Institute of Economics

Ehrenbergstraße 29
Ernst-Abbe-Zentrum

D-98 684 Ilmenau

Phone 03677/69-4030/-4032
Fax 03677/69-4203

http://www.wirtschaft.tu-ilmenau.de ISSN 0949-3859

Assessment of the Environmental Performance of European Countries over Time: Addressing the Role of Carbon Leakage and Nuclear Waste

Thomas Grebel[a]

Michael Stuetzer[a]

[a] Ilmenau University of Technology, Chair of Economic Policy, Ehrenbergstr. 29, 98693 Ilmenau, Germany

1. Introduction

The European strategy to reduce greenhouse gas (GHG) builds on the actualization of technological progress: countries should catch up and/or advance their economy-wide production system via more efficient, that is, less CO_2 emitting technologies. As incentive system, the European Union Emission Trading System (EU ETS) was introduced in 2005. The system is characterized by a cap on the total amount of GHG that can be emmited by firms. Within the cap, emission allowances are traded among firms which buy or sell the pollution rights for GHG. Demand and supply of those allowances are equilibrated by the price fo emission allowances of this 'Coasian-type' market. The higer the price for allowances, the higher the incentive to innovate on GHG-efficient technologies. Unfortunately, the price for allowances is quite low (today and in the past) as too many allowances were issued (Clò 2010). This low price threatens the innovation incentive effect of the EU ETS.

The mal-functioning side in this market is the supply side. The demand for allowances is determined by firms' decision-making process, that is, firms choose between the lowest cost strategy of either buying allowances or innovating on CO_2-efficient technologies. The supply of allowances is determined by the cap of GHG emissions set by the EU in a policitcal process. This cap is reduced each year by 1.74% in order to meet the goal of reducing EU's GHG by 20% until 2020. While more ambitious reduction targets may contribute to slowing down global warming, unilateral actions can reduce the international competitiveness of Europeans industrial sectors. One key issue in this respect is the carbon leakage effect which occurs when a country reduces its greenhouse gas emissions by substituting own production of carbon intensive goods with imports from another country (OECD 2006). The reason for this substitution is that a country with strict GHG regulations imposes high costs for producing carbon intensive goods which can lead to a shutdown or relocation of the carbon intensive industries to countries with less strict regulations and thus lower production costs (Babiker and Rutherford 2005; Copeland and Taylor 2004). The carbon leakage effect is less a problem within the EU ETS but more problematic in the relation of the EU with other major economies where differences in regulation are distinct.

Several solutions to the carbon leakage problem have been proposed. Carbon tariffs on imports of carbon intensive goods from countries with less strict regulations feature prominently in the discussion. The aim of this paper is to develop a correction mechanism for the leakage of pollutants to which the country-specific total supply of CO_2 emission allowances can be aligned to. To make it a generally accaptable one, this indicator must fulfill several conditions: (a) it has to consider the heterogeneity among member countries with respect to their specific production systems, (b) it has to be adjusted for carbon leakage, i.e. when firms reduce own CO_2-emissions by relocating their production to other countries or simply substitute their production for imports and (c) it should also consider the problem of 'nuclear leakage', i.e. when CO_2-intensive energy transformation systems are replaced by nuclear power be it self-produced or imported.

On methodological grounds, we draw on works by e.g. Sueyoshi and Goto (2013) and Zhou et al. (2008). Using a Data Envelopment Analysis (DEA), we identify the best-practice frontier of countries in terms of CO_2-emissions. This non-parametric approach allows us to take into account the heterogeneity of countries. As in Sueyoshi and Goto (2013), we distinguish the 'managerial disposability' and the 'natural disposability' approach, address the role of multiple projections and projection sets, and discuss the role of slackness conditions. As inputs and outputs we use the following longitudinal data for 23 European countries (years: 2000-2009): primary energy input, final energy and non-energy consumption as 'good (or desirable)' outputs, CO_2-emissions adjusted for carbon leakage and nuclear waste produced by countries adjusted for nuclear leakage as 'bad (or undesirable)' outputs. The adjustment weights for leakage-corrected CO_2 are calculated on the sector level using I/O-tables from Wiot, while the calculations for the adjustment weights for leakage-corrected nuclear waste are based on energy imports and exports.

In the empirical section we compare the results with leakage adjustment with those without leakage adjustment, providing a first estimation of the impact of the CO_2 and nuclear waste leakage issue on countries' environmental performance. Our analysis reveals that efficiency scores with leakage correction substantially differ from scores without leakage correction. This suggests that the leakage of pollutants has a strong effect on the environmental efficiency of countries. Thereby carbon leakage seems to have a stronger effect on the efficiency scores than the leakage of nuclear waste.

The remainder of the paper is structured as follows. Section 2 describes the methodological approach of performance measurement and the leakage issue. Section 3 presents methods and data. Section 4 presents the results and discusses policy conclusions.

2. DEA and the leakage of bad outputs

2.1. DEA and bad outputs

Beginning with the first oil crisis in 1973-1974 and accelerating with the growing awareness of environmental problems, research in the field of energy planning has increased substantially (Løken 2007). One of the key research questions in this field addresses the modelling and measurement of the environmental performance of decision making units (DMU), ie. firms and countries. Among the wide array of modelling techniques (Zhou et al. 2006; 2008b), the use of the data envelopment analysis (DEA) has increased over time.

DEA as a non-parametric benchmarking technique allows evaluating the relative performance of DMUs. Early work applied DEA to the performance evaluation production processes (Charnes et al. 1978). For each DMU of a sample an efficiency score is calculated by comparing a vector of inputs and outputs of the DMU against the best-practice production frontier of the sample. The lower the efficiency score, the more inputs a DMU needs to reduce in order to produce the same amount of outputs as the most efficient DMU of the sample (assuming the input-oriented form of DEA). In other words, the lower the efficiency score, the larger the distance between the DMU and the best-practice production frontier to which the DMU is compared.

An important extension to this basic DEA setup is the distinction between "good" or desirable and "bad" or undesirable outputs (Färe et al. 1989). According to (Pittman 1983) a good output is an output of the production process that can be sold for a positive price at markets. Many products and services produced by firms are prime examples of good outputs. In contrast, bad outputs are by-products of a production process such as pollutants. These by-products often cannot be sold on markets but instead impose costs on the producer in case they are abated or take the form of technological externalities if there is no abatement effort from the producer. DEA as a non-parametric approach is particularly well suited to deal with bad outputs. This is because one can forego specifying the weights a priori which are usually price information for the inputs and outputs. Prices of technological externalities from pollutants are notoriously hard to determine (Chen 2013).

2.2 Carbon leakage

Previous studies applying the DEA methodology to measure the environmental performance of countries usually compile the list of inputs the countries use to produce outputs. One group of studies uses inputs such as labour and capital for the production of goods and services with greenhouse gas emissions such as CO2 as a bad output process (Färe et al. 2004; Zhou et al. 2010; Zofío and Prieto 2001). Other studies look at the efficiency of country's energy production and relate inputs such as coal or natural gas to the production of good outputs such as energy and heat again with CO_2 as a bad output (Sueyoshi and Goto 2013). This approach builds on a production accounting principle which allocates inputs and outputs to the country where the production takes place. This line of thinking is follows from the original conception and application of DEA to estimate production frontiers (Charnes et al. 1978; Farrell 1957). However, this production based approach has some limits when looking at the carbon leakage phenomenon.

Carbon leakage occurs when a country reduces its greenhouse gas emissions by substituting own production of carbon intensive goods with imports from another country (OECD 2006). The economic reason behind this substitution process often lies in different environmental regulations among countries which impose high costs for producing carbon intensive products in countries with restrictive regulations and low costs in countries with lax regulations. Firms may take advantage of such cost differentials and reallocate production from their home country with restrictive regulations to a country with less strict regulation country while still selling to customers in the country with strict regulations (Antimiani et al. 2013). In this case, emissions in the importing country with restrictive regulations are reduced while emissions in the exporting country with lax regulations increase. As Babiker and Rutherford (2005) points out, in the extreme case of perfectly substitutable and homogenous goods, carbon intensive industries completely relocate to lax regulation countries which can even increase the total amount of emitted CO_2 – totally offsetting abating efforts in strict regulation countries.

The interrelation between environmental regulation, trade and CO_2 emissions embodied in the traded goods has sparked a controversy about who is responsible for CO_2 emissions: the producer or the consumer (Guo et al. 2010; Liu et al. 2013). The answer to this question has changed over time. While traditionally, the producing site was held accountable for emissions, recent contributions emphasize a shared responsibility of both consumers and producers. The carbon leakage issue has important policy implications and is part of the recent negotiations for the new implementation agreement of United Nations Framework Convention on Climate Change (UNFCCC) (Arto et al. 2014). Recent estimates for the case of China – a large exporter of carbon intensive goods – reveal a difference of 38% in CO_2 emissions between a production based measurement approach compared to a consumption based measurement approach (Liu et al. 2013). Other studies also report differences between production and consumption based CO_2 for Spain and Italy (Alcántara and Padilla 2009; Marin et al. 2012) Brazil (Machado et al. 2001) and several Asian economies (Su and Ang 2011).

Building on these findings, we address the carbon leakage issue in this paper by using CO_2 as bad output based on *consumption* accounting approach in a DEA assessment. This differs from previous studies which measure CO_2 based on a *production* accounting approach and demarks a contribution of this paper. This means that a country's CO_2 output is measured on base of CO_2 embodied in the products and services consumed by this country. In the empirical section we show how both approaches to measure CO_2 result in different estimations of countries' technical efficiency and technical progress.

2.2 Nuclear waste and its leakage

The commercial generation of nuclear power rests on the fission of nuclear fuel – mostly consisting of Uranium 235 and Plutonium 239. The fission process releases large quantities of thermal energy which is transformed into electrical energy for commercial use. A by-product of the fission process is a variety of radionuclides which are in its current form no longer usable for energy generation (Crowley 1997). This "spent fuel"[1] is radioactive and decays over time. While some radionuclides have a short half-life period and decay in few decades, some other have very long half-life periods of 10,000+ years. The Nuclear Energy Agency estimates that of 2010 the cumulative amount of spent fuel in storage is approximately 175,000 tonnes of heavy metal (HM) while additional 5,000 tonnes HM arise each year (OECD 2012).

Previous studies investigating the environmental performance of countries have not incorporated nuclear waste as bad output but mainly concentrated on greenhouse gases as an undesirable output (Sueyoshi and Goto 2013; Zhou et al. 2008a). This is because these studies first and foremost made methodological contributions thereby paving the way to an adequate use of DEA methodology in the assessment of the environmental performance. Therefore they neglected using nuclear waste as bad output. However, there are important reasons why nuclear waste should be considered as a bad output. Firstly, a comparison of CO_2 and nuclear waste reveals similarities in important characteristics that qualify CO_2 as a bad output. Nuclear energy contributes a non-negligible share to the energy production

[1] Spent fuel is irradiated nuclear fuel which does no longer sustain a nuclear reaction in a nuclear power plant. We use the terms nuclear waste and spent fuel interchangeable throughout the paper.

in many industrialized economies. Nuclear waste is as inevitable a by-product of nuclear power generation as CO_2 is in the combustion of fossil fuels. In addition, there are high costs associated with nuclear waste either in reprocessing nuclear waste or a direct disposal in geological sites. Similar to CO_2, there are external effects and thus costs associated with particularly the disposal of spent fuel. Typically, these costs are underestimated and vary substantially due to a high degree of uncertainty and the long half-lives (Bunn et al. 2003; Taebi and Kloosterman 2008; von Hippel 2001). Taken together, CO_2 and spent fuel share important characteristics regarding the production of energy – making the case for spent fuel to be treated as bad output.

Secondly, the current nature of the Kyoto Protocol focussing on CO_2 abatement provides an incentive for countries to switch from fossil based energy production to nuclear power generation. By doing so, countries might emit fewer CO_2 but this comes at the cost of an increase in nuclear waste. Not considering nuclear waste in any assessment of environmental performance will arguably lead to distorted results in favour of countries relying on nuclear power (Cantner et al. 2007).

Quite similar to CO_2, there is also a leakage issue associated to spent fuel. This leakage issue arises if a country substitutes its energy production with imports of electrical energy from nuclear power plants from another country. Applying the idea of consumer responsibility in this case suggests that a country importing nuclear energy should be held responsible for the associated spent fuel arisings. Although, the amount of electrical energy imported or exported is relatively small compared to the total amount of energy produces in European countries, it is quite likely that a substantial share of this energy traded stems from nuclear power plants. This is due to the low operational costs of nuclear energy of existing nuclear power plants compared to the operational costs of power plants combusting fossil fuels. We, thus, adjust the amount of spent fuel with the amount of exported and imported spent fuel due to trade of electrical energy.

3. Methods and data

In the following, we present the DEA model we apply to measure the environmental performance of countries. Thereby we follow closely the approach of (Sueyoshi and Goto 2012a; Sueyoshi and Goto 2013). We compute annual leakage corrected and uncorrected efficiency scores for the years 2000-2009. Thereafter, we compare the deviation in the average of the leakage corrected scores over this time span and the average of the uncorrected scores. [2]

3.1 Strategic concepts for improving environmental performance

According to (Sueyoshi and Goto 2013), there are two basic approaches how DMUs can improve their environmental performance. The first of these approaches – termed as "managerial disposability" – emphasizes the role of technical progress in improving performance in complying with a set emission target for bad outputs. They make the example of a power plant that applies new technology to abate bad outputs. So even if the power plant increases its fuel input in order to increase energy production the undesirable emission of greenhouse gases decreases. In our setting, the environmental performance of a country improves because innovations in the energy sector (e.g., more efficient fuel, application of filter techniques) allow an increase in increase in unit output of good outputs per unit bad output.

The second approach is referred to as "natural disposability". Under natural disposability, a DMU complies to a set emission target for bad outputs by reducing the amount of inputs in the production process. Using again the power plant example from (Sueyoshi and Goto 2013), the power plant's objective is to reduce its inputs and bad outputs by obtaining a certain level of good outputs. In our setting, the environmental performance of countries improves by a simple reduction of inputs leading to a reduction of bad outputs.

[2] Unlike Sueyoshi and Goto Sueyoshi, T., and Goto, M. (2013). "DEA environmental assessment in a time horizon: Malmquist index on fuel mix, electricity and CO2 of industrial nations." *Energy Economics*, 40(0), 370-382. we are not interested in the development of environmental performance over time but restrict ourselves to a cross-sectional comparison of countries. The reason for this restriction is that we are interested in the differences of efficiency scores due to leakage correction but not in the dynamics of efficiency scores due to technical progress.

The difference of both approaches lies in the treatment of the DMUs' inputs in the DEA model which can substantially impact the DEA results. In order to avoid such methodology driven results differences confounding our analysis – aimed at revealing the impact of bad output leakage on the environmental performance of DMUs – we conduct our analysis under both strategic concepts. The robustness of our results is assured if differences in the environmental performance of DMUs due to bad output leakage persist under both the managerial and the natural disposability setting.

3.2 DEA model

Using the notation of (Sueyoshi and Goto 2013), suppose that there are n DMUs $(j = 1, \dots, n)$. The j-th DMU uses a vector of m inputs $\left(X_j = \left(x_{1j}, x_{2j}, \dots, x_{mj}\right)^T\right)$ to produce a vector of s good outputs $\left(G_j = (g_{1j}, g_{2j}, \dots, g_{sj})^T\right)$ but also a vector of h bad outputs $\left(B_j = (b_{1j}, b_{2j}, \dots, b_{hj})^T\right)$. It is assumed that these three vectors are strictly positive, which means that there is no decision making unit with a zero entry in one of the inputs or outputs. A vector of structural variables $(\lambda = (\lambda_1, \lambda_2, \dots, \lambda_n)^T)$ connects the inputs with the good and bad outputs by a convex combination. We apply a radial DEA approach.

Under *managerial disposability*, the degree of unified efficiency (UEM) for the k-th DMU is calculated by

(1) $UEM_k = 1 - \left[\xi^* + \varepsilon\left(\sum_{i=1}^{m} R_i^x d_i^{x*} + \sum_{r=1}^{s} R_r^g d_r^{g*} + \sum_{f=1}^{h} R_f^b d_f^{b*}\right)\right]$ with

Maximize $\xi + \varepsilon\left[\sum_{i=1}^{m} R_i^x d_i^x + \sum_{r=1}^{s} R_r^g d_r^g + \sum_{f=1}^{h} R_f^b d_f^b\right]$

s.t. $\sum_{j=1}^{n} x_{ij}\lambda_j - d_i^x = x_{ik} \quad (i = 1, \dots, m)$

$\sum_{j=1}^{n} g_{rj}\lambda_j - d_r^g - \xi g_{rk} = g_{rk} \quad (r = 1, \dots, s)$

$\sum_{j=1}^{n} b_{fj}\lambda_j + d_f^b + \xi b_{fk} = b_{fk} \quad (f = 1, \dots, h)$

$\lambda_j \geq 0 \ (j = 1, \dots, n) \ \xi = URS, d_i^x \geq 0 \ (i = 1, \dots m)$

$d_r^g \geq 0 \ (r = 1, \dots, s), \& \ d_f^b \geq 0 \ (f = 1, \dots, h).$

Under *natural disposability*, the degree of unified efficiency (UEN) is calculated for the k-th DMU by

(2) $UEN_k = 1 - \left[\xi^* + \varepsilon\left\{\sum_{i=1}^{m} R_i^x d_i^{x*} + \sum_{r=1}^{s} R_r^g d_r^{g*} + \sum_{f=1}^{h} R_f^b d_f^{b*}\right\}\right]$ with

Maximize $\xi + \varepsilon\left[\sum_{i=1}^{m} R_i^x d_i^x + \sum_{r=1}^{s} R_r^g d_r^g + \sum_{f=1}^{h} R_f^b d_f^b\right]$

s.t. $\sum_{j=1}^{n} x_{ij}\lambda_j + d_i^x = x_{ik} \quad (i = 1, \dots, m)$

$\sum_{j=1}^{n} g_{rj}\lambda_j - d_r^g - \xi g_{rk} = g_{rk} \quad (r = 1, \dots, s)$

$\sum_{j=1}^{n} b_{fj}\lambda_j + d_f^b + \xi b_{fk} = b_{fk} \quad (f = 1, \dots, h)$

$\lambda_j \geq 0\ (j = 1, \dots, n), \xi{:}\ URS, d_i^x \geq 0\ (i = 1, \dots m)$

$d_r^g \geq 0\ (r = 1, \dots, s), \&\ d_f^b \geq 0\ (f = 1, \dots, h).$

In Eq. (1) and (2) ξ denotes the inefficiency score of the k th DMU. This linear programs uses a series of slack variables for the inputs (d_i^x), good outputs (g_i^x) and bad outputs (b_i^x). The scalar ε balances the impact of the inefficiency score and the amount of slacks for the degree of technical efficiency.[3] The Rs in Eq. (1) and (2) determine the range of inputs, good and bad outputs as specified by:

$R_i^x = (m + s + h)^{-1}\left(\max\{x_{ij}|j = 1, \dots, n\} - \min\{x_{ij}|j = 1, \dots, n\}\right)^{-1}$,

$R_r^g = (m + s + h)^{-1}\left(\max\{g_{rj}|j = 1, \dots, n\} - \min\{g_{rj}|j = 1, \dots, n\}\right)^{-1}$, and

$R_f^b = (m + s + h)^{-1}\left(\max\{b_{fj}|j = 1, \dots, n\} - \min\{b_{fi}|j = 1, \dots, n\}\right)^{-1}$.

The efficiency scores (UEM and UEN) denotes the degree of efficiency of an DMU. An efficiency score of unity signals that the DMU is part of the efficiency frontier all inefficient DMUs are evaluated against. The lower the efficiency score, the less efficient the DMU is compared to the best practice efficiency frontier.

3.3 Data

We aim at a complete coverage of all forms of energy from their origins through to final uses. As this imposes high requirements for data availability, we limit our analysis to 23 countries in the European Union. Data for inputs and good outputs stem from the energy balances provided by Eurostat (see for a description of energy balances (OECD et al. 2005). Data for bad outputs are taken from various sources as described below. Note that time coverage for all data is 2000-2009. We

[3] We follow standard procedures to set this scalar to a very small number ($\varepsilon = 0.00001$).

however suppress the time subscript for notational ease. All data sources are summarised in Table 1.

Inputs: We regard the Gross Inland Consumption of all energy products (e.g., fossil fuels, nuclear heat, renewables) as input.

Good outputs: We use the sum of the Final Energy Consumption (fuels used for energy production purposes) and the Final Non-Energy Consumption (fuels used for non-energy purposes such as the transformation to synthetic organic products) as good output of the countries. Data stem from the country's energy balances (OECD et al. 2005).

Bad output CO_2: As Sections 2.1 and 2.2 indicate this study considers two bad outputs: CO_2 and nuclear waste as the by-product of energy production. Regarding the first bad output, it is well known that beside CO_2 other greenhouse gases such as Methan (CH_4) and Nitrous Oxide (N_2O) contribute to global warming. However, CO_2 is by a wide margin the most important of these greenhouse gases. According to estimates from the IPCC, CO_2 make up approximately three quarter of all greenhouse gas emissions.

We address the carbon leakage issue by using CO_2 as bad output based on the *consumption* accounting approach. This concerns the total amount of CO_2 embodied in all products and services consumed within a country. Recall that this consumption based approach differs from the often used *production* accounting approach under which one would use all CO_2 emitted in the production of goods and services as bad output of a country.

In order to calculate the leakage corrected CO_2 emissions for a set of EU-countries, we draw on the recently developed World Input-Output Database (WIOD) as described in (Timmer 2012). WIOD is a joined effort to provide statistical data on production processes that "are characterized by international fragmentation leading to an interdependent production structure" (Dietzenbacher et al. 2013). This interdependent production structure is due to the fact that globalization does not only fuel the international division of labour in the production of final products and services but also in intermediate goods (Grossman and Rossi-Hansberg 2008). In other words, while cars might be still assembled (and exported) in Germany, many of their components are not produced in Germany; they are imported. World input-output tables (WIOTs) allow following the flow of products both for intermediate and final use across industries and countries (see Dietzenbacher, Los, Stehrer, Timmer, & de Vries, 2013 for details of the WIOT construction process). An additional feature of the WIOD project are supplementary environmental accounts encompassing information on the emission of greenhouse gases at the industry level for the countries. Combining the world-input-output tables with the environmental accounts allows computing CO_2 emissions for countries based on a consumption approach as described below.

Suppose n countries $(j = 1, \dots, n)$ can be both producers and consumers of goods produced in s industrial sectors $(s = 1, \dots, b)$. From the viewpoint of production, countries and sectors are denoted with the subscript p and from the viewpoint of consumption the subscript c is used to denote the countries and sectors. The goods and services produced in sector sp in country jp and used in sector sc in country jc is given by $x_{jp,jc,sp,sc}$. The total sector output in a country is given by $x_{jp,sp} = \sum_{jc} \sum_{sc} x_{jp,jc,sp,sc}$ and the relatedCO$_2$ emissions before leakage correction in this sector is given by $CO2_{jp,js}$. Note that data on consumption of goods and services as well as CO_2 are on a yearly base (2000-2009). We however suppress the time subscript for ease of notation. In a first step we compute the share in total sector output $a_{jp,jc,sp,sc}$ of country (jp) producing goods in sector (sp) and exports them to sector (sc) of country (jc).

$$a_{jp,jc,sp,sc} = \frac{x_{jp,jc,sp,sc}}{x_{jp,sp}} \forall jp, jc, sp, sc$$

In a second step, we distribute the CO_2 emitted in the production process in sector sp in country jp among those sc sectors in the jc countries consuming the goods and services. This reads as in the following:

(4) $\quad CO2_{jp,jc,sp,sc} = a_{jp,jc,sp,sc} \cdot CO2_{jp,js}.$

Note that $CO2_{jp,jc,sp,sc}$ represents all CO_2 embodied in goods and services which are produced by sector jp in country sp but are consumed in sector js in country jc. Finally, we compute the leakage-corrected CO_2 emissions of country cj by aggregating leakage-corrected CO_2 emissions over all countries jp as well as all sectors sc and sp:

(5) $$CO2_{jc} = \sum_{jp} \sum_{sp} \sum_{sc} CO2_{jp,jc,sp,sc}$$

Hence, $CO2_{jc}$ denotes the total amount of CO_2 embodied in the goods and services consumed by country jc and corrected for carbon leakage.

Bad output nuclear waste: Nuclear waste is the second bad output this study considers. As an indicator for nuclear waste of the energy production we use spent fuel arisings taken from the yearly Nuclear Energy reports published by OECD/NEA. Note that the time series data is incomplete for Sweden and Slovenia. Missing values are interpolated using data on yearly changes in spent fuel storage and long run averages in the production of nuclear energy. For Bulgaria, Romania and Lithuania, no information on spent fuel arisings are reported at all. These data were estimated by an auxiliary regression explaining spent fuel arisings with the amount of nuclear energy produced in the OECD countries. This regression explains 71% of the variance in spent fuel arisings. The estimated coefficient for nuclear energy produced was then used in the linear prediction of spent fuel arisings.

As with CO_2, we address the leakage issue for nuclear waste following the consumption accounting approach. The leakage is due to the fact that nuclear energy is produced in one country but exported to and consumed in a different country. In order to calculate the leakage corrected spent fuel arisings we draw on data on electricity imports and exports of the European countries as published by Eurostat (NRG_125a and NRG_135a). These data represent the physical flow of energy between neighbouring countries. Combining these data with data on total net production of electrical energy (NRG_105a) allows the computation of leakage corrected nuclear waste which follows very closely the above described procedure of the allocation of CO_2 by constructing an Input-Output table. The main difference between the CO_2 and nuclear waste leakage correction is that information on energy production, energy trade, and nuclear waste is not available at the industry sector level but only at the country level.

Using the data on electricity imports, exports, and net electricity generation, we first build a matrix of the use of electricity production. Thereby $el_{jp,jc}$ denotes the amount of electricity produced in country jp but consume in country in country jc. The total amount of electricity generated is given by $el_{jp} = \sum_{jc} el_{jp,jc}$. The nuclear waste associated with this electricity generation before leakage correction is given by NW_{jp}. We then compute the share of consumption of electricity by country jc of electricity generated by country jp with

(6) $$a_{jp,jc} = \frac{el_{jp,jc}}{el_{jp}}.$$

Thereafter, we distribute the nuclear waste emitted in country jp among those jc countries consuming the electricity produced in country jp, which reads:

(7) $$NW_{jp,jc} = a_{jp,jc} \cdot NW_{jp}.$$

As a final step, we compute the leakage-corrected nuclear waste emissions of country jc by aggregating leakage-corrected nuclear waste emissions over all jp countries:

(8) $$NW_{jc} = \sum_{jp} NW_{jp,jc}.$$

NW_{jc} then denotes the total amount of nuclear waste embodied in the electricity consumed by country jc and corrected for nuclear waste leakage.

4. Results and discussion

4.1. Results

We begin presenting the results by displaying the importance of leakage correction. Figure 1 displays the percentage difference between the level of bad outputs before and after leakage correction. Regarding CO_2, most countries have higher CO_2 emissions after leakage correction. This concerns in particular Sweden (+34%) and Luxemburg (+42%). A few other countries such as Denmark (-22%) and Bulgaria (-15%) have lower CO2 emissions when applying the consumption accounting approach for leakage correction.

Regarding nuclear waste, Figure 1 only displays (for mathematical reasons) the percentage differences between leakage corrected and uncorrected spent fuel arisings for those countries which produce nuclear energy.[4] In general these differences are smaller in magnitude when compared to the CO_2 leakage differences. However, for some countries larger deviations arise. For example, the Netherlands (+16%) and Czech Republic (+5%) have higher levels of nuclear waste after leakage correction, while Hungary (-7%) and Slovenia (-5%) have considerably less nuclear waste after leakage correction. Not shown in Figure 1 are countries which do not produce nuclear energy but can be held accountable for some nuclear waste due to the import of energy from countries which produce nuclear energy. The absolute level of "imported" nuclear waste for these countries is rather low because the most important part of electrical energy is not exported but consumed in the country where it is produced.[5]

Table 2 displays the unified efficiency scores under managerial disposability (Eq. 1) and natural disposability (Eq. 2) for all countries. Note that we report the average of the yearly efficiency scores by countries. Thereby we distinguish between the efficiency scores with and without leakage correction. Recall that a higher efficiency score signals higher efficiency of the country transforming fuels into energy (with a maximum value of 1). Comparing the efficiency scores with leakage correction and without leakage correction reveals two interesting findings. Firstly, under managerial disposability much fewer countries have the highest possible efficiency score of unity with leakage correction (10 out of 23 countries) compared to without leakage correction (5 out of 23 countries). This suggests that many countries which would be regarded as efficient in the production of energy under the standard production accounting approach are not efficient under the consumption accounting approach. Analyzing the efficiency scores under natural disposability reveals the same pattern.

Secondly, most countries have lower efficiency scores with leakage correction then without leakage correction as shown in Figure 2.[6] Under managerial dis-

[4] Otherwise no percentages can be calculated.

[5] Nevertheless, the leakage correction helps solving a methodological problem inherent in DEA. Without leakage correction, many countries would have no nuclear waste and thus a zero in one of the output variables. Radial DEA approaches cannot handle zero entries. Thus, without leakage correction, a joint assessment of the environmental efficiency of countries using nuclear power with countries without nuclear power would not be possible.

[6] Some part of the changes in the efficiency scores might arise from changing projection sets.

posability only 6 out of 23 countries have higher efficiency scores without leakage correction, while 23 countries have lower efficiency scores (4 countries have unchanged efficiency scores). Denmark (-57%), Latvia (-37%) and Austria (-30%) account for the biggest drops in efficiency. In contrast Bulgaria (+19%) and Slovak Republic (+5%) are the only countries with substantial gains in efficiency when applying the consumption accounting approach.

We conducted several robustness checks. A major concern in DEA analysis is that the results might be sensitive to the method used. For our main analysis we used the DEA framework as described by (Sueyoshi and Goto 2012b). A drawback of this approach is that not all but only one optimal solution is found. Thus, we rerun the DEA analysis using the recently introduced DEA/SCSC model which imposes strong complementary slackness conditions on the maximization problem (Sueyoshi and Goto 2012a). The DEA/SCSC model can be found in the Appendix. Under managerial disposability, the results of the DEA/SCSC model do not differ substantially from our original DEA model.[7]

We also compare the DEA model with approaches applying different treatments of pollutants as bad output. The standard DEA model introduced by (Banker et al. 1984) (referred to as BCC) can be adjusted by treating pollutants as inputs which are minimized in the linear optimization model (Førsund 2009). Applying this procedure and treating CO_2 and nuclear waste as inputs does not substantially change our results.

4.2. Policy implications

The aim of the paper was to develop a correction method to address the leakage of pollutants which can be applied to the EU ETS framework. Based on a non-parametric benchmarking technique we evaluated the relative performance of EU countries using energy consumption as good output and nuclear waste and CO_2 as

[7] By conducting the DEA/SCSC model, we encountered the same problems as described by Krivonozhko, V. E., Førsund, F. R., and Lychev, A. V. (2012). "A note on imposing strong complementary slackness conditions in DEA." *European Journal of Operational Research*, 220(3), 716-721. such as DMUs with below unity efficiency scores being part of the reference set for other inefficient DMUs. In addition, no unique solution could be identified under natural disposability.

bad outputs. We corrected for leakage with the application of a consumption accounting approach which allocated bad outputs not to the country producing carbon intensive goods or nuclear energy but to the country consuming these goods and using this nuclear energy. As a result countries which do not produce but import carbon intensive goods and services (or nuclear energy) have lower efficiency scores when correcting for leakage.

This mechanism effectively addresses the leakage issue and can be applied to the allocation of allowances in the EU ETS. In the current phase of the EU ETS, most allowances are allocated by benchmarking. An installation is granted allowances for CO_2 emissions not based on their historical emission level (grandfathering) but receive allowances of the average of the 10% best performing installations in the industrial sector (adjusted for the size of the installation). This level of allocated allowances can be adjusted by a leakage correction factor. For example, under managerial disposability Finland is 9% less efficient with leakage correction compared to without leakage correction. All Finish installations, then, receive 9% less allowances reflecting leakage correction. In contrast, all Lithuanian installations would receive 2% more allowances in the benchmarking setting then before.

The above paragraph admittedly describes only a sketch of the applicability of our leakage correction framework. In more advanced settings not only the relative performance at one point in time for each country could be used to determine a correction factor but also the change of the performance over time. Countries that invest in technological progress shift the DEA best-practice production frontier leading to fewer emissions. In a dynamic DEA approach the effect of technological progress can be singled out by comparing best-practice production frontiers in different time periods. Countries at the forefront of the technological development can be rewarded by receiving more allowances than other countries.

One major advantage of our leakage correction approach is that it is doesn't distort international trade. Other approaches for carbon leakage suggest carbon tariffs on imports and rebates for exports based on the carbon content of the traded goods and services. Although carbon tariffs are in general legal under current WTO law, there are many legal obstacles that limit the applicability of such taxing and rebating (Veel 2009). Of course the problem remains that our approach works best when all major economies participate in this scheme. Another advantage of our approach is that it can be easily linked with the current system of allowance allocation within the EU ETS.

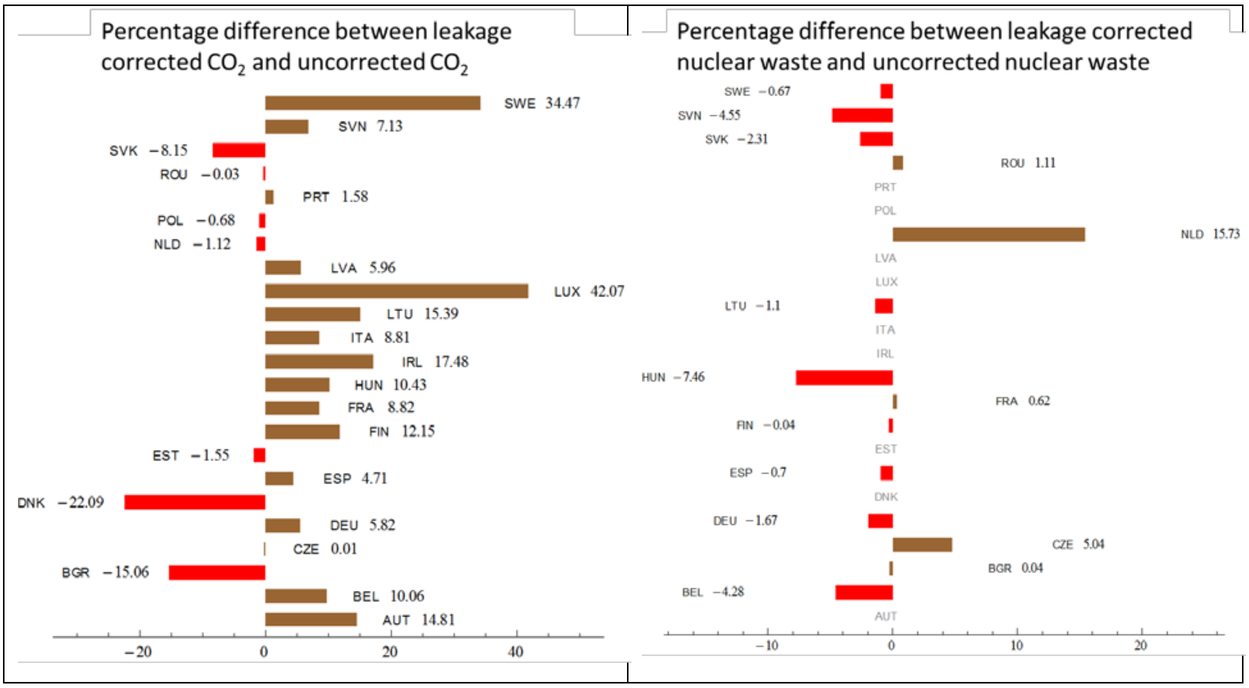
Table 1: Average of inputs and outputs (2000-2009)

Country	Gross inland consumption of energy products in 1000 tonnes of oil equivalent	Final energy + non-energy consumption in 1000 tonnes of oil equivalent	CO_2 before leakage correction in 1000 tonnes	CO_2 before leakage correction in1000 tonnes	Nuclear waste in tonnes of heavy metal before leakage correction	Nuclear waste in tonnes of heavy metal after leakage correction
AUT	637	2193	52497	60323	0.00	2.22
BEL	904	3663	99065	108697	118.54	113.25
BGR	1007	1516	47094	39464	159.42	159.61
CZE	2851	6042	105408	105654	68.83	71.84
DEU	12404	16291	697904	737924	406.67	399.75
DNK	758	407	79710	61663	0.00	2.42
ESP	3172	2943	267247	279961	155.17	154.02
EST	404	193	15287	15114	0.00	0.62
FIN	1026	1523	61612	69102	69.71	69.74
FRA	2273	8711	284515	309850	1028.67	1034.81
HUN	468	1059	47007	52183	47.96	44.25
IRL	382	1033	32210	37754	0.00	0.00
ITA	2580	6290	381718	414717	0.00	0.36
LTU	30	282	12387	14185	145.00	143.62
LUX	13	133	3203	4550	0.00	0.82
LVA	15	124	7400	7855	0.00	6.08
NLD	1386	2801	166394	165155	11.00	12.42
POL	8736	20248	284973	282581	0.00	4.30
PRT	538	200	57557	58478	0.00	0.47
ROU	1249	2248	93473	93312	131.71	133.17
SVK	680	2251	36847	33644	57.04	55.76
SVN	204	166	12836	13746	15.08	14.44
SWE	434	2133	49736	67043	179.25	177.35

Table 2: Unified Efficiency under different models

	Mangerial Disposability		Natural Disposability	
Country	Unified efficiency without leakage correction	Unified efficiency with leakage correction	Unified efficiency without leakage correction	Unified efficiency with leakage correction
AUT	1.00	0.70	1.00	1.00
BEL	0.68	0.64	1.00	1.00
BGR	0.74	0.88	0.64	0.72
CZE	0.91	0.90	0.90	0.89
DEU	1.00	1.00	0.76	0.76
DNK	1.00	0.43	1.00	0.31
ESP	0.39	0.37	0.27	0.26
EST	1.00	1.00	1.00	0.88
FIN	0.58	0.53	0.53	0.49
FRA	0.60	0.57	1.00	1.00
HUN	0.50	0.47	0.57	0.55
IRL	1.00	0.78	1.00	0.95
ITA	1.00	1.00	1.00	1.00
LTU	0.56	0.57	0.99	0.99
LUX	1.00	1.00	1.00	1.00
LVA	1.00	0.64	1.00	0.85
NLD	0.39	0.39	0.60	0.60
POL	1.00	1.00	1.00	1.00
PRT	1.00	0.83	1.00	0.78
ROU	0.51	0.52	0.53	0.52
SVK	0.94	0.99	1.00	1.00
SVN	0.71	0.72	0.40	0.45
SWE	0.77	0.63	1.00	1.00

Figure 1: Differences in bad outputs due to leakage correction

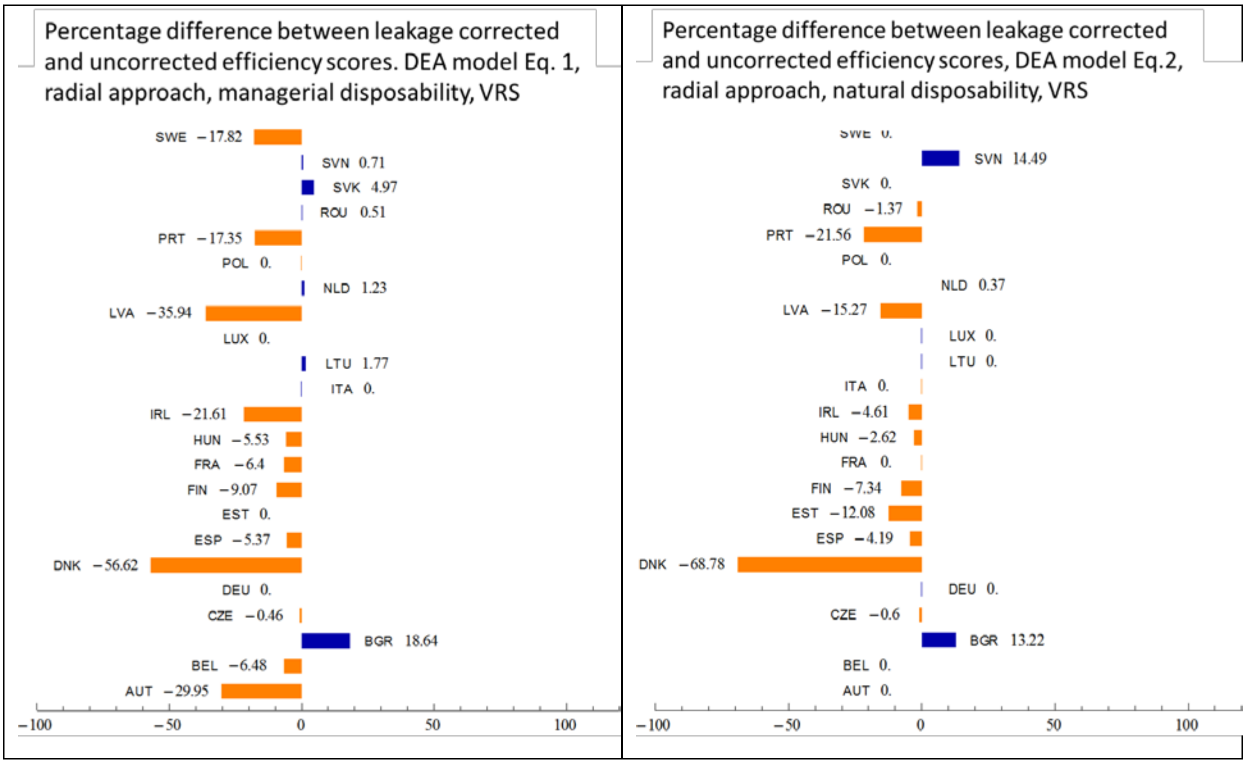


Notes: Percentage difference between leakage corrected and uncorrected bad outputs

Left: CO2, $\frac{CO2_{cj}-CO2_{jp}}{CO2_{jp}}$, mean values 2000-2009

Right: Nuclear waste, $\frac{NW_{jc}-NW_{jp}}{NW_{jp}}$, mean values 2000-2009

Figure 2: Differences in efficiency scores due to leakage correction



Notes: Percentage difference of efficiency scores

Left: $\frac{UEM_{cj} - UEM_{jp}}{UEM_{jp}}$, mean values 2000-2009

Right: $\frac{UEN_{jc} - UEN_{jp}}{UEN_{jp}}$, mean values 2000-2009

Appendix

DEA models with SCSCs

For every primal model of a linear program – as displayed in Eqs. (1) and (2) – there exists a corresponding dual model. Both, the primal and the dual model can have a set of feasible solutions. In order to find an optimal and unique solution of both, the dual and the primal model, the linear program must satisfy the strong complementary slackness conditions (SCSCs) (Sierksma, 1996). One way to incorporate SCSCs is to combine the primal and dual problem and additionally introducing a new decision variable η that assures an optimal solution of the linear program (Sueyoshi and Goto, 2012).

Under *managerial disposability*, the DEA model with SCSCs can be calculated by

(3) $UEM_k = 1 - \left[\xi^* + \varepsilon\left(\sum_{i=1}^m R_i^x d_i^{x*} + \sum_{r=1}^s R_r^g d_r^{g*} + \sum_{f=1}^h R_f^b d_f^{b*}\right)\right]$ with

Maximize $\xi + \varepsilon\left[\sum_{i=1}^m R_i^x d_i^x + \sum_{r=1}^s R_r^g d_r^g + \sum_{f=1}^h R_f^b d_f^b\right]$

s.t. $\sum_{j=1}^n x_{ij}\lambda_j - d_i^x = x_{ik}$ $(i = 1, \dots, m)$

$\sum_{j=1}^n g_{rj}\lambda_j - d_r^g - \xi g_{rk} = g_{rk}$ $(r = 1, \dots, s)$

$\sum_{j=1}^n b_{fj}\lambda_j + d_f^b + \xi b_{fk} = b_{fk}$ $(f = 1, \dots, h)$

$\lambda_j \geq 0$ $(j = 1, \dots, n)$ $\xi: URS, d_i^x \geq 0$ $(i = 1, \dots m)$

$d_r^g \geq 0$ $(r = 1, \dots, s), \& \; d_f^b \geq 0$ $(f = 1, \dots, h)$

Minimize $-\sum_{i=1}^m v_i x_{ik} - \sum_{r=1}^s u_r g_{rk} + \sum_{f=1}^h w_f b_{fk} + \sigma$

s.t. $-\sum_{i=1}^m v_i x_{ij} - \sum_{r=1}^s u_r g_{rj} + \sum_{f=1}^h w_f b_{fj} + \sigma \geq 0, (j = 1, \dots, n)$

$\sum_{r=1}^s u_r g_{rk} + \sum_{f=1}^h w_f b_{fk} = 1$

$v_i \geq \varepsilon R_i^x$ $(i = 1, \dots, m)$, $u_r \geq \varepsilon R_r^g$ $(r = 1, \dots, s)$, $w_f \geq \varepsilon R_f^b$ $(f = 1, \dots, h)$

σ: URS.

Additional constraints

$\varepsilon\left[\sum_{i=1}^m R_i^x d_i^x + \sum_{r=1}^s R_r^g d_r^g + \sum_{f=1}^h R_f^b d_f^b\right] = \sum_{i=1}^m v_i x_{ik} - \sum_{r=1}^s u_r g_{rk} + \sum_{f=1}^h w_f b_{fk} + \sigma$

$\lambda_j + \sum_{i=1}^m v_i x_{ij} - \sum_{r=1}^s u_r g_{rj} + \sum_{f=1}^h w_f b_{fj} + \sigma \geq \eta, (j = 1, \dots, m)$

$d_i^x + v_i - \varepsilon R_i^x \geq \eta$ $(i = 1, \dots, m)$

$d_r^g + u_r - \varepsilon R_r^g \geq \eta$ $(r = 1, \dots, s)$

$d_f^b + w_f - \varepsilon R_f^b \geq \eta$ $(f = 1, \dots, h)$

$\eta \geq 0.$

Under *natural disposability*, the DEA model with SCSCs can be calculated by

(4) $UEN_k = 1 - \left[\xi^* + \varepsilon\left(\sum_{i=1}^m R_i^x d_i^{x*} + \sum_{r=1}^s R_r^g d_r^{g*} + \sum_{f=1}^h R_f^b d_f^{b*}\right)\right]$ with

Maximize $\xi + \varepsilon\left[\sum_{i=1}^m R_i^x d_i^x + \sum_{r=1}^s R_r^g d_r^g + \sum_{f=1}^h R_f^b d_f^b\right]$

s.t. $\sum_{j=1}^n x_{ij}\lambda_j + d_i^x = x_{ik}$ $(i = 1, \dots, m)$

$\sum_{j=1}^n g_{rj}\lambda_j - d_r^g - \xi g_{rk} = g_{rk}$ $(r = 1, \dots, s)$

$\sum_{j=1}^n b_{fj}\lambda_j + d_f^b + \xi b_{fk} = b_{fk}$ $(f = 1, \dots, h)$

$\lambda_j \geq 0$ $(j = 1, \dots, n)$ $\xi: URS, d_i^x \geq 0$ $(i = 1, \dots m)$

$d_r^g \geq 0$ $(r = 1, \dots, s), \& \; d_f^b \geq 0$ $(f = 1, \dots, h)$

$$\text{Minimize } -\sum_{i=1}^{m} v_i x_{ik} \ -\sum_{r=1}^{s} u_r g_{rk} \ +\sum_{f=1}^{h} w_f b_{fk} + \sigma$$

s.t. $\sum_{i=1}^{m} v_i x_{ij} \ -\sum_{r=1}^{s} u_r g_{rj} \ +\sum_{f=1}^{h} w_f b_{fj} + \sigma \geq 0, (j = 1, \dots, n)$

$\sum_{r=1}^{s} u_r g_{rk} \ +\sum_{f=1}^{h} w_f b_{fk} = 1$

$v_i \geq \varepsilon R_i^x \ (i = 1, \dots, m),\ u_r \geq \varepsilon R_r^g \ (r = 1, \dots, s),\ w_f \geq \varepsilon R_f^b \ (f = 1, \dots, h)$

$\sigma\text{: URS.}$

Additional constraints

$\varepsilon\left[\sum_{i=1}^{m} R_i^x d_i^x + \sum_{r=1}^{s} R_r^g d_r^g + \sum_{f=1}^{h} R_f^b d_f^b\right] = \sum_{i=1}^{m} v_i x_{ik} \ -\sum_{r=1}^{s} u_r g_{rk} \ +\sum_{f=1}^{h} w_f b_{fk} + \sigma$

$\lambda_j + \sum_{i=1}^{m} v_i x_{ij} \ -\sum_{r=1}^{s} u_r g_{rj} \ +\sum_{f=1}^{h} w_f b_{fj} + \sigma \geq \eta, (j = 1, \dots, m)$

$d_i^x + v_i - \varepsilon R_i^x \geq \eta \ (i = 1, \dots, m)$

$d_r^g + u_r - \varepsilon R_r^g \geq \eta \ (r = 1, \dots, s)$

$d_f^b + w_f - \varepsilon R_f^b \geq \eta \ (f = 1, \dots, h)$

$\eta \geq 0$

References

Alcántara, V., and Padilla, E. (2009). "Input–output subsystems and pollution: An application to the service sector and CO2 emissions in Spain." *Ecological Economics*, 68(3), 905-914.

Antimiani, A., Costantini, V., Martini, C., Salvatici, L., and Tommasino, M. C. (2013). "Assessing alternative solutions to carbon leakage." *Energy Economics*, 36(3), 299-311.

Arto, I., Rueda-Cantuche, J. M., Andreoni, V., Mongelli, I., and Genty, A. (2014). "The game of trading jobs for emissions." *Energy Policy*, 66(0), 517-525.

Babiker, M. H., and Rutherford, T. F. (2005). "The economic effects of border measures in subglobal climate agreements." *The Energy Journal*, 26(4), 99-125.

Banker, R. D., Charnes, A., and Cooper, W. W. (1984). "Some models for estimating technical and scale inefficiencies in data envelopment analysis." *Management Science*, 30(9), 1078.

Bunn, M., Fetter, S., Holdren, J., and van der Zwaan, B. (2003). *The economics of reprocessing vs. direct disposal of spent nuclear fuel*. Harvard University, Cambridge, MA.

Cantner, U., Krüger, J., and Hanusch, H. (2007). *Produktivitäts- und Effizienzanalyse: der nichtparametrische Ansatz*, Berlin: Springer.

Charnes, A., Cooper, W. W., and Rhodes, E. (1978). "Measuring the efficiency of decision making units." *European Journal of Operational Research*, 2(6), 429-444.

Chen, C.-M. (2013). "A critique of non-parametric efficiency analysis in energy economics studies." *Energy Economics*, 38(0), 146-152.

Clò, S. (2010). "Grandfathering, auctioning and Carbon Leakage: Assessing the inconsistencies of the new ETS Directive." *Energy Policy*, 38(5), 2420-2430.

Copeland, B. R., and Taylor, M. S. (2004). "Trade, growth, and the environment." *Journal of Economic Literature*, 42(1), 7-71.

Crowley, K. D. (1997). "Nuclear waste disposal: The technical challenges." *Physics Today*, 50(6), 32.

Dietzenbacher, E., Los, B., Stehrer, R., Timmer, M., and de Vries, G. (2013). "The construction of world input-output tables in the WIOD project." *Economic Systems Research*, 25(1), 71-98.

Färe, R., Grosskopf, S., and Hernandez-Sancho, F. (2004). "Environmental performance: an index number approach." *Resource and Energy Economics*, 26(4), 343-352.

Färe, R., Grosskopf, S., Lovell, C. A. K., and Pasurka, C. (1989). "Multilateral productivity comparisons when some outputs are undesirable: a nonparametric approach." *The Review of Economics and Statistics*, 71(1), 90-98.

Farrell, M. J. (1957). "The Measurement of Productive Efficiency." *Journal of the Royal Statistical Society. Series A (General)*, 120(3), 253-290.

Førsund, F. R. (2009). "Good modelling of bad outputs: Pollution and multiple-output production." *International Review of Environmental and Resource Economics*, 3(1), 1-38.

Grossman, G. M., and Rossi-Hansberg, E. (2008). "Trading tasks: a simple theory of offshoring." *American Economic Review*, 98(5), 1978-1997.

Guo, J., Zou, L.-L., and Wei, Y.-M. (2010). "Impact of inter-sectoral trade on national and global CO2 emissions: An empirical analysis of China and US." *Energy Policy*, 38(3), 1389-1397.

Krivonozhko, V. E., Førsund, F. R., and Lychev, A. V. (2012). "A note on imposing strong complementary slackness conditions in DEA." *European Journal of Operational Research*, 220(3), 716-721.

Liu, Y., Jayanthakumaran, K., and Neri, F. (2013). "Who is responsible for the CO2 emissions that China produces?" *Energy Policy*, 62(0), 1412-1419.

Løken, E. (2007). "Use of multicriteria decision analysis methods for energy planning problems." *Renewable and Sustainable Energy Reviews*, 11(7), 1584-1595.

Machado, G., Schaeffer, R., and Worrell, E. (2001). "Energy and carbon embodied in the international trade of Brazil: an input–output approach." *Ecological Economics*, 39(3), 409-424.

Marin, G., Mazzanti, M., and Montini, A. (2012). "Linking NAMEA and Input output for 'consumption vs. production perspective' analyses: Evidence on emission efficiency and aggregation biases using the Italian and Spanish environmental accounts." *Ecological Economics*, 74(0), 71-84.

OECD. (2006). *The political economy of environmentally related taxes*, Paris: OECD.

OECD. (2012). *Nuclear Energy Data 2012*. Paris.

OECD, IEA, and Eurostat. (2005). *Energy Statistics Manual*, Paris.

Pittman, R. W. (1983). "Multilateral productivity comparisons with undesirable outputs." *The Economic Journal*, 93(372), 883-891.

Su, B., and Ang, B. W. (2011). "Multi-region input–output analysis of CO2 emissions embodied in trade: The feedback effects." *Ecological Economics*, 71(0), 42-53.

Sueyoshi, T., and Goto, M. (2012a). "DEA radial and non-radial models for unified efficiency under natural and managerial disposability: Theoretical extension by strong complementary slackness conditions." *Energy Economics*, 34(3), 700-713.

Sueyoshi, T., and Goto, M. (2012b). "Returns to scale and damages to scale on U.S. fossil fuel power plants: Radial and non-radial approaches for DEA environmental assessment." *Energy Economics*, 34(6), 2240-2259.

Sueyoshi, T., and Goto, M. (2013). "DEA environmental assessment in a time horizon: Malmquist index on fuel mix, electricity and CO2 of industrial nations." *Energy Economics*, 40(0), 370-382.

Taebi, B., and Kloosterman, J. L. (2008). "To Recycle or Not to Recycle? An Intergenerational Approach to Nuclear Fuel Cycles." *Science and Engineering Ethics*, 14(2), 177-200.

Timmer, M. E. (2012). *The world input-output database (WIOD): contents, sources and methods*.

Veel, P.-E. (2009). "Carbon tariffs and the WTO: An evaluation of feasible policies." *Journal of International Economic Law*, 12(3), 749-800.

von Hippel, F. N. (2001). "Plutonium and reprocessing of spent nuclear fuel." *Science*, 293(5539), 2397-2398.

Zhou, P., Ang, B. W., and Han, J. Y. (2010). "Total factor carbon emission performance: A Malmquist index analysis." *Energy Economics*, 32(1), 194-201.

Zhou, P., Ang, B. W., and Poh, K. L. (2006). "Decision analysis in energy and environmental modeling: An update." *Energy*, 31(14), 2604-2622.

Zhou, P., Ang, B. W., and Poh, K. L. (2008a). "Measuring environmental performance under different environmental DEA technologies." *Energy Economics*, 30(1), 1-14.

Zhou, P., Ang, B. W., and Poh, K. L. (2008b). "A survey of data envelopment analysis in energy and environmental studies." *European Journal of Operational Research*, 189(1), 1-18.

Zofío, J. L., and Prieto, A. M. (2001). "Environmental efficiency and regulatory standards: the case of CO2 emissions from OECD industries." *Resource and Energy Economics*, 23(1), 63-83.

Diskussionspapiere aus dem Institut für Volkswirtschaftslehre der Technischen Universität Ilmenau

Nr. 42 *Steinrücken, Torsten; Jaenichen, Sebastian:* Wer ist wirklich reich? - Zu Problemen der Wohlfahrtsmessung durch das Bruttoinlandsprodukt, April 2005.

Nr. 43 *Steinrücken, Torsten; Jaenichen, Sebastian:* Wo bleiben die Subventionssteuern? - Probleme des Beihilfenrechts und ein alternatives Regulierungskonzept, Mai 2005.

Nr. 44 *Jaenichen, Sebastian; Steinrücken, Torsten; Schneider, Lutz:* Zu den ökonomischen Wirkungen gesetzlicher Feiertage - Eine Diskussion unter besonderer Berücksichtigung der Arbeitszeitpolitik, Juni 2005.

Nr. 45 *Kuchinke, Björn A.:* Qualitätswettbewerb zwischen deutschen Akutkrankenhäusern unter besonderer Berücksichtigung von DRG und Budgets, Juni 2005.

Nr. 46 *Kuchinke, Björn A.; Walterscheid, Heike:* Wo steht der Osten? Eine ökonomische Analyse anhand von Wohlfahrts- und Happinessindikatoren, Juni 2005.

Nr. 47 *Kuchinke, Björn A.; Schubert, Jens M.:* Staatliche Zahlungen an Krankenhäuser: Eine juristische und ökonomische Einschätzung nach Altmark Trans und der Entscheidung der Kommission vom 13.7.2005, August 2005.

Nr. 48 *Steinrücken, Torsten; Jaenichen, Sebastian:* Überkapazitäten zur Absicherung politischer Risiken und Instrumente finanzwirtschaftlicher Gegensteuerung, November 2005.

Nr. 49 *Jaenichen, Sebastian; Steinrücken, Torsten:* Opel, Thüringen und das Kaspische Meer, Januar 2006.

Nr. 50 *Kallfaß, Hermann H.:* Räumlicher Wettbewerb zwischen Allgemeinen Krankenhäusern, Februar 2006.

Nr. 51 *Sickmann, Jörn:* Airport Slot Allocation, März 2006.

Nr. 52 *Kallfaß, Hermann H.; Kuchinke, Björn A.:* Die räumliche Marktabgrenzung bei Zusammenschlüssen von Krankenhäusern in den USA und in Deutschland: Eine wettbewerbsökonomische Analyse, April 2006.

Nr. 53 *Bamberger, Eva; Bielig, Andreas:* Mehr Beschäftigung mittels weniger Kündigungsschutz? Ökonomische Analyse der Vereinbarungen des Koalitionsvertrages vom 11. 11. 2005, Juni 2006.

Nr. 54 *Jaenichen, Sebastian; Steinrücken, Torsten:* Zur Ökonomik von Steuergeschenken - Der Zeitverlauf als Erklärungsansatz für die effektive steuerliche Belastung, Dezember 2006.

Nr. 55 *Jaenichen, Sebastian; Steinrücken, Torsten:* Wirkt eine Preisregulierung nur auf den Preis? Anmerkungen zu den Wirkungen einer Preisregulierung auf das Werbevolumen, Mai 2007.

Nr. 56 *Kuchinke, B. A.; Sauerland, D.; Wübker, A.:* Determinanten der Wartezeit auf einen Behandlungstermin in deutschen Krankenhäusern - Ergebnisse einer Auswertung neuer Daten, Februar 2008.

Nr. 57 *Wegehenkel, Lothar; Walterscheid, Heike:* Rechtsstruktur und Evolution von Wirtschaftssystemen - Pfadabhängigkeit in Richtung Zentralisierung?, Februar 2008.

Nr. 58 *Steinrücken, Torsten; Jaenichen, Sebastian:* Regulierung und Wohlfahrt in einem Modell mit zwei Aktionsparametern, März 2008.

Nr. 59 *Lehnert, Ninja M.:* Externe Kosten des Luftverkehrs - Ein Überblick über den aktuellen Stand der Diskussion, April 2008.

Nr. 60 *Walterscheid, Heike:* Reformbedarf etablierter Demokratien im Kontext dezentralisierter Gesellschaftssysteme - Grundlegende Hindernisse bei Steuersystemreformen", April 2010.

Nr. 61 *Walterscheid, Heike; Wegehenkel, Lothar:* Kostenstruktur, Zahlungsbereitschaft und das Angebot von Mediengütern auf Medienmärkten, Juni 2008.

Nr. 62 *Walterscheid, Heike; Wegehenkel, Lothar:* Wohlstand der Nationen und handlungsrechtliche Struktur eines Gesellschaftssystems, September 2008.

Nr. 63 *Dewenter, Ralf; Haucap, Justus; Wenzel, Tobias:* Indirect Network Effects with Two Salop Circles: The Example oft the Music Industry, Juni 2009.

Nr. 64 *Dewenter, Ralf; Jaschinski, Thomas; Wiese, Nadine:* Wettbewerbliche Auswirkungen eines nichtneutralen Internets, Juli 2009.

Nr. 65 *Dewenter, Ralf; Haucap, Justus; Kuchinke, Björn A.:* Das Glück und Unglück von Studierenden aus Ost- und Westdeutschland: Ergebnisse einer Befragung in Ilmenau, Bochum und Hamburg, Oktober 2009.

Nr. 66 *Kuchinke, Björn A.; Zerth, Jürgen; Wiese, Nadine:* Spatial Competition between Health Care Providers: Effects of Standardization, Oktober 2009.

Nr. 67 *Itzenplitz, Anja; Seifferth-Schmidt, Nicole:* Warum Klimakonferenzen scheitern, aber dennoch zum Wohl des Weltklimas kooperiert wird, Juli 2010.

Nr. 68 *Kallfaß, Hermann H.:* Die Aufmerksamkeit für, die Nutzung der und die Werbung in Medien in Deutschland, November 2010.

Nr. 69 *Budzinski, Oliver:* Empirische Ex-Post Evaluation von wettbewerbspolitischen Entscheidungen: Methodische Anmerkungen, Januar 2012.

Nr. 70 *Budzinski, Oliver:* The Institutional Framework for Doing Sports Business: Principles of EU Competition Policy in Sports Markets, January 2012.

Nr. 71 *Budzinski, Oliver; Monostori, Katalin:* Intellectual Property Rights and the WTO, April 2012.

Nr. 72 *Budzinski, Oliver:* International Antitrust Institutions, Juli 2012.

Nr. 73 *Lindstädt, Nadine; Budzinski, Oliver:* Newspaper vs. Online Advertising - Is There a Niche for Newspapers in Modern Advertising Markets?

Nr. 74 *Budzinski, Oliver; Lindstädt, Nadine:* Newspaper and Internet Display Advertising - Co-Existence or Substitution?, Juli 2012b.

Nr. 75 *Budzinski, Oliver:* Impact Evaluation of Merger Control Decisions, August 2012.

Nr. 76 *Budzinski, Oliver; Kuchinke, Björn A.:* Deal or No Deal? Consensual Arrangements as an Instrument of European Competition Policy, August 2012.

Nr. 77 *Pawlowski, Tim, Budzinski, Oliver:* The (Monetary) Value of Competitive Balance for Sport Consumers, Oktober 2012.

Nr. 78 *Budzinski, Oliver:* Würde eine unabhängige europäische Wettbewerbsbehörde eine bessere Wettbewerbspolitik machen?, November 2012.

Nr. 79 *Budzinski, Oliver; Monostori, Katalin; Pannicke, Julia:* Der Schutz geistiger Eigentumsrechte in der Welthandelsorganisation - Urheberrechte im TRIPS Abkommen und die digitale Herausforderung, November 2012.

Nr. 80 *Beigi, Maryam H. A.; Budzinski, Oliver:* On the Use of Event Studies to Evaluate Economic Policy Decisions: A Note of Caution, Dezember 2012.

Nr. 81 *Budzinski, Oliver; Beigi, Maryam H. A.:* Competition Policy Agendas for Industrializing Countries, Mai 2013.

Nr. 82 *Budzinski, Oliver; Müller, Anika:* Finanzregulierung und internationale Wettbewerbsfähigkeit: der Fall Deutsche Bundesliga, Mai 2013.

Nr. 83 *Doose, Anna Maria:* Methods for Calculating Cartel Damages: A Survey, Dezember 2013.

Nr. 84 *Pawlowski, Tim; Budzinski, Oliver:* Competitive Balance and Attention Level Effects: Theore-tical Considerations and Preliminary Evidence, März 2014.

Nr. 85 *Budzinski, Oliver:* The Competition Economics of Financial Fair Play, März 2014.

Nr. 86 *Budzinski, Oliver; Szymanski, Stefan:* Are Restrictions of Competition by Sports Associations Horizontal or Vertical in Nature?, März, 2014.

Nr. 87 *Budzinski, Oliver:* Lead Jurisdiction Concepts Towards Rationalizing Multiple Competition Policy Enforcement Procedures, Juni 2014.

Nr. 88 *Budzinski, Oliver:* Bemerkungen zur ökonomischen Analyse von Sicherheit, August 2014.

Nr. 89 *Budzinski, Oliver; Pawlowski, Tim:* The Behavioural Economics of Competitive Balance: Implications for League Policy and Championship Management, September 2014.