ESTIMATION OF ENVIRONMENTAL INEFFICIENCIES AND SHADOW PRICES OF POLLUTANTS: A CROSS-COUNTRY APPROACH

by

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Abstract

ESTIMATION OF ENVIRONMENTAL INEFFICIENCIES AND SHADOW PRICES OF UNDESIRABLE OUTPUTS: A CROSS-COUNTRY APPROACH

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Various measures of technical efficiency, such as output distance function, input distance function and directional distance function can be used as sustainability indicators in the case when some outputs produced are undesirable, such as pollution. Shadow prices of environmental pollution asses short run perspectives of increase in pollution when desirable output is increased and may serve as a reference value for environmental taxes and prices for international emission trade. We make an attempt to estimate environmental efficiencies of countries (based on the output distance function with general directional vector) as well as shadow prices for selected pollutants (CO_2, SO_2 and NO_x). Two alternative estimation approaches are employed: parametric (Translog specification) and nonparametric (DEA). Statistical characteristics of the obtained parametric estimates are assessed using the smooth homogeneous bootstrap technique. Our results indicate that, on average, countries value pollutants proportionally to their direct impact on human health (*i.e.* the most hazardous pollutants have the highest shadow prices). We find that in general both rich and poor countries can be fully environmentally efficient, while most of the countries in transition (CITs) turned out to be inefficient. Our findings imply that under emission permit trade agreements CITs will generally be permit sellers. By selling permits they will hamper their future ability of economic growth, thus some restrictions (which we propose) must be made in such agreements to limit their unsustainability for CITs. Our estimates show that currently global wealth and pollution are allocated inefficiently. We determine that different estimation techniques provide with statistically different estimates. The work provides with illustrative examples of using the estimates to draw forecasts on environmental effect of economic growth; to determine price range on international pollution permit markets and to estimate economically justified rates of environmental taxation. Finally, we provide policy implications and outline potential directions for the future studies in the field.

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LIST OF ABBREVIATIONS

A1-A13	Axiom 1 through 13
BC	bias corrected
CITs	countries in transition
CO_2	carbon dioxide
DEA	data envelopment analysis
DMU	decision making units
DV	directional vector
ER	efficiency rule
ESI	Environmental Sustainability Index
IDF	input distance function
NIRS	non-increasing returns to scale
NO	nitric oxide (nitrogen monoxide)
NO_2	nitrogen dioxide
NO_x	nitrogen oxides
NYSDEC	New York State Department of Environmental Conservation
ODDF	output directional distance function
ODF	output distance function
OHE	output oriented hyperbolic efficiency measure
PPF	production possibility frontier
PPP	purchasing power parity
SD	sustainable development
SFA	stochastic frontier analysis
SO_2	sulfur dioxide
SO_3	sulfur trioxide
VRS	various returns to scale
WB	World Bank
WCED	World Commission on Environment and Development
WEF	World Environmental Forum
WRI	World Resource Institute

Chapter 1

INTRODUCTION

At the modern age characterized by an unprecedented technological breakthrough, the humankind still cannot develop a single technological process producing only desirable products. These outputs vary from fully materialistic, such as pollution from industrial production, to the abstract, such as moral degradation from production of pornography. The undesirable outputs yield negative revenue (*i.e.* cost), since otherwise they would be desirable as any by-product produced at no cost but yielding a revenue, hence increasing a profit. These costs can be carried by the producers, but mostly they are transferred to a third party, in which case we deal with external costs of undesirable products.

Mr. Arthur Cecil Pigou (1948) proposed a relatively simple idea to avoid such transfer in the case of environmental pollution by introducing taxation equal to the marginal external cost: in this case only a part of the external cost is transferred to the society while the other part lies on the producer. Unfortunately, in many cases it is very hard (if possible) to measure the size of the external cost, since no markets for undesirable outputs exist.

An alternative interpretation of Pigou's idea claims that efficient environmental degradation may be achieved by establishing a market for pollution with the prices set using shadow price of the externality as a reference value (Faber and Proops, 1991; Färe *et al.* 1993).

The present work extends the aforementioned ideas by proposing an alternative to the existing methods of environmental valuation by relying on shadow prices of environmental pollutants (as one of the possible undesirable outputs). These shadow prices are considered *the internal valuation of environmental degradation (connected to each pollutant) by a given society*[1]. Having such intuition of shadow prices, it will be possible to determine how high environmental degradation is valued by a society. These prices provide economically justified reference values of environmental taxation and international environmental trade (Färe *et al.* 1993) (*e.g.*, under Kyoto protocol). They may also enable to propose a way of solving a previously unsolvable problem of environmental demand function construction and calculating so called 'green GDP', an environmental analogue of economic GDP, which accounts for the value of environmental pollution (Hueting 1991).

In the process of the shadow prices estimation we will also estimate an environmental efficiency measure (which is, in a sense, a desirable costless by-product of the study). That efficiency measure is an alternative to the numerous sustainability indicators (de Koeijer *et al.* 2002), many of which consider either purely bio-ecological component of sustainability (*e.g.*, Pannell and Glenn 2000) *or* purely socio-economic (*e.g.*, Smyth and Dumanski 1993). Our indicator, in contrast, will look upon *both* ecological and economic aspects of sustainability, *i.e.* evaluating how environmentally sustainable the economy is given its economic development.

It must be emphasized, however, that despite the fact that many previous works have discussed the importance of implication of shadow prices and efficiency measurements, all (at least more or less known) of these studies were measuring

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1 The intuition of shadow prices will be discussed in Chapter 4, while mathematical formalization of this concept will be developed in Chapter 5.

efficiencies and shadow prices of undesirable outputs for separate plants within an industry (mostly pulp and paper). In contrast, the present study looks on the country level; to our knowledge, it is the first attempt to apply the methodological approach of environmental production microeconomics to the issues of environmental macroeconomics and public policy. In addition, it is the first time such environmental efficiencies and shadow prices of environmental pollutants are estimated for the countries in transition (CITs).

The main research question of the study is: '*How* inefficient are individual countries and *What* is the internal valuation of environmental pollution by these countries?'

The work will also attempt to answer a number of additional questions. These include but are not limited to:

- How far are individual countries from their technological potential, *i.e.* by how much it is technologically possible to decrease their undesirable outputs production provided their good output or, alternatively, by how much they are technologically capable of increasing their good output provided their level of bad outputs production?

- Provided the countries or regions keep the same level of technological inefficiency with respect to the environment, what is the increase in the undesirable output production level that accompanies a 1% increase in the good output production?

- Do shadow prices of undesirable outputs witness about efficient global allocation of wealth and pollution?

- How different are the estimates of efficiencies and shadow prices obtained using parametric and nonparametric approaches and what are the errors of these estimates?

The cornerstone hypothesis of the work is that basic information about inputs and outputs of a set of economies can provide with the information on environmental efficiencies of these economies and shadow prices of environmental pollutants. Thus, the work has the following objectives:

- Set up a set of assumptions and definitions as well as theoretical models that allow to estimate environmental efficiencies and shadow prices of pollutants on a country level as well as errors of these estimates

- Produce a computer code and make the estimations using it.

- Attempt to answer the research questions using the obtained estimates.

- Develop policy recommendations based on the results of the study.

- Prepare ground and propose the directions for further studies in the field.

The study has the following structure. We will estimate shadow prices and environmental efficiencies of economies (called hereafter as decision making units, DMUs) using parametric (*Translog* specification) and nonparametric (data envelopment analysis, DEA-based) approaches towards estimating output directional distance function. We will also estimate statistical characteristics of the parametrically obtained estimates. Based on these characteristics as well as kernel estimated densities of the estimates, we will conclude on compatibility of these two approaches. In addition, we will draw conclusions and policy recommendations based on individual values of shadow prices of separate pollutants as well as environmental inefficiencies of individual countries.

The rest of the work proceeds as follows. The second chapter provides literature review of the most important works related to the estimation of the environmental efficiencies and shadow prices of undesirable outputs. The third chapter introduces a reader to the basic theory of sustainable development. The forth and fifth chapter builds up a basic economic model by providing economic intuition of the model (forth chapter) and makes definitions and the assumptions used in the work as well as explains parametric and nonparametric approach towards estimating the efficiencies and shadow prices (fifth chapter). The sixth chapter develops a methodology of numerical estimation of environmental inefficiencies and shadow prices by parametric and nonparametric techniques and statistical characteristics of the obtained estimates. The seventh chapter introduces the data used in the empirical part of the study; presents the results of the estimation and provides discussion of the obtained results as well as three illustrative examples. The final chapter concludes and provides policy implications and further research recommendations.

Chapter 2

LITERATURE REVIEW

All of the previous studies (at least among those we are aware of) on estimation of environmental efficiencies and shadow prices of pollution were considering separate plants within a single state's or country's industry (*e.g.*, pulp and paper plants in Michigan and Wisconsin, Dutch sugar-beet industry or electric power plants in Korea). Even these studies are by no means numerous. Therefore, our choice of the literature may be considered limited provided that (a) there are not many studies estimating environmental efficiencies of DMUs and shadow prices of pollutants, (b) there are no studies on estimating these for any DMUs related to CITs, and (c) there are no studies measuring these parameters on the macro level, *i.e.* considering countries or regions within a single country as DMUs.

In order to structure the literature on the topic more efficiently we will first review literature taking alternative methodological approaches towards estimating shadow prices and environmental inefficiencies, then we will see how the topic has been developing in general until now and finally acknowledge alternative methods of measuring sustainability.

2. 1. Approaches towards estimating efficiencies and shadow prices

It is important to make a note how shadow prices are usually estimated. A ratio of shadow prices of undesirable and desirable outputs (which is numerically equal to the slope of the technology set in a given point) can be estimated based on the Shephard-type distance functions[2] that give a dual representation of a technology. It is crucial to notice, however, that distance function measures efficiency of a DMU, while ratio of shadow prices measures marginal rate of technical substitution of a desirable output for undesirable. In other words, distance function and shadow price measure different things: the former indicates how far from the technological potential the DMU is, while the latter shows how much desirable output the DMU should forfeit if it wants to decrease undesirable output by one unit keeping the efficiency fixed, *i.e.* distance function measure rather long run perspective of the economy, while shadow prices points on its short-run perspectives.

Two approaches are often observed in literature on estimating of shadow prices and distance functions. The first is parametric approach based on the methodology proposed by Aigner and Chu (1968) for estimating production function and then extended to estimating cost functions (Pollak *et al.* 1984) and distance functions (Pittman 1981; Pittman 1983; Färe *et al.* 1993). The second is nonparametric, DEA-based approach.

Practically all studies before 2000 approached the problem of undesirable outputs production by using parametric specification of the distance functions (*e.g.*, Färe *et al.* 1993; Coggins and Swinton 1996; Chung *et al.* 1997; Färe *et al.* 2003). The main reason for this is that derivation of the shadow price out of the distance function involves differentiation of the latter with respect to the outputs. In the case of parametric specification it is more convenient to do. DEA approach was used in the recent studies mostly when determining shadow prices was not the

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[2] Shephard (1970) proposed output distance function, which was later used as a basis for input distance function and directional distance functions.

purpose of the work (Zaim and Taskin 2000; De Koeijer *et al.* 2002). At the moment, only one study attempted to estimate shadow prices of undesirable outputs using nonparametric framework via DEA (Lee *et al.* 2002).

These two approaches usually provide similar but not the same results with respect to the absolute values of the efficiencies (Coelli and Perelman 1999) in the case of only desirable outputs. The comparison is based on using assumption on the normal distribution of the estimates without estimating true statistical characteristics of them. Similar studies when some outputs are undesirable have not been executed. It is also not studied if there is any qualitative difference in the obtained efficiency estimates (*i.e.*, the DMU ranking with respect to efficiencies) and shadow prices.

2. 2. History of the studies in the field

Now, after we reviewed the literature that uses different approaches towards measuring environmental efficiencies and shadow prices of undesirable outputs, let us turn towards reviewing the progress in the area until now to develop an understanding of what is the investment of the current study in this field.

Although the earliest works on estimation of shadow prices of undesirable outputs (called 'bads' as an antonym to 'goods') were published in the beginning of 1980s (Pittman 1981; Pittman 1983), such studies are not numerous, nevertheless provide theoretically well thought-out models suitable for such estimations.

These works of Pittman estimate shadow prices of pollutants of pulp and paper industry and give realistic figures pointing on inefficient distribution of resources in the industry. A decade later Färe *et al.* (1993) reviewed these results and pointed that the earlier studies were unable to determine the shadow prices of the individual plants. For this reason, the authors use their previous theoretical work (Färe *et al.* 1989) regarding the use of nonparametric approach towards the efficiency analysis of the industries producing undesirable outputs in order to parametrically estimate shadow prices of individual pulp and paper plants of Michigan and Wisconsin.

The estimation of the shadow prices is based on the assumption of full efficiency, *i.e.* the estimation takes place on the production possibility frontier. This approach provides plausible results and that leads to the acceptance of it as a fundamental approach in the further works on the estimation of the shadow prices of pollutants.

Other works differ from the Färe's works mainly by the choice of the directional vector of the output distance function. Particularly, Färe *et al.* use the hyperbolic (Färe *et al.* 1989) and radial (Färe *et al.* 1993) efficiency rules; Boyd *et al.* (1996) use horizontal and vertical efficiency rules; Chambers *et al.* (1996) and Chung *et al.* (1997) make use of the general directional efficiency rule. Unfortunately, since the studies considered different object, it is hard to compare the results of these studies. However, it is possible to argue that in theory the choice of different directional vectors may give different absolute values of the shadow prices of the individual objects as well as alters their relative efficiency (*i.e.* the objects having the same efficiency ranking according to one efficiency rule may have different efficiency rankings according to the other efficiency rule).

A recent study of the power plants in South Korea of Lee *et al.* (2002)[3] is notable among all other studies in the field. This paper proposes to estimate the shadow

[3] For critique of theoretical development in the work of Lee *et al.* (2002), see Salnykov and Zelenyuk (2004a)

prices of pollution taking into account environmental inefficiency of production processes and pay attention to the theoretical validation of the efficiency rule. The study explicitly incorporates the weak efficiency assumption over the whole range of frontier in the output domain. The work itself bases its efficiency rule on the annual environmental protection plans of the plants.

Although such a method of choosing the directional vector may hardly be implemented (especially in transitional countries, where these plans are either difficult to access or do not exist at all), a consideration of environmental inefficiency of economies in estimation of the shadow prices of bads is an important modification of the model of Färe *et al.*(1993). This modification enables aggregation of the shadow price and environmental efficiency of economy into a single indicator suitable to statistical comparison across countries and regions.

Another important innovation proposed by Lee *et al.* (2002) is its use of nonparametric specification of distance function in estimating shadow prices. This is an crucial breakthrough that allows to compare not only efficiency estimates from two approaches, but also shadow prices estimates.

2. 3. Approaches to evaluate sustainability

The use of shadow prices and environmental efficiency of production as a sustainability indicator is justified by de Koeijer *et al.* (2002) in their sustainability analysis of the Dutch sugar-beet industry. The main advantage of the use of these values to measure sustainability is a simultaneous analysis of biophysical and socioeconomic components of sustainability. Unlike purely biophysical (*e.g.*, Pannel and Glenn 2000) or purely socioeconomic aggregated measures (Smyth and Dumanski 1993), environmental efficiency of production measure its efficiency in the context of both environmental and economic parameters. That idea of components of sustainability closely corresponds to the division of environmental performance on bio-physical and institutional components proposed by Cherp and Salnykov (2004).

It must be acknowledged, however, that few studies attempted to aggregate social environment and natural environment. For example, Environmental Sustainability Index (ESI) developed by the WEF's Global Leaders for Tomorrow Environment Task Force in collaboration with the Yale Center for Environmental Law and Policy and the Center for International Earth Science Information Network (WEF *et al.* 2002). ESI measures a country's estimated ability to "maintain favourable environmental conditions in the future" on the basis of five core phenomena: the state of environmental systems; the stresses on those systems; human vulnerability to environmental change; capacity to deal with environmental challenges; participation to global efforts to conserve resources. ESI for each country is based on 68 variables, ranging from air and water quality to child mortality, and from greenhouse gas emissions to institutionalised corruption. At the same time, some environmental groups dubbed ESI "grossly misleading" (Cherp and Salnykov 2004) by accusing it to promote a "deeply unsustainable growth model" by placing rich countries at the top of the list and following an *a priori* assumption that democracy is good for the environment. Another common critique of this class of sustainability indicators is that they sum up apples and oranges by putting an equal weight in aggregating, for example, low child mortality and low level of nitrogen oxides (NO_x) emissions per capita (Salnykov 2002).

2. 4. Conclusions

From our review of the limited scope of the literature in the field we may conclude that there is a number of substantial niches exist, which we may attempt to fill by the current work:

- No previous studies attempted to look on the countries as DMUs and, hence, estimate both their environmental efficiencies and shadow prices of undesirable outputs jointly.

- Estimates of environmental efficiencies and shadow prices of undesirable outputs using different specifications (parametric and nonparametric) have not been compared yet.

- Statistical characteristics (such as confidence intervals, standard errors, kernel density) of environmental efficiencies and shadow prices of undesirable outputs are not known for any of the specifications used (parametric and nonparametric). Estimating these characteristics would provide us more justified results while comparing them.

- Many of the existing sustainability indicators are developed based on the biased *a priori* assumption on sustainability and aggregating unadjusted measures. An alternative indicator can be developed, which does not have these deficiencies.

C h a p t e r 3

ELEMENTS OF SUSTAINABLE DEVELOPMENT

This and the following chapter of the work will introduce the reader to the most persistent environmental theories the paper is related to, provide with the main definitions and assumptions used in the study as well as attempt to replicate the most important results on using the distance functions as estimates of efficiencies and derivation of shadow prices from the distance functions.

It should be absolutely clear that before applying economic theory to environmental science issues, one should be familiarized with the basic aspects of environmental science, which are related to the study in order to understand how economic theory may address environmental issues.

Recent developments in environmental science resulted in a separation of a new field of sustainable development (Rao 2000). Sustainable development (SD) is often considered a semi-philosophical concept that defines a utopian point of view on human development. The classical definition of SD was introduced in the famous Bruntland Report in 1987 and defines SD as the "…development that meets the needs of the present without compromising to the ability of future generations to meet their own needs" (WCED 1987). Of course, such approach must seem utopian, since from economic perspective the term "meeting the needs" remains much room for speculation. In addition, it is hard to define the criteria of "compromising the ability of future generations to meet their own needs".

Much more comprehensive definition was proposed in 1991 by Robert Costanza. He proposes to define SD as

> *a relationship between dynamic human ecosystems and larger dynamic, but normally slower-changing ecological systems, in which*
> *(a) human life can continue indefinitely,*
> *(b) human individuals can flourish,*
> *(c) human cultures can develop, but in which*
> *(d) effects of human activities remain within bounds, so as not to destroy the diversity, complexity, and function of the ecological life support system*
>
> (Costanza 1991).

Although this definition also is not absolutely clear from the economic perspective, *e.g.* the term 'flourishing' does not seem to be absolutely understandable, this definition provides with the basic idea what SD is mainly about. Sustainability involves three main components: economic sustainability (point *b* of Costanza's definition), social sustainability (point *c*) and environmental sustainability (point *d*). Therefore, it is appropriate to talk about three forms of capital SD involves: economic capital (man-made capital in the traditional economic sense); social capital (cultural heritage, morality, health, *etc.*); and environmental capital (natural and environmental resources).

Using idea of capital as a cornerstone of SD, two forms of sustainability are distinguished: weak and strong sustainability. Weak sustainability is usually defined as

> *a process of socioeconomic development which is built on the sustainability approach, with an additional requirement that the worth of the capital stocks vector (valued at applicable shadow prices) is maintained constant, or undiminished, at each time interval, for ever*
>
> (Rao 2000).

In other words, weak sustainability allows capital to transfer from one form to the other, *e.g.* from environmental to economic, while ensuring the total stock of capital is held undiminished. In contrast, strong form of sustainability constraints the total stock of each form of capital to stay undiminished, *i.e.* the transfer of environmental to economic capital is possible only in the case if an equivalent transfer is made back from economic to environmental capital. Corollary, in economic terms, we may consider development of a given economy weakly sustainable if the total of all desirable and undesirable outputs multiplied by the respective shadow prices is nonnegative. The development is strongly sustainable if the value of social expenditures on environment is not less than the total of all undesirable outputs multiplied by the respective shadow prices.

It is often told that SD has two pillars: intra and inter-generational equity. Intra-generational equity ensures that needs of all people within a given generation are satisfied equally. In turn, inter-generational equity requires satisfying the needs of the representatives of different generations equally. The latter aspect of equity is sometimes referred to as 'fathers vs. sons' conflict and is considered a necessary condition of development, while the former is called is often reviewed in the context of 'North-South' conflict and is a necessary condition for sustainability.

The hypothesis of North-South conflict is the theory that the developed countries (mainly located in the Northern hemisphere, therefore called 'North'), owing to the fact that their basic needs are mostly satisfied, have a higher awareness regarding the use of natural resources. They are characterized by high marginal rates of substitution of environmental degradation for economic development and high environmental efficiencies of economies. At the same time, developing countries (called 'South', since they are mostly located in the Southern hemisphere) tend to satisfy their needs in economic development through an intensive exploitation of environmental and natural resources. These countries have low marginal rates of substitution of environmental degradation for economic development and low environmental efficiencies of economies (Rao 2000).

Taking into consideration the fact that the transition countries greatly differ from both North and South economically and politically (Przeworski 1995), the position of CITs within the context of the North-South conflict is not that obvious. Moreover, taking into consideration an insignificant number of empirical studies in the field of sustainable development in CITs, there are no reasons to regard these countries as either North or South. In addition to this, because of their heterogenic economic and environmental structure, different regions of many CITs may have features of different groups.

Identification of the role of the countries in the context of the North-South conflict is an important component of development of sustainable policy of national and regional economic development in line with Rio Declaration of 1992 and especially with Principles 3 and 6. These principles urge to develop the policies, which would equitably meet the environmental needs of all people of the Earth with a special attention paid to the least developed and the most environmentally vulnerable countries and regions.

Thus, the 'South' countries must pay attention to the environmental efficiency of their economies and sustainability of the national development. Their 'North' neighbors should consider transboundary effects of environmental degradation and in line with Principles 12 and 17 of the Declaration (about cooperation in sustainable development issues) promote environmental efficiency and sustainability of the 'South' countries. In addition, national policy should pay special attention to those regions that demonstrate the relative instability of development through promotion of regional economic development programs that would improve efficiencies of those regional economies.

After discussing elements of sustainable development, we can conclude that the current study is important for sustainable development in many aspects including:

- Efficiency measure will provide with a distance of a given country to the best-practice frontier, *i.e.* a criterion to judge what is a potential of the country to increase its output without causing harm to the environment;

- Calculating total value of desirable and undesirable outputs produced by the DMU can provide with an additional sustainability indicator and basically may serve as a criterion for judging whether the DMU's development is sustainable or not;

- Estimates of shadow prices of environmental pollutants provide with marginal rates of substitution of desirable output for undesirable outputs.

- Corollary, we may able to forecast the growth in environmental pollution accompanied by a 1% growth of desirable output production within a given country *ceteris paribus*.

Chapter 4

ELEMENTS OF PRODUCTION THEORY IN THE PRESENCE OF UNDESIRABLE OUTPUTS: INTUITIVE MODEL

Before discussing an intuitive model of production in the presence of undesirable output, we must introduce several simple, yet crucial, concepts.

4. 1. Basic concepts of production theory

By *technology* here and below we mean a certain process that transforms a number of production factors or *inputs* into a number of products or *outputs*. The latter can be intended or *desirable*, such as many economic goods, *e.g.* guns, butter, *etc.* or unintended or *undesirable*, such as environmental damage, pollution, *etc.*

We will refer to *efficient production* throughout this work in the meaning of *technical efficiency*. Technical efficiency does not necessary imply revenue efficiency, cost efficiency or any other form of efficiency. In some sense, technical efficiency may be though as similar to Pareto-efficiency: the DMU is technically efficient or the input is used technically efficiently if it is not possible to produce more of any desirable output or less of any undesirable output without diminishing another desirable output or increasing another undesirable output given the DMU's input endowment.

We will refer to *feasible production* in the meaning of *technological feasibility*. Technological feasibility of certain input-output combination means that given the existing technologies it is possible to produce these outputs out of given inputs. Technological feasibility does not mean that the production is efficient.

4. 2. Non-separable production of desirable and undesirable outputs

We start from observing economic activity of a number of DMUs. Each of the DMUs' economies produces desirable outputs (economic goods) and undesirable outputs (environmental pollution, degradation), which are produced jointly or *non-separably*. In the process of production the DMUs employ a number of inputs, such as labor, capital, land and energy.

Desirable outputs production in the closed DMU is usually aggregated in the form of gross domestic product (GDP). This measure is a reliable estimate (subject to statistical discrepancies) of what is produced within the geographical boundaries of a given country.

Undesirable outputs, however, are produced in a number of forms, which are not suitable for direct aggregation. This is one of the reasons why calculation of so called 'green GDP' is a disputable issue until now. 'Green GDP' is an indicator that attempts to measure the level of society's welfare by adjusting value of conventional GDP, *i.e.* an economic desirable output, by a total value of undesirable outputs, where the latter is a total of quantities of undesirable outputs weighted on their respective shadow prices (Hueting 1991).

We assume that in the case of desirable outputs a society attempts to maximize total economic value of it, *i.e.* GDP. Therefore, we may imagine a DMU as a single production unit producing one desirable output and a number of undesirable outputs using production factors provided. For the sake of illustration, let us review a case of one input, one good and one bad output.

4. 2. 1. Desirable output production holding undesirable output production fixed

First, let us consider how change in input impacts desirable output production holding undesirable output fixed and provided input is used in the most efficient way. This is an ordinary case of conventional production function discussed in many economics textbooks (*e.g.*, Mas-Colell *et al.* 1995) with some minor modifications. According to this concept, maximum possible desirable output increases as input increases, but as input growth progresses, increase in desirable output becomes smaller (diminishing marginal product concept). Graphically, desirable output production function can be drawn as depicted on Figure 1.

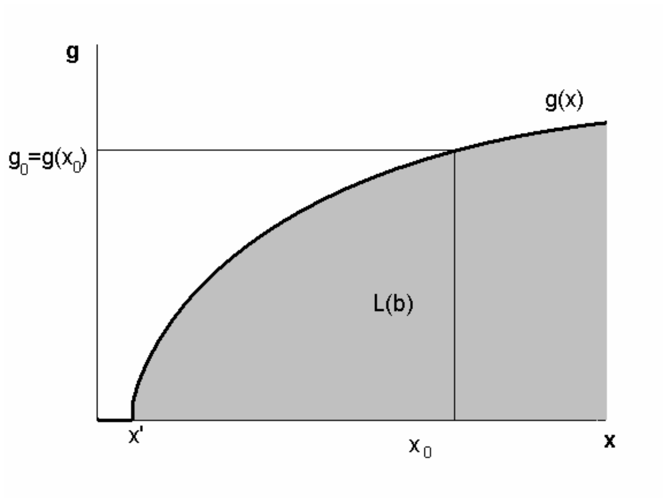

Figure 1. Graphical representation of desirable output production

Here we plot dependence between input x and desirable output g keeping undesirable output fixed and assuming efficient use of input as a curve $g(x)$. It should be noted, however, that production of a desirable output can start only after the given level of undesirable output production is achieved (suppose it requires at least x' input). Before that input is used for production, simply no desirable output will be produced.

If we continue to keep undesirable output fixed but don't restrict production to efficient use of resources anymore (*i.e.*, a DMU can waste the input) then at any given input x_0 a DMU can produce desirable output at level less or equal than g_0, which corresponds to the most efficient use of x_0. Intuitively, if a DMU works efficiently, it produces as much as it technically capable to. If it does not work efficiently, it produces less than it could otherwise.

Similarly to conventional production theory, we introduce an *desirable output-input set, L(b)*, which is a set containing all technologically feasible combinations of desirable output and input holding undesirable output fixed, *i.e.* a set containing combinations of input and desirable output such as this level of input can produce this level of desirable output and the level of undesirable output set exogenously at level *b*. Graphical illustration of undesirable output set is given on Figure 1 as a shaded area. It should be understood in the following way: once we set undesirable output production on the fixed level, we plot all technologically feasible combinations of input and desirable output with different levels of efficiency. The resulting area is desirable output-input set.

4. 2. 2. Undesirable output production holding desirable output production fixed

Similarly, we can elaborate on production of undesirable output. Since undesirable outputs are similar to desirable outputs in the sense that they are also physical outputs. The following discussion of production of undesirable outputs is based on Figure 2.

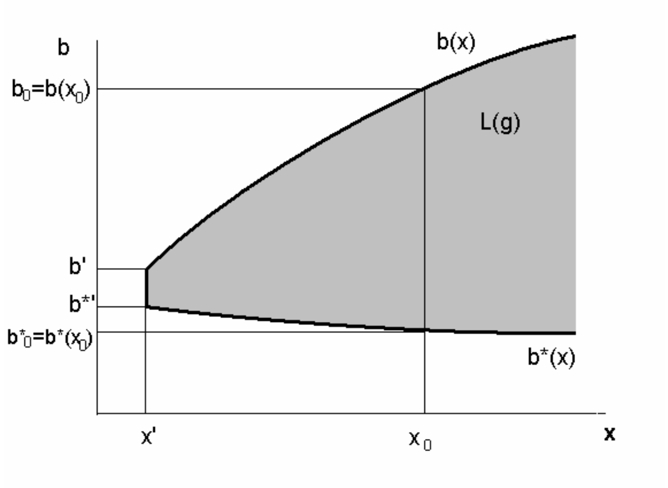

Figure 2. Graphical representation of undesirable output production

Given the level of the desirable output production, production of undesirable output can start only after at least *b'* of undesirable output is produced, or if a DMU uses the pollution abatement technologies, after at least *b*'* is produced. These levels of desirable and undesirable outputs require investment of *x'* of input. If we start increasing output (keeping desirable output production constant), undesirable output level will change along the path *b(x)* if no pollution-abatement technologies are used, $b^*(x) \leq b^{*'}$ if all possible pollution-abatement technologies are used, or any level between these two values depending on the level of execution of pollution-abatement technologies. We will distinguish between *b(x)* and *b*(x)* by calling them undesirable output production function and abated undesirable output production function respectively. At this, we agree to consider *b*(x)* technologically efficient, while *b(x)* technologically inefficient.

Therefore, at any given level of input $x_0 > x'$ we may expect a DMU to produce $b^*(x_0)$ of undesirable output if it is functioning in the most efficient way, $b_0 = b(x_0)$ if it is functioning in the most inefficient way or any level in between these two assuming that production of the desirable output remains constant. Corollary, we will call the set containing all technologically feasible combinations of undesirable output and input required to produce it given that desirable output level is held constant *undesirable output-input set*, which is depicted by shaded area on the picture and denoted by *L(g)*. It should be understood in the following way: once we set desirable output production on the fixed level, we plot all technologically feasible combinations of input and undesirable output with different levels of efficiency. The resulting area is desirable output-input set.

4. 2. 3. Joint desirable output – undesirable output production holding input fixed

Finally, we consider the relationship between undesirable and desirable output production levels holding input fixed. This relationship is illustrated on Figure 3.

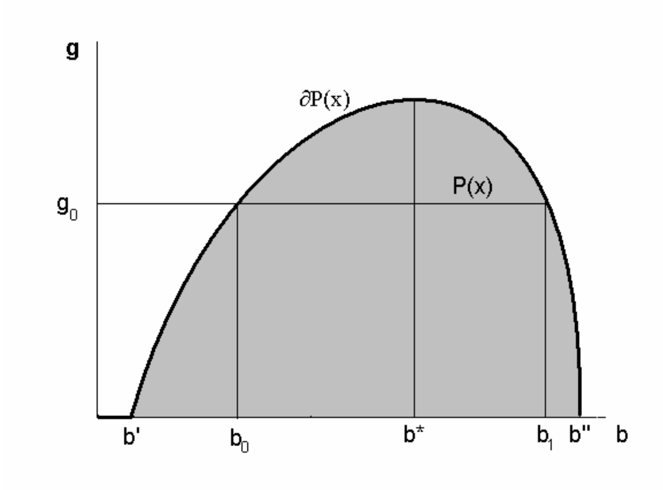

Figure 3. Graphical representation of joint desirable-undesirable output production

Provided an input level, a DMU can decide on how much of each outputs it wants to produce. At this, if it decides to produce less than some critical amount of undesirable output *b'*, no desirable output can be produced. Intuitively it should be understood in the following way: if a DMU wants to produce something, it should first experience some environmental damage prior any production takes place. These damages may include heating up machinery (and producing air pollution), constructing facility (and damaging land and creating fragmentation of habitats), *etc.* They are non-productive (in terms of desirable output), but required to enable any desirable output production. We agree to call this critical amount as a *minimum technically efficient undesirable output*. On the other hand, physical laws restrict total undesirable output production to a limited number *b"* (in other words, given 1 kilogram of fuel it is impossible to produce more than 1 kilogram of pollution). We will call such level *maximum possible undesirable output*.

If a DMU decides to produce an amount of desirable output equal to g_0, its choice of undesirable output production is restricted to a minimum of b_0 (the most efficient point) to a maximum b_1 (the least efficient point). We agree to call all technologically feasible combinations of desirable and undesirable outputs given the level of input *output set*. This set is depicted by the shaded area and should be understood in the following way: once we set input on the fixed level, we plot all technologically feasible combinations of desirable and undesirable outputs with different levels of efficiency. The resulting area is output set.

An important value of the output set is that it allows an explicitly focus on substitutability between desirable and undesirable outputs and study them holding inputs fixed. That is especially crucial as we observe that many of the inputs (labor, land) can be considered as given exogenously.

The solid line on the drawing represents the maximum possible desirable output, which can be produced given the input and the level of undesirable output.

However, not all these points are favorable for a DMU. The points to the right of the point *b** have the respective points to the left of *b**, which provide the same level of desirable output, but smaller level of undesirable output (*e.g.*, consider the pair b_0 - b_1). Therefore, left part of the solid part is more favorable to the DMUs in terms of efficiency (excluding its horizontal portion). We agree to call this part of the line as *production possibility frontier (PPF)* and denote it by ∂P(**x**), while *b** is agreed t be accepted as the *maximum technologically efficient undesirable output*.

4. 2. 4. Joint production of outputs at different input levels

We summarize our discussion of production process in the presence of undesirable outputs by constructing a *technology set*. It is defined as all possible combinations of inputs, desirable and undesirable outputs that are technically feasible. General shape of technology set in the case of one input, one desirable and one undesirable output is depicted on Figure 4.

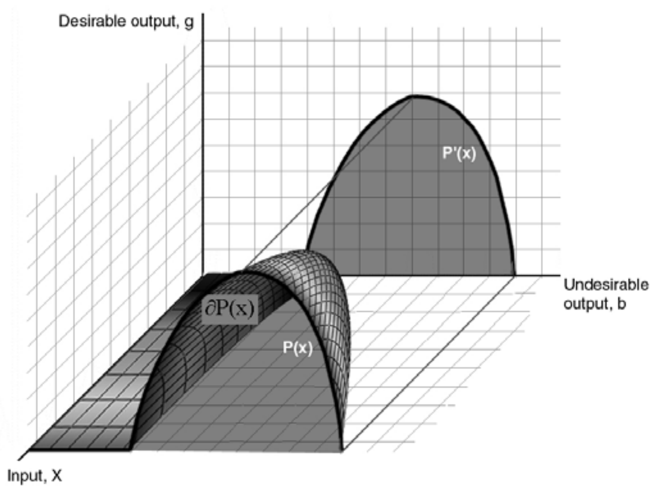

Figure 4. Graphical representation of technology set

This three-dimensional picture provides with a pretty good idea of what input-output combinations are feasible. We agree to call the set containing all technologically feasible combinations *technology set*. In one input-one desirable-one undesirable output case it will have a shape as depicted on the diagram. The technology set will include the convex hull (including points inside the shell) and the surface on the left of the hull. The intuition of including this surface in the technology set is absolutely the same as including horizontal portion on the lest of P(**x**) discussed in the previous section.

The left portion of the hull surface represents technologically efficient combinations of inputs and outputs and has the same intuition as PPF in the previous section.

When we know the input endowment we posses, we can cut a slice of the technology set at the given input level. The resulting area corresponds to the output set discussed before.

4. 3. Environmental efficiency

Let us return to the choice of DMU once it decides to produce g_0. Since b is undesirable, a DMU would want to produce as little of it as possible, *i.e.* b_0. However, this is not always the case. In practice, some DMUs decide to produce more than this amount, *i.e.* to be inefficient. Therefore, the important question is: why a DMU would decide to be inefficient and produce more undesirable output than it could otherwise? An answer to this question is: this happens either due to the market failures or due to a profit-maximizing behavior of a DMU. The first option involves asymmetric information, where a DMU plainly does not know that it could produce less of undesirable output. The second option involves a conclusion of a DMU that it is too expensive to be efficient in the sense that efficient technologies it has an access to are to expensive to justify a decrease in the undesirable output.

After discussing that a DMU can be efficient or inefficient, it is logical to develop a measure of a DMU's efficiency. For this purpose we propose to use *Shephard-type directional output distance function*. An intuition of the former can be understood from Figure 5.

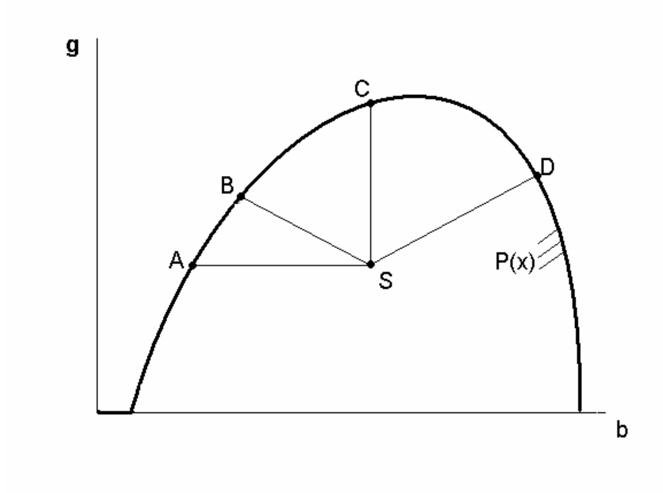

Figure 5. Graphical illustration of efficiency measure using ODDF: horizontal (A), general (B), vertical (C) and radial (D) direction.

We start from observing a DMU producing an inefficient combination of outputs (point S). We accept distance of this point to $\partial P(\mathbf{x})$ in a given direction as a measure of efficiency. If this distance is equal to zero, the observation is fully efficient. It should be noted that this direction is set by ourselves and has roots in our understanding of how a DMU should behave in its attempt to become more efficient. Suppose, we believe that an efficiency increase must imply decrease in undesirable output preserving desirable output on the constant level. It means that we restrict movement of the DMU towards the efficient point to *horizontal* direction represented by the line SA on the drawing. Similarly, we may believe that an increase in efficiency must be accompanied with a growth of desirable output while holding an undesirable output constant. By this, we set a *vertical* direction represented by a line SC on the drawing. Finally, we may think that a DMU must increase its desirable and decrease its undesirable outputs if it wants to become more efficient. By thinking so, we set a *general* direction represented by the line SB on the drawing. All these directions project an observation to an efficient position A, B or C. At this, distances SA, SB and SC will represent the efficiency measures, which depend on our belief of the DMUs 'optimal' behavior.

It must be acknowledged, however, that some previous studies (*i.e.*, Färe *et al.* 1993) attempted to employ *radial* direction by assuming that a DMU should increase both desirable and undesirable output in its attempt to become more efficient (radial direction SD). However, such approach will lead us to a point D, which is inefficient according to our understanding of efficiency as it was discussed above).

An important question related to measuring efficiency is: what direction is the best proxy of the DMUs 'optimal' behavior. We expect that a typical society will tend to both increase desirable and decrease undesirable output in their attempts of being more efficient, and, hence, follow general direction.

We agree to call the principle according to which the society changes its outputs while becoming more efficient as *efficiency rule* (ER). Here and below we distinguish horizontal ER, vertical ER and general ER as those based on the respective directions.

In the empirical part of the work we focus on the latter efficiency rule. This is mostly due to the fact that the directional function with this efficiency rule was demonstrated to have some nice properties: (i) it is the first order approximation of the hyperbolic efficiency measure and (ii) it can be viewed as a counterpart of the Shephard's output distance function when some outputs are undesirable. The issue of the choice of the efficiency rule will be discussed more closely in the following chapter.

4. 4. Shadow prices

Our final section in the intuitional framework is devoted towards explaining the intuition of the shadow prices and the theoretical way to approach their measurement.

Shadow prices of undesirable outputs can be considered as a cornerstone in the environmental accounting. Hueting (1991) acknowledged that impossibility to measure shadow prices of environmental pollution disables many important achievements in the field, such as correction of national income for environmental degradation, constructing environmental demand curve and setting an efficient environmental taxation.

Shadow prices of environmental resources are often understood as

> *the "true" worth of a resource … [they] are related to the specification of objectives, derived from the general socioeconomic philosophy … these prices are designed to reflect the opportunity cost and, thus, the real worth of a resource.*
>
> (Rao 2000).

This intuition allows us to consider shadow prices of pollution as *the internal valuation of environmental degradation (connected to each pollutant) by a given society*. Logically enough, this concept is closely related to the society's utility function and the respective mathematical demonstrations will be provided in the following section.

Since there is no market for environmental pollution, it is not possible to observe shadow prices of the pollutants. For this reason, a number of approaches to evaluate environmental resources have been developed. These include contingent valuation method, travel cost method, hedonic price methods, *etc.* Most of these methods involve sociological or market analyses, which are subject to serious drawbacks related to representativeness of the sample, limited choice of pollutants and aggregation issues.

In order to propose an alternative method of measuring shadow prices, we may start from recalling a well-known economic fact that according to the rationality assumption a rational revenue-maximizing DMU will be always located at the point on PPF, where the slope of the latter is equal to the ratio of the prices of the outputs. Figure 6 represents measure of shadow price in one desirable – one undesirable output case.

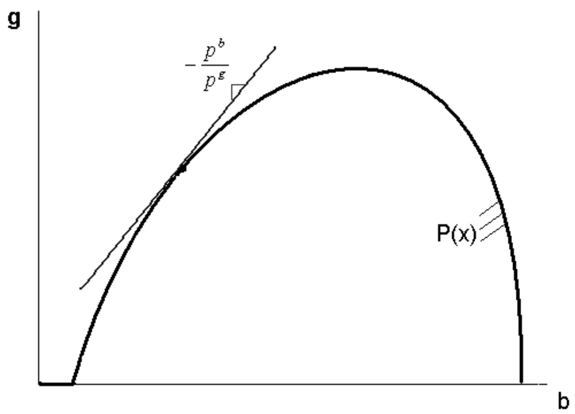

Figure 6. Measure of shadow price of undesirable output

The slope of the PPF in the point of observation equals the negative ratio of the shadow price of pollutant to the shadow price of desirable output. We agree to call this ratio *normalized shadow price* of undesirable output. Minus in front of the ratio points on negative shadow price of the undesirable output, which is understandable, since people are willing to pay to get rid of it, not to get more of it as in the case with desirable outputs. If we assume that shadow price of desirable output equals its market price, we can neglect the denominator and obtain absolute shadow price of undesirable output.

An important interpretation of the normalized shadow price of an undesirable output is: *normalized shadow price of a bad shows how much of a good output should be foregone in order to decrease bad output by one unit provided the efficiency remains the same.* Alternatively, *it shows the increase of a bad output should good output increase by one unit and efficiency stays the same.* A valuable application of this interpretation is that it allows seeing the environmental outcomes (in terms of increasing pollution) of economic growth (in terms of growing output). For example, we may estimate if a country can meet its Kyoto protocol targets given its economic targets and estimated environmental inefficiency.

It has been demonstrated that once we estimated an efficiency measure, we can derive a normalized shadow price out of this estimate. Such method of shadow prices estimation is clearly superior to the aforementioned methods of environmental valuation, since it estimates the slope of PPF rather than relies on subjective questionnaires or market studies. Moreover, it should be possible to estimate statistical characteristics of the shadow prices estimates, while in the case of environmental valuation methods it is hardly possible.

Now, after we discuss an intuitive approach to the theoretical model, we will formalize it mathematically.

C h a p t e r   5

ELEMENTS OF PRODUCTION THEORY IN THE PRESENCE OF UNDESIRABLE OUTPUTS: MATHEMATICAL MODEL

In this chapter we introduce elements of production theory when some outputs are undesirable. We start from definitions of technology set and its projections on input and output spaces. That gives a ground for further development of the discussion to putting certain restrictions (assumptions) on the technology set, which would enable restrictions while modeling the technology set. Following this, we introduce an instrument for such modeling, Shephard-type distance functions in its original form (output and input distance functions) proposed by Shephard (1970), which also can be used as efficiency measure in the traditional context. Then, however, we show that in the presence of undesirable output distance function does not meet the intuition of the model, but the other efficiency measure, hyperbolic efficiency, does. We show that output directional distance function can serve as a substitute for this measure and can also be a measure of efficiency. Finally, we show how estimating this function allows estimating shadow prices. The theoretical underpinnings introduced here justify our choice of efficiency measure, shadow prices derivation and will be extensively used while modeling the technology.

5. 1. Modeling multi-output technology: primal approach

Suppose we observe K DMUs. The k^{th} of these DMUs produces L desirable outputs, which form an Lx1 vector of good outputs $\mathbf{g}^k=(g_1^k\ g_2^k \dots g_L^k)^{\mathrm{T}} \in \Re_+^L$ and

M undesirable outputs, which are represented by the Mx1 vector of bad outputs $\mathbf{b}=(b_1^k\ b_2^k\ \ldots\ b_M^k)^{\mathrm{T}} \in \Re_+^M$, where we agree to denote the number of a DMU by a superscript and a number of the element in the vector by a subscript. L good and M bad outputs of a DMU form $(L+M)$x1 general vector of outputs of this DMU $\mathbf{y}^k = (\mathbf{g}^k,\ \mathbf{b}^k) = (g_1^k \quad g_2^k \quad \ldots \quad g_L^k \quad b_1^k \quad b_2^k \quad \ldots \quad b_M^k)^T \in \Re_+^{L+M}$.

In order to produce these outputs, the DMU is using Nx1 vector of inputs $\mathbf{x}^k=(x_1^k\ x_2^k\ \ldots\ x_N^k)^{\mathrm{T}} \in \Re_+^N$.

Here and further we agree to specify the number of desirable and undesirable outputs and inputs in the following form: LxMxN, where L denotes the number of desirable, M – undesirable outputs and N – number of inputs respectively.

The set of desirable and undesirable outputs and the inputs required to produce these outputs have a primal representation in a form of a *technology set* T defined similarly to Färe and Grosskopf (2000) as

$$T \equiv \{(\mathbf{x}, \mathbf{g}, \mathbf{b}) : \mathbf{x} \in \Re_+^N \text{ can produce } (\mathbf{g}, \mathbf{b}) \in \Re_+^{L+M}\} \qquad (5.1.1).$$

The illustration of the technology set in 1x1x1 case was provided on Figure 4 with the explanation followed the diagram.

The *desirable output–input requirement set* specifies the desirable output – input combinations, which are technologically feasible with the given undesirable output vector. Formally it may be defined as

$$L(\mathbf{b}) \equiv \{(\mathbf{g}, \mathbf{x}) : (\mathbf{x}, \mathbf{g}, \mathbf{b}) \in T\}, \mathbf{b} \in \Re_+^M . \qquad (5.1.2)$$

The illustration of the desirable output–input requirement set in 1xMx1 case (M≥0) was provided on Figure 1 with the explanation followed the diagram.

The *undesirable output – input requirement set* specifies the undesirable output – input combinations, which are technologically feasible with the given desirable output vector. Formally it may be defined as

$$L(\mathbf{g}) \equiv \{(\mathbf{b},\mathbf{x}) : (\mathbf{x},\mathbf{g},\mathbf{b}) \in T\}, \mathbf{g} \in \Re_{+}^{L}. \tag{5.1.3}$$

The illustration of the undesirable output – input requirement set in Lx1x1 case ($L \geq 0$) was provided on Figure 2 with the explanation followed the diagram.

We generalize (5.1.2) and (5.1.3) by defining *output requirement* or *input set* as technologically feasible vectors of inputs able to produce the output combination

$$L((\mathbf{g},\mathbf{b})) \equiv \{\mathbf{x} : (\mathbf{x},\mathbf{g},\mathbf{b}) \in T\}, (\mathbf{g},\mathbf{b}) \in \Re_{+}^{L+M}$$

or alternatively

$$L(\mathbf{y}) \equiv \{\mathbf{x} : \mathbf{y} = (\mathbf{g},\mathbf{b}); (\mathbf{x},\mathbf{g},\mathbf{b}) \in T\}, \mathbf{y} \in \Re_{+}^{L+M}, \mathbf{g} \in \Re_{+}^{L}, \mathbf{b} \in \Re_{+}^{M}. \tag{5.1.4}$$

A set of technologically possible outputs provided the inputs is defined through the *input requirement* or *output set* P($\mathbf{x}$) similarly to Färe and Primont (1995) as

$$P(\mathbf{x}) \equiv \{(\mathbf{g},\mathbf{b}) : (\mathbf{x},\mathbf{g},\mathbf{b}) \in T\}, \mathbf{x} \in \Re_{+}^{N}. \tag{5.1.5}$$

The illustration of the output set in 1x1xN case (where $N > 0$) was provided on Figure 3 with the explanation followed the diagram.

It should be noted, however, that the sets (5.1.1)-(5.1.5) include not only observed inputs and outputs, but also those, which are technologically feasible.

The representations of technology by these five sets "are equivalent, but highlight different aspects of production" (Chung 1996). For example, output set clearly illustrates the output substitutability while technology set the best illustrates the scale properties of a technology (Färe and Grosskopf 1994). Similarly to Shephard (1970), who proved it for the general case (without undesirable outputs), we note that

$$\left(\mathbf{x},\mathbf{g},\mathbf{b}\right)\in\mathbf{T}\Leftrightarrow(\mathbf{g},\mathbf{x})\in L(\mathbf{b})\Leftrightarrow(\mathbf{b},\mathbf{x})\in L(\mathbf{g})\Leftrightarrow\mathbf{x}\in L(\mathbf{y})\Leftrightarrow(\mathbf{g},\mathbf{b})\in P(\mathbf{x}). \qquad (5.1.6)$$

In the present work we will closely focus on the output set P(**x**) as it provides us with a possibility to focus on the substitutability between desirable and undesirable outputs with a given input vector, which is one of the main focuses of our research.

By *production possibility frontier* ∂P(**x**) we mean a combination of outputs produced with the most efficient use of inputs. Mathematically,

$$\partial \mathrm{P}(\mathbf{x})\equiv\left\{\left(\mathbf{g},\mathbf{b}\right)\in \mathrm{P}(\mathbf{x}):\mathbf{b}_1\leq\mathbf{b},\ \mathbf{g}_1\geqq\mathbf{g},\ \left(\mathbf{g}_1,\mathbf{b}_1\right)\notin \mathrm{P}(\mathbf{x})\right\}^4. \qquad (5.1.7)$$

The intuitive explanation of (5.1.7) is as follows: we assume that the observations represent the most efficient use of the technology, if it is technologically impossible to increase (or at least keep the same) desirable output level and contract undesirable output level simultaneously, while keeping inputs on the same level. We will refer to all points on ∂P(**x**) as to *technically efficient*. Graphical interpretation ∂P(**x**) for 1x1xN case was provided on Figure 3.

Recall that we stated in the previous chapter that there is some critical level of undesirable production called *minimum technically efficient undesirable output*, **b'**. If undesirable output is below this level, no desirable production takes place, if it is above it, desirable production is possible. At the same time, according to our definition of technical efficiency in terms of ∂P(**x**), **b'** can be formally defined as

[4] Here an further we accept the following notations for comparing two vectors **a** and **b** of the same size:

i. **a** = **b** if and only if each element of **a** is equal to each corresponding element of **b**;
ii. **a** ≥ **b** if and only if at least one element of **a** is bigger than the corresponding element of **b**, while all other elements of **a** are not smaller than the corresponding elements of **b**;
iii. **a** > **b** if and only if each element of **a** is strictly bigger than the corresponding element of **b**;
iv. **a** ≧ **b** if and only if each element of **a** is bigger or equal to the corresponding element of **b** (**a**=**b** is possible, but nut necessary).

$$\mathbf{b}' : \Re_+^N \times \Re_+^L \to \Re_+^M$$
$$\mathbf{b}'(\mathbf{x},\mathbf{g}) \equiv \inf_{\mathbf{b},\mathbf{g}} \left\{ \mathbf{b} > \mathbf{0}_M \ : (\mathbf{g},\mathbf{b}) \in \partial P(\mathbf{x}), \mathbf{g} \in \Re_{++}^L \ \right\}. \qquad (5.1.8)$$

As **b'** may be different for various input levels, we represented it as a mapping from $\Re_+^N$ to $\Re_+^M$.

We assume that there may exist a level of undesirable output, **b*** at which the maximum possible desirable output is achieved (provided technical efficiency). See Figure 3 for graphical illustration of this point. As above this undesirable output level desirable output does not increase, all points on the right of **b*** are inferior to the respective points on the left of **b*** or **b*** itself. Hence, **b*** is the highest undesirable output level, which is still on ∂P(**x**). Therefore we refer to **b*** as to *maximum technically efficient undesirable output* and formally define it as

$$\mathbf{b}^* : \Re_+^N \times \Re_+^L \to \Re_+^M$$
$$\mathbf{b}^*(\mathbf{x},\mathbf{g}) \equiv \sup_{b,g} \left\{ \mathbf{b} > 0 : (\mathbf{g},\mathbf{b}) \in \partial P(\mathbf{x}), \mathbf{g} \in \Re_+^L \ \right\}. \qquad (5.1.9)$$

5. 2. Assumptions on the technology

In this work we follow the axiomatic approach proposed by Shephard (1970) and later followed widely (*e.g.*, Färe and Primont 1995). This approach suggests that the production technology should satisfy certain axioms to be a valid model of production. As our work centers on P(**x**), we state most of the axioms in terms of this set (although they may be redefined in terms of other sets as needed). We need these axioms in order to account for specifics of technology when some outputs are undesirable. These axioms are later used in making restrictions while modeling technology set. Each axiom begins with the reference to the source, where similar axiom was introduced or used. Axioms introduced by myself are not acknowledged.

Axiom 1 (Färe and Primont 1995). Doing nothing is possible. At any level of input we can shut off the production process completely, which will result zero levels in both desirable and undesirable outputs. As this alternative is technologically feasible, we may state that

$$\left(\mathbf{0}_L, \mathbf{0}_M\right) \in P(\mathbf{x}), \forall \mathbf{x} \in \Re_+^N .$$

Axiom 2 (Färe and Primont 1995). There is no free lunch. If no input is invested, non-zero output (desirable or undesirable) cannot be obtained due to the basic physical laws. Formally,

$$\left(\mathbf{g}, \mathbf{b}\right) \notin P(\mathbf{0}_N), \forall \left(\mathbf{g}, \mathbf{b}\right) \geq \left(\mathbf{0}_L, \mathbf{0}_M\right) .$$

Corollary 1 From Axiom 1 and 2 we may draw a conclusion that the only possible output at zero input level is zero:

$$P(\mathbf{0}_N) = \left(\mathbf{0}_L, \mathbf{0}_M\right).$$

Axiom 3 (Färe and Primont 1995). Input is strongly disposable. If input does not decrease, producing the same outputs is possible:

$$\left.\begin{array}{c} \left(\mathbf{g}_0, \mathbf{b}_0\right) \in P(\mathbf{x}_0) \\ \mathbf{x}_1 \geqq \mathbf{x}_0 \end{array}\right\} \Rightarrow \left(\mathbf{g}_0, \mathbf{b}_0\right) \in P(\mathbf{x}_1), \forall \left(\mathbf{g}_0, \mathbf{b}_0\right) \in \Re_+^L \times \Re_+^M .$$

Axiom 4 (Färe and Primont 1995). Desirable output is strongly disposable. If desirable output does not increase and the undesirable output and input stays the same, the production is technologically feasible:

$$\left.\begin{array}{c} \left(\mathbf{g}_0, \mathbf{b}_0\right) \in P(\mathbf{x}_0) \\ \mathbf{g}_0 \geqq \mathbf{g}_1 \end{array}\right\} \Rightarrow \left(\mathbf{g}_1, \mathbf{b}_0\right) \in P(\mathbf{x}_0), \forall \left(\mathbf{b}_0, \mathbf{x}_0\right) \in \Re_+^M \times \Re_+^N .$$

Assuming similar thing about undesirable output is not reasonable, since decreasing undesirable output may involve some decrease of desirable output (especially for efficient DMUs). Recall the definition from (5.1.8) to obtain the alternative to strong disposability.

Axiom 5 Output is relatively weakly disposable, *i.e.* reduction of undesirable output is possible if the simultaneous decrease of the desirable output occurs. The word 'relatively' emphasizes that the simultaneous contraction of outputs is happening relatively to a specific point, which we defined before as minimum technically efficient undesirable output. The following axiom formalizes the statement that reducing undesirable output is costly:

$$(\mathbf{g}_0, \mathbf{b}_0) \in P(\mathbf{x}_0) \Rightarrow (\psi\, \mathbf{g}_0, [\mathbf{b}' + \psi(\mathbf{b}_0 - \mathbf{b}')]) \in P(\mathbf{x}_0),$$
$$\forall (\mathbf{g}_0, \mathbf{b}_0, \mathbf{x}_0) \in \Re^L_+ \times \Re^M_+ \times \Re^N_+, \psi < 1$$

and equivalently

$$(\mathbf{g}_0, \mathbf{b}_0) \in P(\mathbf{x}_0) \Rightarrow (\psi\, \mathbf{g}_0, [(1-\psi)\mathbf{b}' + \psi\, \mathbf{b}_0]) \in P(\mathbf{x}_0),$$
$$\forall (\mathbf{g}_0, \mathbf{b}_0, \mathbf{x}_0) \in \Re^L_+ \times \Re^M_+ \times \Re^N_+, \psi < 1.$$

As this axiom has been introduced in the previous works in somewhat different form (mostly due to the fact that they assumed that the minimum technically efficient undesirable output is equal to zero), some discussion of it and illustration may be useful. Illustration of the axiom is provided on Figure 7.

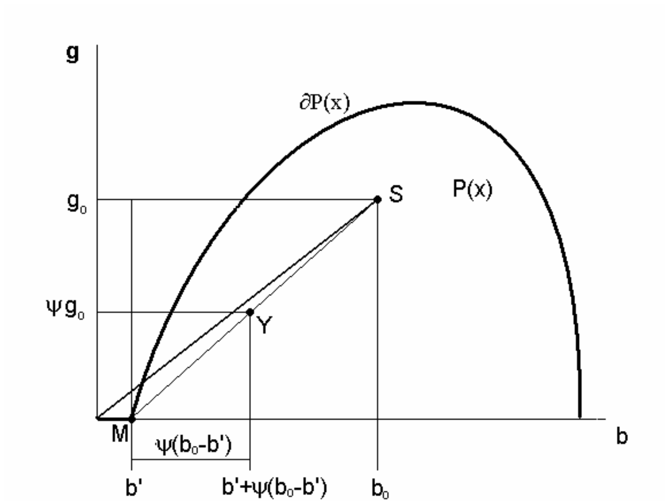

Figure 7. Graphical representation of the Axiom 5.

The Axiom 5 suggests radial contraction of the technologically feasible output vector along the ray from point M on the horizontal axis corresponding to the minimum technically efficient undesirable output. The Axiom implies that any point on the MS line is in the output set. This axiom generalizes previously accepted axiom of weak disposability of outputs, which suggested contracting the output vector along the ray from the origin (Chung 1996, Lee *et al.* 2002).

Axiom 6 (Färe and Primont 1995). P(**x**) is closed. We assume that all points located on the boundary of the output set are included in the set.

Axiom 7 (Färe and Primont 1995). P(**x**) is bounded. We assume that DMUs cannot produce negative amounts of outputs (all outputs are bounded from downwards). In addition, the maximum possible amount of any output is limited by the total amount of input invested in production due to the basic physical laws, *e.g.* a firm cannot produce more than 1 kg of output if it has only 1 kg of input (all outputs are bounded from upwards).

Corollary 2 Axiom 6 and 7 imply that P(**x**) is compact.

Axiom 8 (Färe and Primont 1995). P(**x**) is convex for $\forall \mathbf{x} \in \Re_{+}^{N}$.

Axiom 9 Finally, we make an assumption on the shape of ∂P(**x**). We assume that once a minimum technically efficient undesirable output is achieved, it has positive slope that gradually diminishes.

5. 3. Modeling multi-output technology with distance functions

In the first section of this chapter we have seen a primal approach to model technology by constructing the respective set. Here, we discuss an alternative method of representing multi-output technology by the distance functions.

Distance functions is a class of functions founded by Shephard (1970) able to represent a wide spectrum of existing technologies. Under certain assumptions on technology many of them are complete characterizations of the technology. That is why they obtained an enormous widespread in production economics.

Shephard (1970) defined *output distance function* (ODF) on the output set as

$$D_O : \Re_{+}^{N} \times \Re_{+}^{L+M} \to \Re_{+}^{1} \cup \{+\infty\}$$

$$D_O(\mathbf{x}, \mathbf{y}) \equiv \inf_{\theta} \{\theta > 0 : \mathbf{y} / \theta \in P(\mathbf{x})\}, \tag{5.3.1}$$

which can be intuitively understood as the *smallest* possible number on which we can divide *output* vector provided input to obtain an input-output combination, which is still technologically feasible (which is equivalent to the simultaneous multiplication of all outputs by the same number). This function suggests radial expansion of the output vector until it hits the boundary of the output set. The ratio of the initial output vector to the expanded vector is the value of the ODF.

Another function proposed by Shephard (1970) is *input distance function* (IDF) defined on the input set as

$$D_I : \Re_+^{L+M} \times \Re_+^N \to \Re_+^1 \cup \{+\infty\}$$

$$D_I(\mathbf{y}, \mathbf{x}) \equiv \sup_{\lambda} \{\lambda > 0 : \mathbf{x} / \lambda \in L(\mathbf{y})\}, \qquad (5.3.2)$$

which can be intuitively understood as the *biggest* possible number on which we can divide *input* vector provided output to obtain an input-output combination, which is still technologically feasible. This function suggests radial contraction of the output vector until it hits the boundary of the input set. The ratio of the initial output vector to the contracted vector is the value of the IDF.

Under weak disposability these functions completely characterize multiple-output technology. ODF is linearly homogeneous in outputs and IDF is linearly homogeneous in inputs (Shephard 1970).

However, as we consider inputs fixed in the short-run, it is not reasonable to use IDF in studying the topic of countries producing undesirable outputs. Similarly, as it has no sense to expand output production (both desirable and undesirable) in the attempts to become more efficient, ODF is also not the best choice of modeling our technological process. Therefore we must come out with a function that may credit expansion of desirable outputs and contraction of undesirable outputs provided fixed inputs.

Such functions called distance functions were introduced by Luenberger (1992) and were applied by a number of recent studies (Chung 1996; Lee *et al.* 2002, *etc.*).

5. 4. Hyperbolic efficiency and directional distance function

Färe *et al.* (1989) introduced output oriented hyperbolic efficiency measure (OHE). This efficiency measure allows to credit expansion of some of the outputs and contraction of the others. In the case when some outputs are undesirable OHE can be defined as

$$H_O : \Re_+^N \times \Re_+^{L+M} \to \Re_+^1 \cup \{+\infty\}$$

$$H_O(\mathbf{x}, \mathbf{g}, \mathbf{b}) \equiv \sup\{\theta > 0 : (\theta \mathbf{g}, \mathbf{b}/\theta) \in P(\mathbf{x})\}, \mathbf{x} \in \Re_+^N, \qquad (5.4.1)$$

Graphical comparison of OHE against efficiency measure based on the ODF (or Farrell's measure after Farrell 1957) is provided on Figure 8.

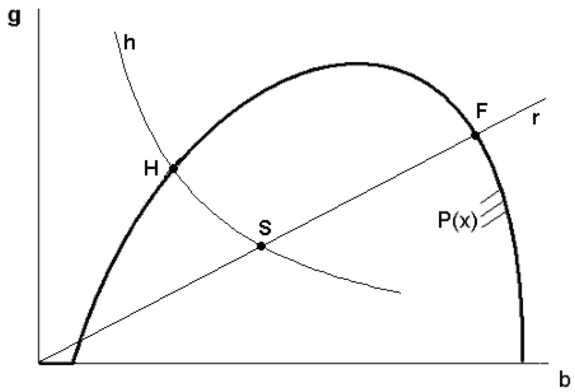

Figure 8. Graphical comparison of OHE against Farrell's output-oriented efficiency measure.

It is clearly seen that in the case of undesirable outputs these two measures of technical inefficiency have contrastingly different logics. Farrell's efficiency measure attempts to maximize both desirable and undesirable outputs proportionally to the observed values S by expanding them along the radial line *r* until point F, whereas OHE attempts to increase good output while decreasing bad output along the hyperbolic curve *h* until point H. Obviously enough, the latter strategy better corresponds to the real-life strategies of the societies. OHE can be approximated by using output directional distance function, a function from the class of directional distance functions.

Directional distance functions is a class of functions initially proposed by Luenberger (1992) for dual estimation of benefit function and defined as

$$\vec{D}:\Re^{N}_{+}\times\Re^{L+M}_{+}\times\Re^{N}_{+}\times\Re^{L+M}_{+}\rightarrow\Re^{1}_{+}\cup\{+\infty\}$$

$$\vec{D}\left(\mathbf{x},\mathbf{y}\,\middle|\,\mathbf{d}_{\mathbf{x}},\mathbf{d}_{\mathbf{y}}\right)\equiv\sup\left\{\tau>0:\left(\mathbf{x}-\tau\,\mathbf{d}_{\mathbf{x}},\ \mathbf{y}+\tau\,\mathbf{d}_{\mathbf{y}},\right)\in T\right\}, \tag{5.4.2}$$

where $\mathbf{d}_{\mathbf{x}}$ and $\mathbf{d}_{\mathbf{y}}$ are *N*x1 and (*L*+*M*)x1 column vector that set directions of change in inputs and inputs respectively. Graphical interpretation of directional distance function in 1x0x1 case is provided on Figure 9.

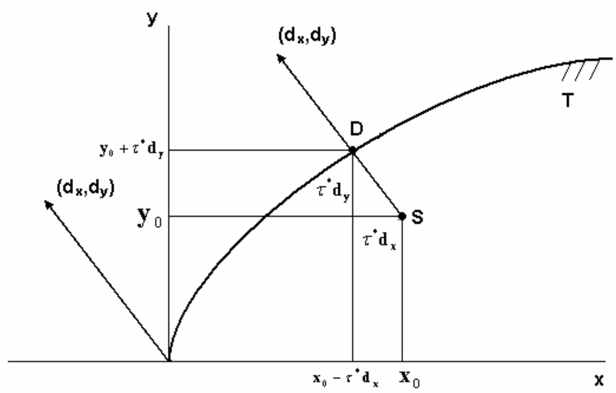

Figure 9. Graphical interpretation of directional distance function

Once we set $\mathbf{d}_{\mathbf{x}}$ and $\mathbf{d}_{\mathbf{y}}$, which are called *directional vectors* (DVs), we start changing the observed values S ($\mathbf{x}_0$, $\mathbf{y}_0$) in the direction provided until we reach the boundary of the technology set (point D). The ratio of the obtained vector of change to the DVs is exactly the value of the directional distance function τ^*.

It should be noted, however, that DVs are set arbitrary and are based on the researcher's belief about how a DMU should behave as it increases its efficiency.

By setting $\mathbf{d_x} = \mathbf{0}_N$ Chung (1996) introduced a specific case of directional distance function: output directional distance function (ODDF), which he defined as

$$\vec{D}_O : \Re_+^N \times \Re_+^L \times \Re_+^M \to \Re_+^1 \cup \{+\infty\}$$

$$\vec{D}_O\left(\mathbf{x}, \mathbf{g}, \mathbf{b} \middle| \mathbf{d_g}, \mathbf{d_b}\right) \equiv \sup\{\tau > 0 : (\mathbf{g} + \tau\,\mathbf{d_g},\ \mathbf{b} - \tau\,\mathbf{d_b},) \in P(\mathbf{x})\}. \tag{5.4.3}$$

ODDF allows simultaneous increase in desirable and decrease in undesirable outputs. ODDF may be demonstrated to possess some important properties discussed in the following section.

Chung (1996) proposed to use DV $\mathbf{d_g} = \mathbf{g},\ \mathbf{d_b} = \mathbf{b}$ later called *general DV* by Lee *et al.* (2002). Sometimes it is suggested that DV sets an *efficiency rule* (ER) according to which a DMU moves in its attempt to become more efficient. We will use terms DV and ER interchangeably.

ODDF with a general ER sets direction of change in outputs proportionally to the existing production level, just like ODF does. However, unlike ODF it credits contraction of undesirable output, while ODF credits extension of it. Therefore ODDF with a general DV is similar to ODF in the principle of proportional change and to OHE in terms of the crediting increase of desirable and decrease of undesirable outputs.

Chung (1996) approximated OHE by the first order Taylor expansion of the $\mathbf{b}/\theta$ term around θ=1 to obtain:

$$\begin{aligned} H_O(\mathbf{x},\mathbf{g},\mathbf{b}) \quad &\equiv \sup\left\{\theta > 0 : \left(\theta\mathbf{g}, \frac{\mathbf{b}}{\theta}\right) \in P(\mathbf{x})\right\}, \mathbf{x} \in \Re_+^N \\ &\approx \sup\{\theta > 0 : (\theta\mathbf{g}, (2-\theta)\mathbf{b}) \in P(\mathbf{x})\}, \mathbf{x} \in \Re_+^N \\ &= \sup\{\theta > 0 : ((\mathbf{0}_L, 2\mathbf{b}) + \theta(\mathbf{g}, -\mathbf{b})) \in P(\mathbf{x})\}, \mathbf{x} \in \Re_+^N \\ &= \sup\{\theta > 0 : ((\mathbf{g},\mathbf{b}) + (\theta-1)(\mathbf{g}, -\mathbf{b})) \in P(\mathbf{x})\}, \mathbf{x} \in \Re_+^N \\ &= 1 + \sup\{(\theta-1) > 0 : ((\mathbf{g},\mathbf{b}) + (\theta-1)(\mathbf{g}, -\mathbf{b})) \in P(\mathbf{x})\}, \mathbf{x} \in \Re_+^N \\ &= 1 + \sup\{\tau = (\theta-1) > 0 : ((\mathbf{g},\mathbf{b}) + \tau(\mathbf{g}, -\mathbf{b})) \in P(\mathbf{x})\}, \mathbf{x} \in \Re_+^N \\ &= 1 + \vec{D}_O(\mathbf{x},\mathbf{g},\mathbf{b} \mid \mathbf{g},\mathbf{b}) \end{aligned} \tag{5.4.4}$$

This represents a crucial result that determines our choice of ODDF with general DV as a tool for constructing the technology set (its duality to the technology will be proved in the next section. The choice is made in favor of this function for the following four reasons:

1. ODDF is a complete characterization of technology.

2. ODDF with a general DV is a first order approximation of a OHE, which is suitable for assessing technological efficiencies, when some outputs are undesirable.

3. ODDF with a general DV "may be considered as a generalization of the usual … [ODF] approach where the observed output vector is also used in determining the direction of expansion" (Chung 1996).

4. ODDF with a general DV has a property of commensurability as defined by Russell (1988) as opposing to those DVs, which are not proportional to the observed values of outputs (*e.g.*, $\mathbf{d_g}$=$\mathbf{1}_L$, $\mathbf{d_b}$=$\mathbf{1}_M$) as demonstrated by Salnykov and Zelenyuk (2004b).

5.5. Properties of output directional distance function

Below we discuss a number of properties of ODDF, which will be used later in modeling the technology set or justify a choice of ODDF as an efficiency measure.

Here we closely follow the findings of Chung (1996), who made use of the results of Luenberger (1992) to show that ODDF satisfies the following properties.

a) Monotonicity in input vector: If $(\mathbf{g},\mathbf{b}) \in P(\mathbf{x})$ and $\mathbf{x}' \geq \mathbf{x} \Rightarrow (\mathbf{g},\mathbf{b}) \in P(\mathbf{x}')$ (*i.e.*, A3 holds), then $\vec{D}_O(\mathbf{x}',\mathbf{g},\mathbf{b} \mid \mathbf{d_g},\mathbf{d_b}) \geq \vec{D}_O(\mathbf{x},\mathbf{g},\mathbf{b} \mid \mathbf{d_g},\mathbf{d_b})$. That allows us to expect that among two DMUs with identical output levels the one with the higher input will have the higher ODDF value, *i.e.* will be less efficient, which is coherent with the common logic.

b) Monotonicity in desirable output vector: If $(\mathbf{g},\mathbf{b}) \in P(\mathbf{x})$ and $\mathbf{g} \geq \mathbf{g}' \Rightarrow (\mathbf{g}',\mathbf{b}) \in P(\mathbf{x})$ (*i.e.* A4 holds), then $\vec{D}_O(\mathbf{x},\mathbf{g}',\mathbf{b} \mid \mathbf{d_g},\mathbf{d_b}) \geq \vec{D}_O(\mathbf{x},\mathbf{g},\mathbf{b} \mid \mathbf{d_g},\mathbf{d_b})$. In words, among two DMUs with identical inputs and undesirable output production, the one with the lower desirable output production will have the higher ODDF value, *i.e.* will be less efficient.

c) Sign preservation: $(\mathbf{g},\mathbf{b}) \in P(\mathbf{x}) \Rightarrow \vec{D}_O(\mathbf{x},\mathbf{g},\mathbf{b} \mid \mathbf{d_g},\mathbf{d_b}) \geq 0$. That along with (e) tells that the domain of ODDF is restricted from 0 to unity with 0 value for the efficient DMU. That allows simple interpretation of ODDF as a technologically feasible percentage increase in desirable output with simultaneous percentage decrease in undesirable output.

Some specific properties for the case when $(\mathbf{d_g}, \mathbf{d_b}) = (\mathbf{g}, \mathbf{b})$ can be mentioned:

d) Commensurability: $\vec{D}_O(\mathbf{x}, \mathbf{g}, \mathbf{b} \mid \mathbf{g}, \mathbf{b})$ is commensurable in line with Russell (1988) as showed by Salnykov and Zelenyuk (2004b). This property is useful, since we want to ensure that efficiency measure stays the same as we change the units of measurements of inputs or outputs.

e) Upper bound of the domain: $(\mathbf{g}, \mathbf{b}) \in P(\mathbf{x}) \Rightarrow \vec{D}_O(\mathbf{x}, \mathbf{g}, \mathbf{b} \mid \mathbf{g}, \mathbf{b}) \leq 1$. Intuitively, the efficiency measure will not indicate that any of the DMUs is able to decrease its undesirable production by more than 100% percent.

Finally, we restate the most desired and most crucial for our study result of Chung (1996) that

f) $(\mathbf{g}, \mathbf{b}) \in P(\mathbf{x}) \Leftrightarrow \vec{D}_O(\mathbf{x}, \mathbf{g}, \mathbf{b} \mid \mathbf{d_g}, \mathbf{d_b}) \geq 0$, *i.e.* ODDF is a complete characterization of technology. This result allows to model technology relying solely on modeling ODDF.

There is a number of other properties of ODDF not provided here for the sake of conciseness as these properties are not used in modeling. For the detailed discussion of them as well as for the proves of (a) – (c) and (f), see Chung (1996).

5.6. Duality between the revenue function and the ODDF

This section also follows closely the study of Chung (1996).

Let $(\mathbf{p^g}, \mathbf{p^b}) \in \Re_+^L \times \Re_-^M$ be the vector of output prices of the output vector $(\mathbf{g}, \mathbf{b})$. We allow for nonnegative prices of desirable outputs and nonpositive prices of undesirable ones. In line with Chung (1996) we define revenue function (sometimes also cross-referenced as benefit function) as

$$R(\mathbf{x},\mathbf{p}^{\mathbf{g}},\mathbf{p}^{\mathbf{b}}) = \max_{\mathbf{g},\mathbf{b}}\{(\mathbf{p}^{\mathbf{g}}\mathbf{g}+\mathbf{p}^{\mathbf{b}}\mathbf{b}) : (\mathbf{g},\mathbf{b}) \in P(\mathbf{x})\}, \mathbf{x} \in \Re^{N}_{+} . \tag{5.6.1}$$

Chung (1996) proves the duality between revenue function and ODDF. His finding can be summarized as follows:

Let $(\mathbf{p}^{\mathbf{g}},\mathbf{p}^{\mathbf{b}}) \in \Re^{L}_{+} \times \Re^{M}_{-}$ and $\mathbf{p}^{\mathbf{g}}\mathbf{d}_{\mathbf{g}} + \mathbf{p}^{\mathbf{b}}\mathbf{d}_{\mathbf{b}} > 0$. Then,

(a) $R(\mathbf{x},\mathbf{p}^{\mathbf{g}},\mathbf{p}^{\mathbf{b}}) = \max_{\mathbf{g},\mathbf{b}}\{\mathbf{p}^{\mathbf{g}}\mathbf{g}+\mathbf{p}^{\mathbf{b}}\mathbf{b} + \vec{D}_O(\mathbf{x},\mathbf{g},\mathbf{b} \mid \mathbf{d}_{\mathbf{g}},\mathbf{d}_{\mathbf{b}})(\mathbf{p}^{\mathbf{g}}\mathbf{d}_{\mathbf{g}} + \mathbf{p}^{\mathbf{b}}\mathbf{d}_{\mathbf{b}})\}$

(b) $\vec{D}_O(\mathbf{x},\mathbf{g},\mathbf{b} \mid \mathbf{d}_{\mathbf{g}},\mathbf{d}_{\mathbf{b}}) = \inf_{\mathbf{p}^{\mathbf{g}},\mathbf{p}^{\mathbf{b}}}\{R(\mathbf{x},\mathbf{p}^{\mathbf{g}},\mathbf{p}^{\mathbf{b}}) - (\mathbf{p}^{\mathbf{g}}\mathbf{g}+\mathbf{p}^{\mathbf{b}}\mathbf{b}) : (\mathbf{p}^{\mathbf{g}}\mathbf{d}_{\mathbf{g}} + \mathbf{p}^{\mathbf{b}}\mathbf{d}_{\mathbf{b}}) = 1\}.$

The obtained duality allows to rely on the ODDF, when we believe that DMUs are revenue (as defined by (5.6.1)) maximizers as we do by stating the following.

Axiom 10 All countries maximize their revenues, which we define as a product of all desirable outputs on their respective prices less a product of all undesirable outputs on their respective prices.

As product of all desirable outputs on their respective prices provide us a single number reported in national accounting, we make the following statement.

Axiom 11 All countries produce a single desirable output, which we call Economic Output (later defined in terms of GDP and GDP in PPP).

5.7. Derivation of shadow prices: duality approach

A way of obtaining shadow prices relying on the derivative properties of the ODF and its duality to revenue function was proposed by Färe *et al.* (1993). They showed that ratio of shadow prices of outputs can be estimated as

$$\frac{\hat{p}_m^b}{p_l^g} = \frac{\partial D_O(\mathbf{x},\mathbf{y})/\partial b_m}{\partial D_O(\mathbf{x},\mathbf{y})/\partial g_l}. \tag{5.7.1}$$

In order to estimate absolute value of shadow prices of undesirable outputs the most straightforward way used by Färe *et al.* implies making an assumption on shadow prices of desirable outputs, which we summarize in the following Axiom.

Axiom 12 Shadow prices of desirable outputs equal their market prices, *i.e.* good output worth \$1 is valued by a society as \$1.

Findings of Färe *et al.* (1993) were later extended by Chung (1996) to show that the ratio of shadow prices of desirable outputs can be estimated using ODDF as

$$\frac{\hat{p}_m^b}{p_l^g} = \frac{\partial \vec{D}_O(\mathbf{x},\mathbf{g},\mathbf{b} \mid \mathbf{d_g},\mathbf{d_b})/\partial b_m}{\partial \vec{D}_O(\mathbf{x},\mathbf{g},\mathbf{b} \mid \mathbf{d_g},\mathbf{d_b})/\partial g_l}, \tag{5.7.2}$$

which under A12 enables estimating absolute value of shadow prices of undesirable outputs.

(5.7.1) and (5.7.2) imply that we can calculate the derivative of the distance function at any point (which is possible using parametric approach). However, what if nonparametric approach is employed and we can estimate the derivative of ODDF only on $\partial P(\mathbf{x})$? A solution was proposed (although wasn't proved mathematically) by Lee *et al.* (2002).

Let $\mathbf{g}^e = \left(g_1^e \;\; g_2^e \;\; \ldots g_L^e\right)^T \in \Re_+^L$ and $\mathbf{b}^e = \left(b_1^e \;\; b_2^e \;\; \ldots b_M^e\right)^T \in \Re_+^M$ be the coordinates of the point on $\partial P(\mathbf{x})$ to which a given observation $(\mathbf{g}, \mathbf{b})$ is projected by an ODDF, *i.e.*

$$\mathbf{g}^e = \left(1 + \vec{D}_O\left(\mathbf{x}, \mathbf{g}, \mathbf{b} \middle| \mathbf{d}_\mathbf{g}, \mathbf{d}_\mathbf{b}\right)\right)\mathbf{g} \text{ and} \tag{5.7.3}$$

$$\mathbf{b}^e = \left(1 - \vec{D}_O\left(\mathbf{x}, \mathbf{g}, \mathbf{b} \middle| \mathbf{d}_\mathbf{g}, \mathbf{d}_\mathbf{b}\right)\right)\mathbf{b}\,. \tag{5.7.4}$$

Then ratio of desirable and desirable output shadow prices can be estimated for $(\mathbf{g}, \mathbf{b})$ as

$$\frac{\hat{p}_m^b}{p_l^g} = \frac{\partial \vec{D}_O\left(\mathbf{x}, \mathbf{g}, \mathbf{b} \middle| \mathbf{d}_\mathbf{g}, \mathbf{d}_\mathbf{b}\right) / \partial b_m^e}{\partial \vec{D}_O\left(\mathbf{x}, \mathbf{g}, \mathbf{b} \middle| \mathbf{d}_\mathbf{g}, \mathbf{d}_\mathbf{b}\right) / \partial g_l^e} \cdot \frac{1 - \vec{D}_O\left(\mathbf{x}, \mathbf{g}, \mathbf{b} \middle| \mathbf{d}_\mathbf{g}, \mathbf{d}_\mathbf{b}\right)}{1 + \vec{D}_O\left(\mathbf{x}, \mathbf{g}, \mathbf{b} \middle| \mathbf{d}_\mathbf{g}, \mathbf{d}_\mathbf{b}\right)}. \tag{5.7.5}$$

In our estimation we will follow (5.7.2) in estimating shadow prices in parametric framework and (5.7.5) in nonparametric.

5.8. Concluding remarks

Now, after describing theoretical framework of the model, we will turn to describing the methodology of empirical estimation. That, however, requires an additional axiom related to the quality of the data, which is:

Axiom 13 All observations are technologically feasible.

This axiom allows assuming that no outliers that distort the frontier are included in the sample. In other words, we do allow some observations to be outliers as long as they are inefficient.

In this chapter we provided a brief technical exposition to productivity analysis in the presence of undesirable outputs, justified the choice of the efficiency measure and showed that, in theory, it allows obtaining shadow prices of pollutants. Now, based on the introduced theoretical underpinnings, we are ready to present the methodology of the study, which makes use of the theory presented above.

Chapter 6

METHODOLOGY OF THE EMPIRICAL ESTIMATION

In this chapter we will present methodology to estimate ODDF with general DV and shadow prices of undesirable outputs as well as methods of statistical analysis for them. The chapter will also comment the data to be used as well as issues in forming the sample.

Estimation of the ODDF and the shadow prices can be realized by using various techniques. The traditional studies in the field follow Aigner and Chu (1968), Schmidt (1978) and Greene (1980) in specifying a parametric form of technology and solve for the parameters using the linear programming.

6.1. Estimating ODDF: parametric approach

Chung (1996)[5] proposed to parameterize ODDF by the Translog function for a general DV. This specification is flexible, linear in coefficients and provides second order approximation for any technology. In addition, it does not suggest strong disposability of outputs, which is important when undesirable outputs are under review. Chung defines Translog specification of ODDF (adjusted for the purposes of the current study, where L=1) as

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[5] Similar approach was used by Hailu and Veeman (1998) to estimate input distance function (IDF) and by Färe *et al.* (1993) to estimate ODF.

$$\begin{aligned}
&\ln\left[1+\vec{D}_0(\mathbf{x},\mathbf{g},\mathbf{b}|\mathbf{g},\mathbf{b})\right]= \\
&\qquad \alpha_0+\alpha_1\ln g+\sum_m \beta_m \ln b_m+\sum_n \gamma_n \ln x_n \\
&\qquad +\frac{1}{2}\alpha_{11}(\ln g)(\ln g)+\frac{1}{2}\sum_m\sum_{m'}\beta_{mm'}(\ln b_m)(\ln b_{m'}) \\
&\qquad +\frac{1}{2}\sum_n\sum_{n'}\gamma_{nn'}(\ln x_n)(\ln x_{n'})+\frac{1}{2}\sum_n \delta_n(\ln g)(\ln x_n) \\
&\qquad +\frac{1}{2}\sum_m\sum_n \varepsilon_{mn}(\ln b_m)(\ln x_n)+\frac{1}{2}\sum_m \zeta_m(\ln g)(\ln b_m)
\end{aligned} \tag{6.1.1}$$

where Greek letter are the parameters we solve for.

The reason for having $\ln\left[1+\vec{D}_0(\cdot)\right]$instead of $\ln\left[\vec{D}_0(\cdot)\right]$ is that domain of the logarithmic function is positive numbers, while $\vec{D}_0(\cdot)$ can take a zero value on ∂P(**x**). Therefore, we have to make an artificial restriction of the domain of the function to the positive numbers only.

Chung (1996) then estimates the parameters of (6.1.1) by minimizing the sum of the deviations of the observations from the efficient level, *i.e.* ∂P(**x**). Mathematically, the optimization problem is

$$\begin{aligned}
&\min\sum_k\left[\ln\left(1+\vec{D}_0(\cdot)\right)-\ln\left(1+\vec{D}_0(\cdot)\Big|_{\partial P(\mathbf{x})}\right)\right] \\
&\equiv \min\sum_k\left[\ln\left(1+\vec{D}_0(\cdot)\right)-\ln(1+0)\right]\equiv \min\sum_k\left[\ln\left(1+\vec{D}_0(\cdot)\right)\right]
\end{aligned} \tag{6.1.2}$$

Then (6.1.1) can be estimated by using (6.1.2) as an objective function as

$$\min \sum_k \left[\ln\left(1 + \vec{D}_0(\mathbf{x}^k, \mathbf{g}^k, \mathbf{b}^k \middle| \mathbf{g}^k, \mathbf{b}^k)\right) \right] \tag{6.1.3}$$

s.t.

(i) $\ln\left(1 + \vec{D}_0(\mathbf{x}^k, \mathbf{g}^k, \mathbf{b}^k \middle| \mathbf{g}^k, \mathbf{b}^k)\right) \geq 0 \qquad k = 1..K$

(ii) $\dfrac{\partial\left\{\ln\left(1 + \vec{D}_0(\cdot)\right)\right\}}{\partial(\ln g)} \leq 0$

$\dfrac{\partial\left\{\ln\left(1 + \vec{D}_0(\cdot)\right)\right\}}{\partial(\ln b_m)} \geq 0 \qquad m = 1..M$

(iii) $\alpha_1 - \sum_m \beta_m = -1$

$\alpha_{11} - \sum_m \zeta_m = 0 \qquad m, m' = 1..M$

$\zeta_m - \sum_{m'} \beta_{mm'} = 0 \qquad n = 1..N$

$\delta_n - \sum_m \varepsilon_{mn} = 0$

(iv) $\beta_{mm'} = \beta_{m'm} \quad ; \quad \gamma_{nn'} = \gamma_{n'n}$

Constraint (i) corresponds to Axiom 13 requiring that all observations are technologically feasible as all observations in the technology set have $\vec{D}_0(\cdot) \geq 0$. (ii) guarantees nonnegative shadow prices for good outputs and nonpositive shadow prices for bad outputs. (iii) imposes functional properties of the ODDF as an approximation of the hyperbolic efficiency measure. Finally, (iv) imposes symmetry on Hessian according to the Young's theorem.

Hence, we need to minimize a single objective function subject to a total of $K(M+2)+0.5(M(M+1)+N(N+1))+2$ constraints. The optimization results a set of $3+2M+2N+M^2+MN+N^2$ estimated parameters of (6.1.1). We agree to denote this set of estimates $\hat{\theta}(\mathbf{g}, \mathbf{B}, \mathbf{X})$, where $\mathbf{B} = (\mathbf{b}_1 \ \mathbf{b}_2 \ \ldots \mathbf{b}_M) \in \Re_+^K \times \Re_+^M$ and $\mathbf{X} = (\mathbf{x}_1 \ \mathbf{x}_2 \ \ldots \mathbf{x}_N) \in \Re_+^K \times \Re_+^N$ are matrices containing observed values of undesirable outputs and inputs for all DMUs. $\hat{\theta}(\mathbf{g}, \mathbf{B}, \mathbf{X})$ is an estimate of the true set of parameters of (6.1.1) θ. Plugging into (6.1.1) $\hat{\theta}(\mathbf{g}, \mathbf{B}, \mathbf{X})$ and the observations for a given DMU will result an estimated ODDF value for that DMU in $\ln\left[1+\hat{\vec{D}}_O(\cdot)\right]$ terms. A transformation of it as

$$\hat{\vec{D}}_0\left(\mathbf{x}^k, \mathbf{g}^k, \mathbf{b}^k \middle| \mathbf{g}^k, \mathbf{b}^k\right) = \exp\left\{\ln\left[1+\hat{\vec{D}}_0\left(\mathbf{x}^k, \mathbf{g}^k, \mathbf{b}^k \middle| \mathbf{g}^k, \mathbf{b}^k\right)\right]\right\} - 1 \quad \forall k = 1 \ldots K \quad (6.1.4)$$

will supply $\hat{\vec{D}}_0\left(\mathbf{x}^k, \mathbf{g}^k, \mathbf{b}^k \middle| \mathbf{g}^k, \mathbf{b}^k\right)$, an estimated value of the true ODDF $\vec{D}_0\left(\mathbf{x}^k, \mathbf{g}^k, \mathbf{b}^k \middle| \mathbf{g}^k, \mathbf{b}^k\right)$ for a given DMU. We agree to denote this estimate as $\hat{\tau}^k\left(g^k, \mathbf{b}^k, \mathbf{x}^k \middle| \hat{\theta}(\mathbf{g}, \mathbf{B}, \mathbf{X})\right)$ and the true ODDF value as $\tau^k\left(g^k, \mathbf{b}^k, \mathbf{x}^k \middle| \theta\right)$.

6.2. Estimating shadow prices: parametric approach

The shadow prices are estimated in line with (5.7.2) as

$$\hat{p}_m{}^b = p^g \frac{\partial \hat{\vec{D}}_0(\cdot)/\partial b_m}{\partial \hat{\vec{D}}_0(\cdot)/\partial g}, \quad (6.2.1)$$

where $\hat{\vec{D}}_0(\cdot)$ is a short notation for $\hat{\vec{D}}_0(\mathbf{x}, \mathbf{g}, \mathbf{b} | \mathbf{g}, \mathbf{b})$.

At this,

$$\frac{\partial \hat{\vec{D}}_0(\cdot)}{\partial b_m} = \frac{\partial \hat{\vec{D}}_0(\cdot)}{\partial \ln\left[1+\hat{\vec{D}}_0(\cdot)\right]} \cdot \frac{\partial \ln\left[1+\hat{\vec{D}}_0(\cdot)\right]}{\partial(\ln b_m)} \cdot \frac{\partial(\ln b_m)}{\partial b_m} \quad (6.2.2)$$

and

$$\frac{\partial \hat{\vec{D}}_0(\cdot)}{\partial g} = \frac{\partial \hat{\vec{D}}_0(\cdot)}{\partial \ln\left[1+\hat{\vec{D}}_0(\cdot)\right]} \cdot \frac{\partial \ln\left[1+\hat{\vec{D}}_0(\cdot)\right]}{\partial(\ln g)} \cdot \frac{\partial(\ln g)}{\partial g} \quad (6.2.3)$$

Hence (6.2.1) can be rewritten as,

$$\hat{p}_m^{\ b} = p^g \frac{\dfrac{\partial \hat{\vec{D}}_0(\cdot)}{\partial \ln\left[1+\hat{\vec{D}}_0(\cdot)\right]} \cdot \dfrac{\partial \ln\left[1+\hat{\vec{D}}_0(\cdot)\right]}{\partial(\ln b_m)} \cdot \dfrac{\partial(\ln b_m)}{\partial b_m}}{\dfrac{\partial \hat{\vec{D}}_0(\cdot)}{\partial \ln\left[1+\hat{\vec{D}}_0(\cdot)\right]} \cdot \dfrac{\partial \ln\left[1+\hat{\vec{D}}_0(\cdot)\right]}{\partial(\ln g)} \cdot \dfrac{\partial(\ln g)}{\partial g}}$$

$$= p^g \frac{\partial \ln\left[1+\hat{\vec{D}}_0(\cdot)\right] \Big/ \partial(\ln b_m)}{\partial \ln\left[1+\hat{\vec{D}}_0(\cdot)\right] \Big/ \partial(\ln g)} \cdot \frac{g}{b_m} \tag{6.2.4}$$

Some simple algebra allows to derive from (6.1.4) that

$$\frac{\partial \ln\left[1+\hat{\vec{D}}_0(\cdot)\right]}{\partial(\ln b_j)} = \hat{\beta}_j + \sum_m \hat{\beta}_{mj}(\ln b_m) + \frac{1}{2}\sum_n \hat{\varepsilon}_{jn}(\ln x_n) + \frac{1}{2}\hat{\zeta}_j(\ln g) \tag{6.2.5}$$

$$\frac{\partial \ln\left[1+\hat{\vec{D}}_0(\cdot)\right]}{\partial(\ln g)} = \hat{\alpha}_1 + \hat{\alpha}_{11}(\ln g) + \frac{1}{2}\sum_n \hat{\delta}_n(\ln x_n) + \frac{1}{2}\sum_m \hat{\zeta}_m(\ln b_m) \tag{6.2.6}$$

Corollary, based on Axiom 12, (6.2.4), (6.2.5) and (6.2.6) shadow price of *j*th undesirable output for *k*th DMU can be numerically estimated as

$$\hat{p}_m^{\ b\,k} = \frac{\hat{\beta}_j + \sum_m \hat{\beta}_{mj}(\ln b_m^{\ k}) + \frac{1}{2}\sum_n \hat{\varepsilon}_{jn}(\ln x_n^{\ k}) + \frac{1}{2}\hat{\zeta}_j(\ln g^k)}{\hat{\alpha}_1 + \hat{\alpha}_{11}\left(\ln g^k\right) + \frac{1}{2}\sum_n \hat{\delta}_n(\ln x_n^{\ k}) + \frac{1}{2}\sum_m \hat{\zeta}_m(\ln b_m^{\ k})} \cdot \frac{g^k}{b_m^{\ k}}, \tag{6.2.7}$$

which are estimates of the true value of shadow prices $p_m^{b\,k}$.

6.3. Estimating ODDF: nonparametric approach

In the most recent works (*e.g.*, Lee *et al.* 2002), the estimation of ODDF is realized using nonparametric production modeling.

First, we introduce the model developed by Lee and his co-authors and then we present some modifications to it, which are based on our set of axioms.

Piecewise-linear production technology is described by Lee *et al.* as

$$P(\mathbf{x})=\{(g, b): g\leq\mathbf{Vz}, b\geq\mathbf{Wz}, X\mathbf{z}\leqq\mathbf{x}, \mathbf{e}^T\mathbf{z}\leq 1, \mathbf{z}\in\Re_+^K\}, \tag{6.3.1}$$

where $\mathbf{V}\in\Re_+^K$ is a row vector consisting of the observed good output values; $\mathbf{W}\in\Re_+^K$ is a row vector of the observed bad output values; $X\in\Re_+^N\times\Re_+^K$ is a matrix of the observed inputs; $\mathbf{e}^T$ is a row vector consisting of ones; $\mathbf{z}\in\Re_+^K$ is a column vector representing intensity variables, *i.e.* the variables used to weight different DMUs in constructing the reference frontier, which estimates $P(\mathbf{x})$.

Let $\mathbf{d} = (\alpha, \beta)$ then $\vec{D}_0(\cdot)$ for kth economy can be calculated based on a given production technology by solving the following linear programming problem

$$\max \tau^k \tag{6.3.2}$$

s.t.

(i) $\mathbf{Vz} \geq (1+\alpha\tau^k)g^k \qquad k = 1..K$

(ii) $\mathbf{Wz} \leq (1+\beta\tau^k)b^k$

(iii) $X\mathbf{z} \leqq \mathbf{x}^k$

(iv) $\mathbf{e}^T\mathbf{z} \leq 1$

(v) $\mathbf{z} \geqq \mathbf{0}_K, \tau^k \geq 0$

In contrast to Lee *et al.*, we estimate true output set with

$$\hat{P}(\mathbf{x}\,|\,\text{NIRS})=\{(g, \mathbf{b}): g\leq\mathbf{gz}, \mathbf{b}\geqq\mathbf{Bz}, \mathbf{Xz}\leqq\mathbf{x}, \mathbf{e}^T\mathbf{z}\leq 1, \mathbf{z}\in\Re_+^K\} \tag{6.3.4}$$

under NIRS assumption (which is in line with Lee's assumption on the returns to scale) and

$$\hat{P}(\mathbf{x}\,|\,\text{VRS})=\{(g, \mathbf{b}): g\leq\mathbf{gz}, \mathbf{b}\geqq\mathbf{Bz}, \mathbf{Xz}\leqq\mathbf{x}, \mathbf{e}^T\mathbf{z}=1, \mathbf{z}\in\Re_+^K\} \tag{6.3.5}$$

in the VRS[6] case (which is based on Axiom 5).

In (6.3.4) and (6.3.5) $\mathbf{e}^T$ is a row vector consisting of ones; $\mathbf{z}\in\Re_+^K$ is a column vector representing intensity variables.

ODDF for a k^{th} DMU using our chosen DV will be estimated through

$$\max \tau^k \qquad (6.3.6)$$

s.t.

$$
\begin{array}{lll}
\text{(i)} & \mathbf{Gz} \geq (1+\tau^k)g^k & k = 1..K \\
\text{(ii)} & B\mathbf{z} \leqq (1-\tau^k)\mathbf{b}^k & \\
\text{(iii)} & X\mathbf{z} \leqq \mathbf{x}^k & \\
\text{(iv)} & \mathbf{e}^T\mathbf{z} \leq 1 & \\
\text{(v)} & \mathbf{z} \geqq \mathbf{0}_K, \tau^k \geq 0 &
\end{array}
$$

in the NIRS case and

$$\max \tau^k \qquad (6.3.7)$$

s.t.

$$
\begin{array}{lll}
\text{(i)} & \mathbf{Gz} \geq (1+\tau^k)g^k & k = 1..K \\
\text{(ii)} & B\mathbf{z} \leqq (1-\tau^k)\mathbf{b}^k & \\
\text{(iii)} & X\mathbf{z} \leqq \mathbf{x}^k & \\
\text{(iv)} & \mathbf{e}^T\mathbf{z} = 1 & \\
\text{(v)} & \mathbf{z} \geqq \mathbf{0}_K, \tau^k \geq 0 &
\end{array}
$$

in the VRS case.

Each of the two cases is a set of K problems of linear maximization over $K+1$ parameter subject to $3+M+N+K$ linear inequality constraints (in the NIRS case) or $2+M+N+K$ linear inequality and 1 equality constraint (in the VRS case).

---

[6] DEA estimation under VRS assumption allows wrapping all observations in the smallest possible convex free disposable hull. In such a way, we may allow for good output production start only after a certain threshold in a bad production is achieved.

6.4. Estimating shadow prices: nonparametric approach

Having estimated the ODDF values, we may calculate the values of the shadow prices on the production possibility frontier and out of it. We discuss an exact procedure of doing it using (6.3.7) as an example, but the same pattern can be used to (6.3.6) as well.

The first thing we should do is to find projections of all observations on ∂P(**x**) according to the DV chosen. This point will have the following respective coordinates

$$g^{e^k} = \left(1 + \hat{\vec{D}}_O^k(\cdot)\right) g^k \tag{6.4.1}$$

and

$$\mathbf{b}^{e^k} = \left(1 - \hat{\vec{D}}_O^k(\cdot)\right) \mathbf{b}^k, \tag{6.4.2}$$

where by $\hat{\vec{D}}_O^k(\cdot)$ is a short notation for $\hat{\vec{D}}_O\left(\mathbf{x}^k, \mathbf{g}^k, \mathbf{b}^k \middle| \mathbf{g}^k, \mathbf{b}^k\right)$.

At this, all points will be taken to the estimated ∂P(**x**).

Next, we run K linear programming tasks for each DMU $k=1\ldots K$ on the 'adjusted' data

$$\max_{\mathbf{z},\tau^k} \tau^k \tag{6.4.3}$$

s.t.

(i)	$\mathbf{Gz} \geq (1+\tau^k) g^{ek}$	$k = 1..K$
(ii)	$B\mathbf{z} \leq (1-\tau^k)\mathbf{b}^{ek}$	
(iii)	$X\mathbf{z} \leq \mathbf{x}^k$	
(iv)	$\mathbf{e}^T\mathbf{z} = 1$	
(v)	$\mathbf{z} \geq \mathbf{0}_K, \tau^k \geq 0$	

We obtain a set of new optimal values of **τ** and **z** as well as a set of Lagrange multipliers for each constraint in (6.4.3). The Lagrange multipliers to (i) and (ii) in

(6.4.3) are equal the shadow prices of constraints in the conventional mathematical-programming sense. They are also the normalized shadow prices in the conventional economic sense. Ratios of the respective Lagrange multipliers are equal to the ratios of $\partial \vec{D}_O^k(\cdot)/\partial g^k$ and $\partial \vec{D}_O^k(\cdot)/\partial b_m^k$ (*m*=1…*M*, *k*=1…*K*) respectively. We calculate estimates of the shadow prices for a DMU in line with (5.7.5) as

$$\hat{p}_m^{b\,k} = p^{g\,k} \frac{\lambda_{(ii)m}^k}{\lambda_{(i)}^k} = p^{g\,k} \frac{\lambda_{(ii)m}^k}{\lambda_{(i)}^k} \cdot \frac{1-\hat{\vec{D}}_O^k(\cdot)}{1+\hat{\vec{D}}_O^k(\cdot)}, \tag{6.4.4}$$

where $\lambda_{(i)}^k$ is a Lagrange multiplier for a *k*th DMU's constraint (i) in (6.4.3), $\lambda_{(ii)m}^k$ is a Lagrange multiplier for a *k*th DMU's constraint (ii) for a polluter *m*.

It must be noted however, that nonparametric approach may provide nonunique estimated values of shadow prices (since (6.4.3) may have nonunique solution and, hence, nonunique Lagrange multipliers to each constraint). It is not clear at the moment how to solve the problem of nonuniqueness of estimates and identify a range of estimated values. For that reason, nonparametric approach in estimating shadow prices seems to be less reliable than parametric.

6.5. Evaluating statistical characteristics of estimates: bootstrap technique

We estimate statistical characteristics of the parametrically obtained estimates by adapting a smooth homogeneous bootstrap originally proposed for DEA-estimated efficieincies by Simar and Wilson (1998). We run $Q = 5'000$ iterations to obtain bootstrap estimates of (6.1.1) $\hat{\theta}_q^*$ $q = 1,...,Q$ using the smoothing module that employs kernel estimated densities of ODDF. Plugging $\hat{\theta}_q^*$ and the respective observations into (6.1.4) and (6.2.7) results bootstrap estimates of ODDF and shadow prices $\hat{\tau}{*}_q^k$ and $\hat{p}{*}_{m\,q}^{b\,k}$. We do not employ bootstrap on nonparametric estimates as the size of the sample is too small for it relative to dimensionality of the problem.

The general algorithm of the smooth bootstrap technique employed can be summarized as follows.

Let $\mathbf{g} = (g^1 \dots g^K)^T \in \Re_+^K$, $\mathbf{B} = (\mathbf{b}_1 \dots \mathbf{b}_M) \in \Re_+^K \times \Re_+^M$ and $\mathbf{X} = (\mathbf{x}_1 \dots \mathbf{x}_N) \in \Re_+^K \times \Re_+^N$ be the observed matrices of desirable and undesirable outputs and inputs for *K* DMUs.

1. Using (6.1.3) and observations, obtain estimated values of parameters of (6.1.1), $\hat{\theta}(\mathbf{g}, \mathbf{B}, \mathbf{X})$. Using (6.1.4) calculate $\hat{\tau} = \{\hat{\tau}^1 \dots \hat{\tau}^K\}$ $\hat{\tau}^k\left(g^k, \mathbf{b}^k, \mathbf{x}^k \middle| \hat{\theta}(\mathbf{g}, \mathbf{B}, \mathbf{X})\right)$ $\forall k = 1 \dots K$.

2. Using kernel density estimator and reflection method calculate bandwidth of kernel estimated distribution of estimated ODDF $\hat{\tau} \sim \hat{f}(\hat{\tau})$ as, for example,

   $$h = 1.06 \cdot \min\{\sigma_{\mathrm{T}}, iqr(\mathrm{T})/1.349\} \cdot K^{-0.2}, \qquad (6.5.1)$$

   where T is a vector consisting of those $\hat{\tau}^k > 0$ and reflections of these numbers, *i.e.* $-\hat{\tau}^k : \hat{\tau}^k > 0$, σ_{T} is a standard deviation of T, *iqr*(T) is an interquartile range of T. (6.5.1) is often referred to as Silverman's adaptive rule of thumb (after Silverman (1986)); this rule will be used in our study.

3. Draw a random sample $\{\beta^{*1} \dots \beta^{*K}\}$ with replacement from $\{\hat{\tau}^1 \dots \hat{\tau}^K\}$.

4. Calculate $\left\{\tilde{\theta}^{*1} \ldots \tilde{\theta}^{*K}\right\}$ as

$$\tilde{\theta}^{*k} = \begin{cases} \beta^{*k} + h\varepsilon^{*k} & \text{if} \quad \beta^{*k} + h\varepsilon^{*k} \geq 0 \\ -\left(\beta^{*k} + h\varepsilon^{*k}\right) & \text{otherwise} \qquad \forall k = 1 \ldots K \quad , \end{cases} \tag{6.5.1}$$

where β^{*k} is taken from the Step 3;

h is obtained from (6.5.1);

ε^{*k} is a normally distributed random variable $\varepsilon^{*k} \sim N(0,1)$.

Then $\tilde{\theta}^{*k} \sim \hat{f}(\hat{\tau})$, where $\hat{f}$ is a kernel density estimator for τ. Similar statement was proven by Efron and Tibshirani (1993) and Simar and Wilson (1998).

5. To correct variance, form $\tau^{*} = \left\{\tau^{*1} \ldots \tau^{*K}\right\}$ as

$$\tau^{*k} = \overline{\beta}^{*} + \frac{\tilde{\theta}^{*k} - \overline{\beta}^{*}}{\sqrt{1 + \dfrac{h^2}{\hat{\sigma}_{\hat{\tau}}^2}}} \qquad \forall k = 1 \ldots K, \tag{6.5.2}$$

where $$\overline{\beta}^{*} = \frac{1}{K} \cdot \sum_{k=1}^{K} \beta^{*k} ;$$

$$\hat{\sigma}_{\hat{\tau}} = \sqrt{\frac{1}{K} \sum_{k=1}^{K} \left(\hat{\tau}^{k} - \overline{\hat{\tau}}\right)^2} ;$$

$$\overline{\hat{\tau}} = \frac{1}{K} \cdot \sum_{k=1}^{K} \hat{\tau}^{k} .$$

6. Form $\mathbf{g}^{*} = \left(g^{*1} \ldots g^{*K}\right)^{T} \in \Re_{+}^{K}$, $\mathbf{B}^{*} = \left(\mathbf{b}_1^{*} \ldots \mathbf{b}_M^{*}\right) \in \Re_{+}^{K} \times \Re_{+}^{M}$ as

$$g^{*k} = \frac{1 + \hat{\tau}^{k}}{1 + \tau^{*k}} \cdot g^{k} \qquad \forall k = 1 \ldots K ; \tag{6.5.3}$$

$$b_m^{*k} = \frac{1 - \hat{\tau}^{k}}{1 - \tau^{*k}} \cdot b_m^{k} \qquad \forall k = 1 \ldots K, \quad m = 1 \ldots M . \tag{6.5.4}$$

7. Using (6.1.3) and $\mathbf{g}^*, \mathbf{B}^*, \mathbf{X}$, obtain bootstrap estimated values of parameters of (6.1.1) $\hat{\theta}_q^*(\mathbf{g}^*, \mathbf{B}^*, \mathbf{X})$.

   Using (6.1.4) calculate $\hat{\tau}_q^* = \{\hat{\tau}_q^{*1} \ldots \hat{\tau}_q^{*K}\}$ $\hat{\tau}_q^{*k} = \hat{\vec{D}}_O\left(g^{*k}, \mathbf{b}^{*k}, \mathbf{x}^k \middle| \hat{\theta}_q^*(\mathbf{g}^*, \mathbf{B}^*, \mathbf{X})\right)$ $\forall k = 1 \ldots K$.

   Using (6.2.7) calculate $\hat{p}_{mq}^{*b} = \{\hat{p}_{mq}^{*b1} \ldots \hat{p}_{mq}^{*bK}\}$ $\hat{p}_{mq}^{*bk}\left(g^{*k}, \mathbf{b}^{*k}, \mathbf{x}^k \middle| \hat{\theta}_q^*(\mathbf{g}^*, \mathbf{B}^*, \mathbf{X})\right)$ $\forall k = 1 \ldots K, m = 1 \ldots M$.

8. Repeat Steps 1-7 Q times to estimate $\hat{\tau}^* = \{\hat{\tau}_1^* \ldots \hat{\tau}_Q^*\}$ and $\hat{p}_m^{*b} = \{\hat{p}_{m1}^{*b} \ldots \hat{p}_{mQ}^{*b}\}$ $\forall m = 1 \ldots M$.

95 middle percentiles of the set of $\hat{\tau}*^k$ and $\hat{p}*_m^{bk}$ represent confidence interval of the ODDF estimates and shadow prices estimates respectively for each DMU.

Finally, we construct bias corrected estimates for parametrically estimated values of ODDF as

$$\hat{\tau}_{BC}^k = 2\hat{\tau}^k - \frac{1}{Q}\sum_{q=1}^{Q} \hat{\tau}*_q^k \quad k = 1 \ldots K. \tag{6.5.1}$$

While it was shown that efficiency measures are biased and, thus, require bias correction, presence of bias has not been demonstrated for shadow prices. Nevertheless, we still compute and report bias corrected shadow prices for completeness purposes, but do not rely on these values while discussing the results. Bias corrected shadow prices will be calculated as

$$\hat{p}_{mBC}^{bk} = 2\hat{p}_m^{bk} - \frac{1}{Q}\sum_{q=1}^{Q} \hat{p}*_{mq}^{bk} \quad k = 1 \ldots K, m = 1 \ldots M. \tag{6.5.2}$$

6.6. Comparing estimates obtained by using different approaches

We obtain three different series of estimates for environmental inefficiencies and shadow prices of undesirable output, namely, parametrically obtained estimates and nonparametrically obtained estimates under two assumptions: VRS and NIRS. It seems logical enough to attempt to compare these estimates to each other to find out if different approaches provide with similar results.

The most direct and the easiest way to compare the estimates is to follow Coelli and Perelman (1999) and calculate correlation indexes between the series of estimates. The obtained values of correlation indexes will indicate whether the DMUs that were determined as inefficient according to one approach tend to be considered inefficient according to the other approach. Similarly, correlation indexes will tell whether the DMUs that had high estimates of shadow prices of undesirable outputs according to one approach tend to have also high estimates of them according to the other approach.

In addition, we may make use of the statistical characteristics of the estimates estimated by using the bootstrap technique. In doing so, we notice whether nonparametrically obtained estimates of ODDF and shadow prices fall within 95% confidence interval around parametric estimates. Should it be so, we conclude that for a particular DMU, the difference between nonparametric and parametric estimates is not statistically significant.

6.7. Software used for the estimation

As optimizing over many variables without any technical support is both time consuming and leaves much room for errors, we will be using a mathematical software package MATLAB of MathWorks, Inc. for linear programming and bootstrap. The choice was made in favor of this software for many reasons. First, "MATLAB is ideally suited to handle linear programming problems" (Hunt *et al.* 2002). Second, it is an open code program, which allows modifications in the built-in functions should they be necessary. Thirdly, some scholars working in the field of productivity and efficiency analysis are using this software, so the exchange of working codes is possible. Finally, MATLAB can execute basic statistical analysis of the estimates, so it is not needed (in most cases) to use other software for statistical analysis.

6.8. Statistical analysis of the estimates

Statistical analysis of the estimates will be executed in two main ways.

Firstly, for all estimates we will estimate kernel densities using the reflection method in line with Simar and Wilson (1998). For ODDF we will estimate kernel densities of the monotonically transformed ODDF value, namely

$$\delta = \frac{1}{1-\vec{D}_O(\cdot)} - 1. \qquad (6.8.1)$$

(6.8.1) transforms ODDF to the efficiency measure having domain [0, +∞) as $\vec{D}_O(\cdot) \in [0,1]$.

Comparing visual representations of these densities for estimates obtained with different methodologies will provide with some ground for further discussion on comparability of the methodologies.

Secondly, we will analyze shadow prices of pollutants by comparing means of the medium 90 percentiles. If these means happen to be different, we will conclude that a pollutant with a larger absolute value of the shadow price is valued more by most of the societies, *i.e.* most of the societies agree to forfeit more output in order to get rid of one unit of that pollutant.

6.9. Forming sample: choice of countries

The study will analyze 96 countries including 27 CITs. The rest of countries contain typical North and South representatives for the purpose of comparing CITs with those.

6.10. Forming sample: choice of inputs and outputs

The list of inputs and outputs for each of the DMUs is represented in Table 1 with description that follows. All data used refers to 1995, the last year when environmental data is available for most of the countries of the world. All values are taken in per year terms.

Table 1. The list of inputs and outputs used in the estimation

Desirable Output	Undesirable Outputs	Inputs
Economic output *	CO_2 emissions ** SO_2 emissions ** NO_x emissions **	Labor * Arable land *** Energy consumption ** Capital stock ***

Notes: * Taken from WB (2000)
** Taken from WRI (2004)
*** Adapted from WB (2000).

We employ two specifications, which do not differ in undesirable outputs and first three inputs, but they do differ in terms of desirable output and capital stock. The first specification uses economic output in terms of GDP and capital stock in international dollars, while the second is based on GDP and capital stock in PPP. Intuition behind using each of the outputs/inputs is provided below.

GDP can be used as a measure of total output produced within the boundaries of the country. As we assume countries to be revenue maximizing DMUs (Axiom 10), GDP can be considered the only good output produced (Axiom 11). Shadow prices of pollutants obtained from Specification I, where GDP is used, can be used as a reference values for monetary rates of payments for environmental damage as well as prices for international environmental trade taken in international dollars.

GDP in PPP In Specification II, when we take GDP in terms of PPP, we ensure that one dollar is valued by each country in exactly the same way. Thus, shadow prices obtained in Specification II allow cross-country comparison in order to determine, which countries value environmental damage more in terms of purchasing power of money.

CO_2 emissions are resulted mostly by burning various fuels and is considered one of the main sources of the global climate change. CO_2 does not have a significant impact on human health unless in big concentrations (NYSDEC 2004). The pollutant is selected as an example of the undesirable output, which *a priori* is expected to have **low** shadow price as it does not have any direct impact on people.

SO_2 emissions The major accounted sources of SO_2 emissions are fossil fuel, including coal and oil fired power plants and boilers, ore smelters and oil refineries. Human exposure to sulfur dioxide can result in irritation of the respiratory system which can cause both temporary and permanent damage. Particulates tend to catalyze the atmospheric conversion of SO_2 to sulfur trioxide (SO_3) which combines with water vapor to form sulfuric acid mist (NYSDEC 2004). The pollutant is selected as an example of the undesirable output, which *a priori* should have **medium** shadow price as it has limited direct impact on people and human environment through acidic precipitations.

NO_x emissions (includes nitrogen oxides of different nitrogen valency) Nitrogen dioxide (NO_2), a reddish brown gas with a highly detectable pungent odor, is highly corrosive and a strong oxidizing agent. It is produced from the reaction of atmospheric nitrogen and oxygen during high temperature combustion processes such as the burning of fuel (coal, oil, gas) and internal combustion (motor vehicles). Nitric oxide (NO), a colorless, odorless gas, is also a product of combustion and the combination of NO and NO_2 is commonly referred to as NO_x. While NO by itself is not usually considered a health hazard, NO_2 can cause inflammation of the lungs and bronchial tubes at high concentrations and less severe respiratory problems at lower concentrations. NO_x contributes to haze, reduces visibility, causes serious injury or death to plant tissue, deteriorates fabrics, and forms nitrate salts that can corrode metals (NYSDEC 2004). The

pollutant is selected as an example of the undesirable output, which *a priori* should have **high** shadow price as it has substantial direct impact on people and human environment through forming smog.

Labor is considered one of the major production inputs in the most of production processes. We make estimates based on the total labor force. Thus, increase in unemployment would likely cause increase in inefficiency of the DMU (country).

Arable land is considered one of the production inputs in some production processes. We make estimates based on the arable land available as it is directly involved in production of agricultural output.

Energy consumption was selected as a proxy for all raw materials used in the economy. It is a known fact that the most energy consuming are those countries producing much of the heavy industrial (thus, polluting) output (Cherp and Salnykov 2004). We want to debit countries for using too much energy in the same manner as debiting it for overusing other inputs.

Capital stock is considered one of the major production inputs in the most of production processes. We make estimates based on the total stock of fixed capital at the end of the year.

Ideally, as many inputs and undesirable outputs as possible should be analyzed. However, (i) data for many important undesirable outputs (land degradation, water pollutants discharges, *etc.*) is not available for a vast majority of countries and (ii) including too much inputs and outputs to construct referencing frontier may limit power of the methods involved due to small number of observations.

6.11. Summary

In short, the methodology of the study can be summarized by the diagrams provided on Figure 10 for Specification I. Specification II follows the same general pattern with two major differences: (i) GDP in PPP is used instead of GDP and (ii) we cannot conclude on equilibrium on international pollutants market in Specification II, since shadow prices here are not given in the international dollars.

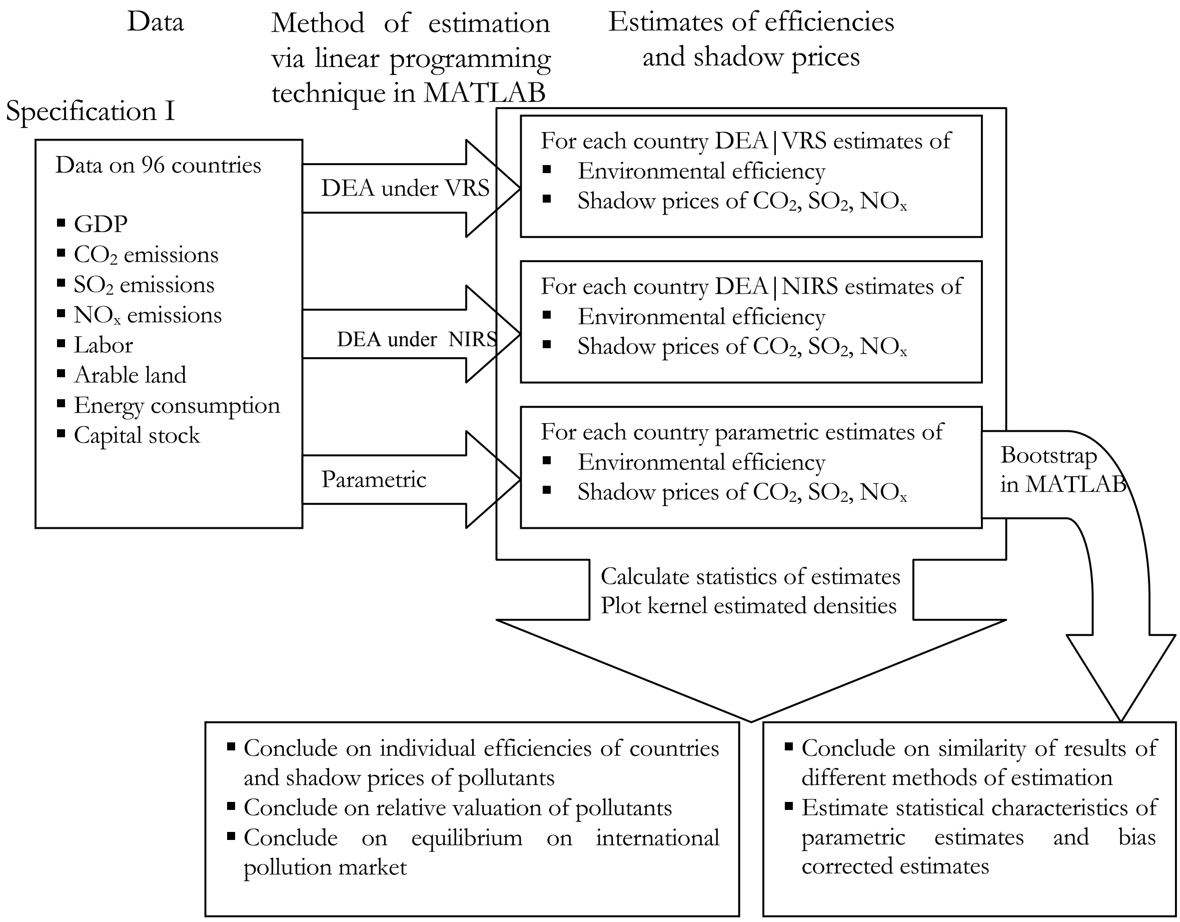

Figure 10. Flow chart of the empirical analysis

Chapter 7

EMPIRICAL ESTIMATION RESULTS AND DISCUSSION

In this chapter we will present basic descriptive statistics of the data used for empirical analysis, provide and discuss estimation results, while the next chapter will list our conclusions and policy recommendations.

After we present empirical results of the study, we will provide a general discussion of the obtained results, illustrative examples on the interpretation of the estimates as well as raise questions regarding the choice of methodology (parametric vs nonparametric). Unless otherwise specified, we will closely focus in our discussion on Specification I, since Specification II is useful in comparing shadow prices within a single country only. This specification provides with shadow prices in terms of PPP and has a similar intuition as economic GDP in PPP: shadow prices are given in terms of purchasing power of money in a given country and appear to be inappropriate for cross-country comparison purposes.

7.1. Data used in the study

General statistics on the data is provided in Appendix 1.

7.2. Parametric estimation

Running MATLAB code written for the estimation of the ODDF in the *Translog* form resulted the values of the estimation parameters as provided in Appendix 2 (for Specification I) and Appendix 3 (for Specification II).

The estimation of ODDF and shadow prices of pollutants resulted the values given in Appendix 4 (for Specification I) and Appendix 5 (for Specification II).

7.3. Nonparametric estimation

The estimation of ODDF and shadow prices of pollutants using nonparametric approach under NIRS assumption resulted the values given in Appendix 6 (for Specification I) and Appendix 7 (for Specification II).

The estimation of ODDF and shadow prices of pollutants using nonparametric approach under VRS assumption resulted the values given in Appendix 8 (for Specification I) and Appendix 9 (for Specification II).

7.4. Statistical characteristics of estimates obtained parametrically

Confidence intervals and bias corrected estimates for Specification I are provided in Appendix 10 (ODDF), Appendix 11 (shadow price of CO_2), Appendix 12 (shadow price of SO_2), and Appendix 13 (shadow price of NO_x) respectively.

Confidence intervals and bias corrected estimates in Specification II are provided in Appendix 14 (ODDF), Appendix 15 (shadow price of CO_2), Appendix 16 (shadow price of SO_2), and Appendix 17 (shadow price of NO_x) respectively.

7.5. Comparing estimates obtained parametrically and nonparametrically

Correlation matrix for estimates obtained in Specification I is provided in Appendix 18.

Correlation matrix for estimates obtained in Specification II is provided in Appendix 19.

7.6. Statistical analysis of the results

Joint graphs for kernel estimated densities distributions are provided in Appendix 20 (for Specification I) and Appendix 21 (for Specification II).

Mean values of the lower (by absolute value) 95% of variables is provided in Appendix 22 (for Specification I) and Appendix 23 (for Specification II).

7.7. Efficiency measures

Our estimates show that regardless of the methodology, countries on the best practice frontier can be either developed (USA) or underdeveloped (Uruguay).

In addition, we observe similar variation of efficiency scores within a group of CITs: while some countries may be on the best practice frontier (*e.g.*, Croatia in parametric and Albania in nonparametric VRS framework), others are far from it. However, it must be noted that a number of CITs on the frontier is extremely low for all methodologies (one country under parametric and nonparametric VRS assumption and no countries under nonparametric NIRS). This fact witnesses on a general tendency of CITs to work below their technological potential. The reason for it (most likely) is a wide use of old Soviet-type polluting technologies as well as underdeveloped institutional capacity (*i.e.* ability to address environmental concerns of the society) in these countries, which often accompanies poor environmental performance (Cherp and Salnykov 2004).

As we restrict measure of efficiency between zero and unity, it has a very simple and intuitive interpretation: it shows by how many per cent a country can increase its GDP and decrease its pollution being within feasible production combination. We will see the application of this fact in the illustrative example presented later.

7.8. Shadow prices of pollutants

As it was discussed before, shadow prices represent the internal valuation of pollution (by a pollutant) by a given country. *A priori* we expected that those pollutants having more direct and more severe effect on human health should be valued by societies more. Particularly, we expected carbon dioxide to have the lowest (by absolute value) shadow price, nitrogen oxides to have the highest shadow price and sulfur dioxide's shadow price to be somewhere in between.

Such *a priori* expectation is strongly supported in *average* terms for both specifications and each of three methodologies employed. Nevertheless, estimated shadow prices for individual countries sometimes demonstrate different ranking of valuation.

7.9. Illustrative example 1: predicting environmental effect of economic growth

Efficiency measure and shadow prices of pollutants highlight different aspects in fighting environmental degradation. Shadow prices of pollution, which can be interpreted as marginal rate of technical substitution between GDP and a specific pollutant, show a short term changes in environmental quality if GDP changes, while technical efficiency stays the same. Efficiency, in contrast, demonstrates a distance of a given country to the best practice frontier and can be understood as a potential percentage increase in GDP and potential percentage decrease in pollution if a country decides to employ the best possible technology.

Let us discuss the implications of the estimates for Ukraine. Here, for the sake of example, we will focus on parametric estimates.

ODDF value of 0.27 indicates that it is technologically feasible for Ukraine to increase its GDP by 27% and simultaneously decrease the level of CO_2, SO_2 and NO_x emissions by 27% should it decide to use the best-practice technologies. As change of technological process is a long-term course of action, a short-term effect of increase in GDP (or a long-term effect subject to holding to the same efficiency) can be calculated based on the shadow prices of pollutants. Below, we demonstrate step-by-step derivation of the forecasts.

Ukrainian GDP is \$49 bln, CO_2 emissions – 428.7 mln tons, SO_2 – 2.6 mln tons, NO_x – 2.4 mln tons. Shadow prices of the pollutants are as follows: -61.3 \$/ton (CO_2); -2,352 \$/ton (SO_2); -26,170 \$/ton (NO_x).

Suppose Ukraine experiences GDP growth of 1% or \$490 mln, while efficiency remains constant. Ratio of shadow prices, which is equal to marginal rate of technical substitution of GDP for CO_2 pollution tells us that such increase in GDP results $\frac{\$490\,\text{mln}}{61.3\ \$/\text{ton}} = 8\,\text{mln ton}$ or 1.87% increase in CO_2 emissions compared to the original value. Similarly, for other pollutants the increase will be 208 ths tons or 8% for SO_2 and 18.7 ths tons or 0.78% for NO_x. That proposes that Ukrainian economic growth would have the biggest impact on SO_2 emissions, while GDP growth will result an increase of NO_x (the most dangerous) emission in approximately 1:1 ratio.

Interestingly, our estimations are similar to the forecasts of Russian government (whose methods we do not know) with respect to Russian economic growth. In December 2003, Andrei Illarionov, President Vladimir Putin's top economic advisor, commented on Russia's withdraw from the Kyoto Protocol signing: "In those countries we analyzed, each percent of GDP growth is accompanied by an increase of carbon dioxide emissions by 2 percent" (Walters, 2003)[7]. Our estimates, in turn, show that Russian growth of 1% of GDP will lead to at least 1.77% increase in CO_2 emissions provided Russian efficiency remains the same. Thus, our estimation methodology provides (at least for Russia) similar estimates as Russian government's methodologies.

7.10. Illustrative example 2: international tradable pollution permit trade

Imagine a simplified version of Kyoto protocol: two countries, Russia and Ukraine, enter an agreement to hold their total CO_2 emission level constant. At this, should any party need to emit more than today, it should negotiate on the price with the other and purchase a permit to emit additional pollution, while the other party should shrink its pollution by the amount sold. Suppose that the government values present gains much more than benefits to future generations.

Assume that technology does not change, but both countries face positive exogenous shock leading to real output growth. Output growth leads to emission increase *ceteris paribus*. At this, according to our estimates, Russia agrees to pay at most $123 for a right to increase its CO_2 emission by 1 ton. In turn, Ukraine agrees to decrease its CO_2 emissions by 1 ton if it is paid at least $61. Since it is

[7] As we doubt wide availability of the source sited, we included scanned article in Appendix 24. Such step is caused by our desire to assist further studies in the field with the additional material.

clearly in the interests of Russia to pay between $61 and $123 to Ukraine to buy 1 CO_2 ton emission permit, so that Ukraine will shrink its GDP and CO_2 emissions, while Russia will expand both GDP and CO_2 production; both countries will gain from such transaction *ceteris paribus*.

As our model predicts, absolute value of shadow price of a pollutant is negatively related to the GDP level and pollution level *ceteris paribus*. Hence, the absolute value of shadow price of CO_2 increases for Ukraine and decreases for Russia. Should countries face the perspective for more economic growth, the trade of permits continues until shadow prices across countries equalize.

Our simple intuitive illustration leads us to two important conclusions. Firstly, introduction of an agreement similar to Kyoto protocol would lead to equalization of shadow prices of pollutants across countries. Secondly, countries with the lowest absolute value of shadow prices will be tradable permit sellers, while those with the highest absolute value of shadow prices will be permit buyers.

Mean estimated shadow price of CO_2 for CITs is -93 $/ton (with the largest -390 $/ton for Hungary) against world mean of -478 $/ton. Thus, we may conclude that under conditions of Kyoto protocol, CITs will most likely be sellers of pollution permits as it was assumed by UN, while developing the protocol.

Subdivision of the CITs on new EU members plus EU acceding countries[8] and those outside EU provides with the mean estimated shadow prices of CO_2 of -156.8 $/ton (for newly EU entered CITs) and -55 $/ton (for the rest of the CITs) respectively. That allows to extend our argument and argue that countries

[8] Czech Republic, Estonia, Hungary, Latvia, Lithuania, Poland, Slovak Republic and Slovenia (new EU members) and Bulgaria and Romania (EU acceding countries).

not heading towards EU will be more active sellers of permits under Kyoto protocol than those, which have entered/entering EU.

Another important implication follows from our analysis. Implementation of Kyoto protocol may cause CITs to decrease their economic output (provided countries don't increase their efficiency). Thus, we may conclude that ratification of the protocol may require additional steps from the CITs' governments to ensure that economic mechanisms do not result suppression of national output in CITs once Kyoto protocol is in force.

CITs will be receiving money exceeding their GDP loss, which is indeed profitable in the short term. However, in the long term these countries would jeopardize their productive factor stock (particularly capital stock) and, thus, receive benefits for the expense of sacrificing future generations' ability to produce.

Therefore, government (national and international) may adopt two amendments to Kyoto protocol *per se*: (i) accomplish pollution permit trading simultaneously with the GDP restructuring, so that GDP growth is achieved by the growth in non-polluting sectors, or (ii) ensure that the money received from the pollution trade goes to improved use of best practice technology (*i.e.* increasing environmental efficiency), not to pockets of individuals.

7.11. Illustrative example 3: developing efficient environmental taxation

Our final example concerns developing environmental taxation on the basis of the estimated shadow prices. Let us depict the derivation of optimal size of pollution tax on the example of NO_x pollution in Ukraine.

Suppose government decides that it is necessary to decrease NO_x pollution from 2.4 mln ton to 2 mln ton. There are two options available: increase efficiency of economy from 0.27 to 0.124 by promoting cleaner technologies or by making NO_x polluters pay a tax and, thus, shrinking both GDP and NO_x production. Here we will review second choice, since it is related to estimated shadow prices.

Suppose Ukraine is not going to change its efficiency and undesirable output emissions level others than NO_x. Then (6.1.1) leads to the following constraint.

$$\begin{aligned}&\alpha_1 \ln g + \beta_3 \ln b_3 + \frac{1}{2}\alpha_{11}(\ln g)(\ln g) + \ln b_3\left(\sum_{m=1}^{2}\beta_{m3}(\ln b_m) + \frac{1}{2}\beta_{33}(\ln b_3)\right) \\ &+ \frac{1}{2}\sum_n \delta_n(\ln g)(\ln x_n) + \frac{1}{2}\ln b_3 \sum_n \varepsilon_{3n}(\ln x_n) + \frac{1}{2}\sum_m \zeta_m(\ln g)(\ln b_m) = const\end{aligned} \quad (7.11.1)$$

Calculating (7.11.1) for current values of outputs and inputs provides with a value of constant -2.2893. Substituting b_3=2 instead of 2.4 and solving for g provides with a new level of GDP of $39.3502 bln. Finally, solving (6.2.7) with new values of NO_x and GDP provides a new estimate of shadow price of NO_x equal -63,111 $/ton. In other words, in order to lower NO_x to a level of 2 mln ton, the government needs to make the society to value 1 ton of emission by $37,000 more, *i.e.* impose a tax of $37 per 1 kg of NO_x emitted.

Three important reservations should be made with respect to calculating environmental tax rate using this methodology. Firstly, the government needs to determine a target level of emissions *ex ante*. Secondly, the methodology of calculation is mathematically cumbersome and is not, by any mean, transparent, which is a desirable property of any taxation system. Thirdly, the taxation rate calculated is a *country-level* rate, which will be (almost for sure) different from the optimal levels of taxation for individual firms (as each firm may have different shadow prices).

With respect to the first complication, we must acknowledge that the government should make a decision on the target level of emissions based on its judgments on what is the socially desirable level of pollution, which is not an easy task. With respect to the second complication, the calculations should be made once by authorities and later altered should target level of emissions change: general public can be given just a final rate of taxation.

The third complication is the most crucial, but still solvable. Two solutions can be proposed. The first is to impose taxation on the country. Such a tax can be levied by the international government (*e.g.* the UN). For example, by imposing a tax on Ukraine of $37 per 1 kg of NO_x emitted, the UN can expect that Ukraine will shrink its NO_x emissions to the level of 2 mln tons per year. The second solution (which also can be considered as a government's response to the first option executed by the UN) involves additional estimations executed by the government on the firm-level data. Following our methodology, the government can estimate shadow prices of pollution for the firms responsible for the largest share of pollution in the country (*e.g.* 95%). Once this set of prices is estimated, the government selects a level of the tax (*i.e.* the number by which the shadow prices should be increased) so that to shrink the total emission level by a desirable number (0.4 mln tons in our case).

7.12. Comparing parametric and nonparametric approaches

We use kernel estimated densities of the estimates and correlation matrices as instruments, which can potentially provide us with a red flag on statistically significant differences in the estimates. Should such signal be received, we must study statistical characteristics of the estimates to determine if the estimates are different indeed.

Comparison of kernel estimated densities for ODDF estimated under three methodologies provides a signal that estimates obtained under different methodologies may be statistically different. Very low correlation coefficients between estimates obtained from different methodologies confirm concerns on incompatibility of the methodologies. For these reasons we need to compare the methodologies based on the statistical characteristics of the estimates.

As we can see from the estimates, out of 96 values of estimated ODDF value under nonparametric NIRS assumption only 22 fall within 95% confidence interval of parametric estimates. The same number for the estimated ODDF values under nonparametric VRS assumption is even lower: only 18 fall within 95% confidence interval of parametric estimates. Similar pattern is common for shadow prices and Specification II.

Based on this, we may argue that parametric and nonparametric approaches give statistically different estimates. For a long time these two techniques have been used interchangeably with more preference given to nonparametric when estimating ODDF and more preference given to parametric when estimating shadow prices. However, bootstrap-identified statistical characteristics of parametric estimates point out that it is needed to pay more attention to the choice of methodology while deciding between these two approaches.

What can be the reasons for such drastic differences in the results? Firstly, the parametric approaches allows to envelope data within a smooth hull restricted by certain parametric form, while nonparametric does it using a piece-wise linear estimate for technology set. Naturally, as these two hulls do not coincide, this difference is one (but by no means the main) reason for differences in estimates. Secondly, nonparametric approach does not allow modeling bounded output set, while parametric does.

A natural question, which arises after problems with compatibility of approaches are identified is: what approach should be trusted more. In estimating ODDF nonparametric approach is widely used and there is no specific reason to prefer parametric approach over nonparametric here. Moreover, since parametric approach is capable to misidentify inefficient DMUs as efficient, probably, we should rely more on nonparametric estimates while estimating ODDF only.

Nonparametric approach, however, turns to be highly inconvenient once we start estimating shadow prices. The methodology we employ allows estimating a shadow price, which can be nonunique due to existence of multiple solution to the linear programming task (this refers to the points, which are located on the kinks of the piece-wise linear frontier). The issue of identifying other solutions of the problem is technically complicated and currently solving this question is in progress. Therefore, until the issue is solved, using parametric approach for estimating shadow prices is, probably, the most reasonable choice.

Finally, nonparametric approach is not a convenient choice when using bootstrap to estimate statistical characteristics of the estimates, when the sample is small, which is the issue in our case.

One of the solutions to the above problems with the methodology choice would be an option of employing Stochastic Frontier Analysis (SFA) approach, which is convenient, when taking derivatives (to estimate shadow prices), but also allows for statistical noise with certain parametric structure, which may absorb some discrepancies missed by the parametric approach. As nobody has done SFA when some outputs are undesirable, setting up theoretical framework and model is a time consuming process and, certainly, is a topic of a separate paper.

Chapter 8

CONCLUSIONS AND POLICY RECOMMENDATIONS

This final section will briefly outline general conclusions of the work, policy implications based on our findings and some limitations of the current research as well as recommendations for the future studies in the field.

8.1. Conclusions

The obtained estimation results clearly demonstrate that with respect to the technical efficiency, both rich and poor countries can turn out to be fully technically efficient. At this, transitional countries mostly take positions of the inefficient. Ukraine seems to be far away from its technical potential being more than two times inefficient than the mean value of the indicator. That clearly points on a significant perspectives our country has in moving towards production possibility frontier.

As the value of the present work for the public policy lays mostly in the domain of the shadow prices as estimates for an efficient environmental taxation, we must note that the estimation results point out that CO_2 is 'the least expensive' pollutant, while NO_x being 'the most expensive' one. Such result is not surprising, as any society would value an undesirable output with an indirect harm (in our case a greenhouse gas affecting global climate) less then an undesirable output having a direct influence on the human health (such as NO_x).

The values of the shadow prices obtained from the estimation can be used as the proxy values in setting efficient environmental tax rates. At the moment, (as far as it can be judged from the personal environmental auditing experience) in Ukraine these rates are far below the estimated values. That provides us with a conclusion that in order to meet the societal valuation of the environment, the government should inevitably raise the rates for air pollutants.

Our conclusions in the field of international pollution trade indicate that should any agreement similar to Kyoto protocol be in force, under assumption of unchanging technology CITs will be major pollution permit sellers. By doing so, CITs will find more beneficial to gain revenues from selling permits than from the own economic development, thus sacrificing perspectives to build up capital stock needed for future generations for the instant revenues for current generations subject to no structural changes in GDP. This conclusions allows us to argue that Kyoto protocol *per se* leads to distortions in the intergenerational aspect of sustainability in transitional countries; thus, additional restrictions on this agreement should be put to secure against these distortions or alternatively national governments should ensure that interest of the generations to come are not hampered. Such restrictions are discussed in the policy recommendations section.

Färe *et al* (1993) indicated that unequal values of shadow prices among DMUs point on the inefficient allocation of resources. For this reason, our estimates show that the global economy's wealth and pollution is allocated inefficiently. One of the ways to change this situation is to set environmental taxes using shadow prices estimates as reference values and allow invisible hand of Adam Smith to lead all countries towards a common valuation of environmental resources.

Kernel estimated densities, correlation matrices and confidence intervals of the estimates obtained using smooth homogeneous bootstrap procedure revealed that nonparametric and parametric approaches generally lead to statistically different estimates, although before these techniques were used interchangeably with little attention paid to justification of the choice of approach.

8.2. Policy recommendations

We provided three illustrative examples, how our empirical findings can be useful in developing national environmental and development policies.

Our first illustrative example showed how our estimates can be used in forecasting environmental outcomes of economic growth within a short run based on the estimates of the shadow prices. Estimates of the efficiency measures allow concluding on technological feasibility and scale of potential simultaneous increase of GDP and decrease of environmental pollution. Particularly, we can argue that practically all CITs including Ukraine are away from the best practice frontier, thus have promising long-term perspectives in simultaneous increase of GDP and decrease of pollution, should they improve the technologies in use. Moreover, below-average shadow prices of most of the pollutants in most of the CITs enable us to conclude that decreasing environmental degradation in these countries requires much less sacrifice of economic output than in the developed countries even if efficiency is not increased (*i.e.*, in the short term).

Second illustrative example shows implication of our study for determining a range of prices for international emission trade on the example of an agreement similar to Kyoto protocol. Besides conclusions on prices, our analysis implies that Kyoto protocol may be deeply unsustainable for transitional countries in a sense that it hampers their potential for economic growth and, thus, jeopardizes ability of future generations to develop. That does not imply that Kyoto protocol is undesirable for CITs: current and future may still benefit from the emission trade subject to preventive measures taken by the national governments. Policy recommendations on this issue can include but are not limited to the following:

(i) ignorance of Kyoto protocol by CITs;

(ii) amendments to the protocol restricting international pollution trade only within separate groups of countries, *i.e.* NIS can trade only with NIS countries, EU can trade only with EU countries, NAFTA can trade only with NAFTA countries, *etc.*;

(iii) steps of national governments aimed on putting quotas or otherwise limiting sizes of permit sales so as to soften the protocol's effect.

The most proactive responses of national governments to the protocol that allow enjoying the benefits of it, while still securing against potential harms, would be:

(iv) structural changes in the economy aimed on achieving economic growth due to growing non-polluting sectors (*e.g.* IT industry, academia, *etc.*); and

(v) ensuring that the payments received from the pollution trade go to increasing environmental efficiency of the existing technologies, not to pockets of individuals.

Our third, final example illustrates how to determine the optimal size of environmental taxation based on the *a priori* knowledge of the socially desired pollution level and estimated values of shadow prices. Although this methodology is not as transparent as a 'perfect' taxation can be, it still allows reaching goal of the society. We demonstrated how a desired level of pollution can be achieved by using both taxes imposed by the international government on the country and by the national government on the domestic firms (subject to additional estimation executed).

In general, this study has promising implications for environmental policy. However, these implications may be more sound should further efforts be invested in the further research in the field.

8.3. Limitations of the study

Our work took a static approach to the problem. In addition, it worked with a rather outdated set of data. Here, we consciously sacrificed recentness of the data for the size of the sample as most of the recent datasets available concern specific limited groups of countries and none of them include CITs. Therefore, should any, more recent big sample become available, it will be possible to update our results and calculate dynamic efficiency indices (*e.g.* Malmquist index). In addition, it would allow using bootstrap technique with respect to the nonparametrically obtained estimates.

Such extension will possibly also enable to analyze a bigger number of undesired outputs subject to availability of data, since number of outputs is closely linked to the size of the sample.

Our study also reviewed big countries (*e.g.* Canada, China, Russian Federation, USA, *etc.*) as single DMUs, while it might be more proper to subdivide them by provinces, oblasts, states, *etc.* to allow for heterogeneity within countries subject to availability of data. Another comment on heterogeneity within DMUs implies that our study did not attempt to identify shadow prices of individual micro-level

DMUs within each country, thus providing only with an aggregated average estimate of the shadow prices and environmental efficiencies.

Finally, our study did not allow to make a confident choice between parametric and nonparametric techniques. This task is clearly a subject of a separate study, which can be only executed after other techniques are studied (specifically, SFA approach).

8.4. Recommendations for further research

Our research was, probably, the first attempt to apply productivity analysis in the presence of undesirable outputs to macro-level data and compare parametric and nonparametric techniques when some outputs are undesirable. Therefore, it is natural that, in addition to addressing the initial questions, it raises additional questions and opens perspectives for further research in the field.

We believe that one of the necessary prerequisites for the further studies is deciding between nonparametric and parametric approach, since their results may be statistically different. In addition, one may attempt to approach the problem via Stochastic Frontier Analysis technique, which is a previously unexplored field. The results obtained then can be compared to the parametrically and nonparametrically obtained estimates to check for compatibility of estimates. In addition, the issue of multiple solutions in identifying shadow prices in nonparametric framework should be solved.

It may be also an interesting issue to check if the choice of directional vector changes the results qualitatively. Should it be so, this choice should be considered crucial in the future studies.

Once the choice of approach is justified, future studies in the field may attempt to analyze larger samples of macro-level panel data in order to estimate dynamic productivity indexes.

The estimates of shadow prices may be applied toward creating an environmental analogue of economic GDP, which is a sum of products of pollution levels and the respective shadow prices. Difference between economic GDP and the obtained measure will display the sustainability of the country in line with the weak sustainability concept. Should it be nonnegative, the country is weakly sustainable and weakly unsustainable otherwise.

Finally, our estimates can be used in estimating environmental demand function. Previously it was an unsolvable issue, mostly because of impossibility to estimate country-level shadow prices.

In general, this research opens a lot of perspectives in the future research activities, which we will hopefully attempt to address in our future studies.

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Appendix 1

DESCRIPTIVE STATISTICS OF THE DATA USED (REFERENCE YEAR: 1995; YEARLY DATA)

Variable	Units of measurement	Mean	Median	Max	Min	St.Dev.
GDP (Specification I)	Bln. US$	292.6969	36.7084	7338.4	1.3094	961.1775
GDP in PPP (Specification II)	Bln. US$	350.2469	69.1840	7489.6	2.6640	920.1799
CO_2	Mln. metric tons	220.4535	43.1684	5193.0	0.0099	656.1127
SO_2	Mln. metric tons	1.3501	0.2541	34.3595	0.0038	4.0896
NO_x	Mln. metric tons	0.9086	0.2075	18.0512	0.0130	2.3575
Labor	Millions	25.2047	4.7758	736.3060	0.5418	87.2378
Arable land	Millions sq.km	123.8742	25.5500	1750.000	0.0100	306.0935
Energy consumption	Th. metric tons of oil equivalent	88.8481	19.7803	2086.2	0.7859	253.0375
Fixed capital	Bil. US$	35.3709	3.3327	836.0959	0.0395	121.8498

Appendix 2

PARAMETRIC ESTIMATION OF SPECIFICATION I: ESTIMATED PARAMETERS

Parameter	Value	Parameter	Value
α_0	2.1356	γ_{31}	-0.0067
α_1	-0.1826	γ_{32}	-0.0023
β_1	0.0942	γ_{33}	-0.0133
β_2	0.0586	γ_{34}	0.0034
β_3	0.6645	γ_{41}	0.0452
γ_1	-0.3889	γ_{42}	0.0591
γ_2	-0.0762	γ_{43}	-0.0067
γ_3	-0.0387	γ_{44}	0.0452
γ_4	-0.0980	δ_1	0.2122
α_{11}	0.1832	δ_2	-0.0677
β_{11}	-0.0453	δ_3	-0.0597
β_{12}	0.0105	δ_4	-0.0383
β_{13}	-0.0005	ε_{11}	-0.3228
β_{21}	0.0105	ε_{12}	0.1376
β_{22}	0.0150	ε_{13}	0.0035
β_{23}	0.0025	ε_{14}	0.0029
β_{31}	-0.0005	ε_{21}	-0.0099
β_{32}	0.0025	ε_{22}	-0.0536
β_{33}	0.1886	ε_{23}	-0.0002
γ_{11}	-0.0792	ε_{24}	0.0010
γ_{12}	0.0431	ε_{31}	-0.0290
γ_{13}	-0.0023	ε_{32}	-0.1517
γ_{14}	0.0591	ε_{33}	-0.0630
γ_{21}	0.0431	ε_{34}	-0.0422
γ_{22}	0.0341	ζ_1	-0.2840
γ_{23}	-0.0133	ζ_2	-0.0353
γ_{24}	-0.0067	ζ_3	0.0279

Appendix 3

PARAMETRIC ESTIMATION OF SPECIFICATION II: ESTIMATED PARAMETERS

Parameter	Value	Parameter	Value
α_0	1.8837	γ_{31}	0.0165
α_1	-0.3334	γ_{32}	0.0103
β_1	0.1476	γ_{33}	-0.0077
β_2	0.0382	γ_{34}	0.0075
β_3	0.4808	γ_{41}	0.1054
γ_1	-0.1970	γ_{42}	0.0272
γ_2	-0.1265	γ_{43}	0.0075
γ_3	-0.0181	γ_{44}	0.0653
γ_4	-0.0372	δ_1	-0.2605
α_{11}	0.2341	δ_2	-0.1885
β_{11}	-0.0185	δ_3	-0.0190
β_{12}	0.0036	δ_4	-0.2025
β_{13}	0.0375	ε_{11}	0.0084
β_{21}	0.0036	ε_{12}	0.0166
β_{22}	-0.0034	ε_{13}	-0.0094
β_{23}	0.0193	ε_{14}	-0.0405
β_{31}	0.0375	ε_{21}	0.0121
β_{32}	0.0193	ε_{22}	-0.0246
β_{33}	0.1353	ε_{23}	-0.0117
γ_{11}	0.0197	ε_{24}	-0.0367
γ_{12}	0.0819	ε_{31}	-0.2810
γ_{13}	0.0165	ε_{32}	-0.1805
γ_{14}	0.1054	ε_{33}	0.0021
γ_{21}	0.0819	ε_{34}	-0.1253
γ_{22}	0.0523	ζ_1	0.0226
γ_{23}	0.0103	ζ_2	0.0195
γ_{24}	0.0272	ζ_3	0.1920

Appendix 4

PARAMETRIC ESTIMATION OF SPECIFICATION I: ESTIMATED VALUES OF INEFFICIEINCIES AND SHADOW PRICES OF POLLUTANTS

Country	ODDF value	Shadow prices, US$/ton		
		CO_2	SO_2	NO_x
Albania	0.0902	-58.32	-9649.50	-19770.00
Algeria	0.0418	-87.79	-24406.00	-137990.00
Argentina	0.0178	-427.93	-77856.00	-310410.00
Armenia	0.0945	-49.52	-8863.60	-24253.00
Australia	0.3335	-460.38	-66186.00	-395920.00
Austria	0.0954	-294.99	-87287.00	-300940.00
Azerbaijan	0.3187	-23.90	-969.79	-13503.00
Bangladesh	0.1029	-816.41	-33756.00	-157390.00
Belarus	0.1707	-74.72	-4463.30	-35361.00
Belgium	0.0361	-1836.00	-81185.00	-1549000.00
Bosnia and Herzegovina	0.26	-70.38	-2814.90	-40534.00
Brazil	0.141	-3360.70 E+10	-168510.00 E+10	-908460.00 E+10
Bulgaria	0.1344	-112.82	-2145.80	-66769.00
Cameroon	0.0836	-3452.30	-13391.00	-117260.00
Canada	0.1794	-1607.80	-86064.00	-708710.00
China	0.1633	-1636.90	-68445.00	-1188400.00
Colombia	0.1027	-971.22	-162260.00	-881010.00
Congo	0.5735	0.00	-49232.00	-152630.00
Croatia	0	-127.87	-29873.00	-176480.00
Czech Rep	0.1319	-106.52	-5079.00	-53523.00
Denmark	0.2034	0.00	-83348.00	-284640.00
Dominican Rep	0.0409	-282.99	-36825.00	-262710.00
Egypt	0.0971	-271.49	-28995.00	-242820.00
El Salvador	0.0166	-641.28	-51669.00	-298450.00
Estonia	0.1796	-38.10	-6018.80	-76359.00
Ethiopia	0	-2792.80	0.00	-32780.00
Finland	0.1461	-453.17	-24066.00	-99620.00
France	0.0447	-2213.90	-61396.00	-431520.00
Gabon	0.3084	-91.25	-15119.00	-116690.00
Georgia	0.1327	-65.12	0.00	0.00
Germany	0.0784	-1255.70	-119040.00	-595890.00
Ghana	0.0652	-1651.60	-22754.00	-175540.00
Greece	0.1145	-411.82	-89727.00	-948410.00
Haiti	0	-7870.50	-243010.00	-1587300.00
Honduras	0.2439	-500.84	-31881.00	-138340.00
Hong Kong	0.0393	0.00	-147840.00	-1693700.00
Hungary	0	-389.69	-15261.00	-267560.00
India	0	-328.55	-12104.00	-102820.00
Indonesia	0	-1487.30	-145090.00	-855100.00
Iran, Islamic Rep	0.0888	-109.42	-7989.90	-66506.00
Ireland	0.0254	0.00	-113940.00	-564770.00
Israel	0.1351	-106.14	-53850.00	-486170.00
Italy	0.1072	-1103.20	-138490.00	-941350.00
Japan	0.1188	-1519.80	-75263.00	-649040.00

Country	ODDF value	Shadow prices, US$/ton		
		CO_2	SO_2	NO_x
Kazakhstan	0.1616	-98.05	-4280.00	-82194.00
Korea, Rep	0.0936	-1970.10	-128490.00	-1844800.00
Kyrgyzstan	0.0418	-57.75	-8062.10	-18458.00
Latvia	0.1162	-79.76	-7081.80	-53659.00
Lithuania	0	-174.28	-9084.50	-92547.00
Macedonia, FYR	0.1426	-19.48	-7504.90	-66154.00
Malaysia	0.1239	-282.19	-61253.00	-433430.00
Mexico	0.0336	-558.82	-35324.00	-308050.00
Moldova, Rep	0.192	-42.71	-4813.20	-29721.00
Morocco	0	-102.40	-34621.00	-194310.00
Namibia	0	-15043.00 E+12	-31622.00	-192800. 00
Nepal	0.0387	-6312.60	-22096.00	-285030.00
Netherlands	0	-796.33	-84247.00	-725330.00
New Zealand	0.0279	-614.63	-61397.00	-493310.00
Norway	0.1393	-999.24	-29639.00	-99324.00
Oman	0	-89.30	-21631.00	-334760.00
Panama	0.1212	-402.40	-72862.00	-364790.00
Paraguay	0	-743.70	-20944.00	-162950.00
Philippines	0.0632	-574.25	-24666.00	-206030.00
Poland	0.1126	-285.65	-16851.00	-295640.00
Portugal	0.0297	-833.37 E+10	-391680.00 E+10	-22140.00 E+12
Romania	0.0008	-164.77	-9109.30	-132180.00
Russian Federation	0	-122.97	-3965.20	-48157.00
Saudi Arabia	0.0085	-218.26	-36349.00	-337310.00
Senegal	0.3331	-1012.10	-46852.00	-194460.00
Serbia and Montenegro	0.2094	-73.07	-4687.20	-59786.00
Singapore	0	-344.51	-112730.00	-2680400.00
Slovakia	0.1433	-118.77	-4899.00	-61941.00
Slovenia	0.1279	-98.12	-16439.00	-115050.00
South Africa	0.1638	-198.60	-18459.00	-165610.00
Spain	0.1064	-1205.60	-105160.00	-759170.00
Sri Lanka	0	-1193.10	-44808.00	-308340.00
Sweden	0	-1790.10	0.00	0.00
Switzerland	0	-598.46	0.00	0.00
Syrian Arab Rep	0.2762	-656.91	-77669.00	-887980.00
Tajikistan	0.0576	-97.97	0.00	-72096.00
Togo	0.2214	-1048.70	-18142.00	-86027.00
Trinidad and Tobago	0.0842	-15.20	-10532.00	-98608.00
Tunisia	0.0399	-220.96	-19122.00	-172340.00
Turkey	0.0065	-756.65	-58036.00	-611290.00
Turkmenistan	0	-53.92	-7027.30	-67664.00
Ukraine	0.2692	-61.31	-2352.00	-26170.00
United Arab Emirates	0.0952	-78.71	-27162.00	-356170.00
United Kingdom	0.0687	-2500.70	-229150.00	-2183700.00
United States	0	-11161.00	-875500.00	-7863200.00
Uruguay	0	-171.37	-120950.00	-480410.00
Uzbekistan	0.1685	-101.36	-8297.20	-107880.00
Venezuela	0.0784	-310.88	-69125.00	-511190.00
Viet Nam	0.0739	-502.23	-15066.00	-127840.00
Yemen	0.1827	-28.53	-16377.00	-67680.00
Zambia	0.8203	-3578.50	-3382.80	-66157.00
Zimbabwe	0.4416	-322.23	-19620.00	-132180.00

Appendix 5

PARAMETRIC ESTIMATION OF SPECIFICATION II: ESTIMATED VALUES OF INEFFICIEINCIES AND SHADOW PRICES OF POLLUTANTS

Country	ODDF value	Shadow prices, US$/ton		
		CO_2	SO_2	NO_x
Albania	0	-62.82	0	-253114.47
Algeria	0.0428	-980.67	-150192.06	-1090962.14
Argentina	0	-1363.71	-73777.89	-855532.62
Armenia	0.1335	-13.44	-5799.25	-47301.33
Australia	0.2458	-1106.83	-58348.05	-760958.34
Austria	0.0193	-183.91	-18143.95	-544153.32
Azerbaijan	0.1827	-66.15	-7024.52	-62093.06
Bangladesh	0.0912	-5915.64	-35662.83	-288968.5
Belarus	0.1175	-152.78	-11934.53	-120613.21
Belgium	0.0273	-868.42	-26563.05	-1020309.24
Bosnia and Herzegovina	0.3509	-37.81	-1255.57	-51030.12
Brazil	0.1044	-22857.8	-389765.56	-2541576.85
Bulgaria	0.0854	-347.23	-6338.34	-343404.82
Cameroon	0.1232	-4563.92	-41696.42	-77428.53
Canada	0.1683	-2274.76	-129447.86	-811902.22
China	0.0384	-2963.62	-55274.08	-780964.13
Colombia	0.0664	-49081.7	-4984002.97	-15191466.4
Congo	0.6939	-317.92	-22848.15	-46457.82
Croatia	0.0472	-141.66	-28541.62	-234177.19
Czech Rep	0.0148	-229.86	-9553.54	-415053
Denmark	0.0931	-59.49	-9075.83	-400530.8
Dominican Rep	0.0654	-1713.06	-142882.67	-979456.84
Egypt	0.0795	-1252.64	-68011.15	-500595.95
El Salvador	0.0398	-2510.05	-229764.66	-643478.97
Estonia	0.1491	-41.95	-10051.15	-196112.59
Ethiopia	0	-6948.14	-20994.39	-13125.88
Finland	0.0786	-63.5	-4960.72	-162992.44
France	0	-1122.47	0	-248798.29
Gabon	0.2658	-232.21	-14526.64	-218893.25
Georgia	0.0379	-123.58	-23102.81	0
Germany	0.0267	-727.77	0	-328420.75
Ghana	0.032	-6215.97	-262683.29	-264299.71
Greece	0.107	-1471.11	-71114.77	-1938066.47
Haiti	0	-7866	-1010912.16	-369215.59
Honduras	0.1965	-3822.91	-326644.16	-571736.95
Hong Kong	0.0083	-3103.86	-385935.22	-1774799.76
Hungary	0	-932.42	-24308.08	-939181.94
India	0	-2207.48	-32313.06	-255226.91
Indonesia	0	-3065.61	-207794.74	-500011.03
Iran, Islamic Rep	0.0323	-684.25	-51999.91	-481463.75
Ireland	0	-134.1	-139057.82	-957748.93
Israel	0.1079	-492.44	-63800.69	-1032918.75
Italy	0.0392	-2927.66	-96455.36	-1856173.72
Japan	0.0384	-809.17	0	0

Country	ODDF value	Shadow prices, US$/ton		
		CO_2	SO_2	NO_x
Kazakhstan	0.1979	-318.72	-13094.53	-262693.11
Korea, Rep	0.0497	-1823.85	-71905.5	-904784.65
Kyrgyzstan	0.0714	0	-8965.36	-49131.66
Latvia	0.0625	-128.38	-15872.26	-217685.06
Lithuania	0	-448.43	-46939.7	-333780.43
Macedonia, FYR	0.1117	0	-7174.47	-190937.02
Malaysia	0.1162	-986.72	-144104.85	-684560.46
Mexico	0.0353	-2625.08	-76653.58	-1032985.68
Moldova, Rep	0.1526	-106.69	-21044.97	-101810.46
Morocco	0.0337	-1181.93	0	-991810.39
Namibia	0	-7.7E+17	-8.31561E+15	-8.80947E+16
Nepal	0	-10558.1	-92678.22	-154724.57
Netherlands	0	-439.58	-64192.16	-356261.11
New Zealand	0.0217	-609.6	-171705.91	-490005.78
Norway	0.0476	-145.18	-1402.44	-273511.77
Oman	0	-64.37	-71609.88	-593905.23
Panama	0.1434	-2291.82	-182885.09	-819272.84
Paraguay	0	-2527.76	-257673.42	-475093.21
Philippines	0.0306	-3919.93	-66169.72	-757343.6
Poland	0.1379	-581.95	-17143.9	-452070.11
Portugal	0.0651	-1.5E+15	-2.31239E+17	-1.15605E+18
Romania	0	-1332.45	-71038.04	-1153110.68
Russian Federation	0.0158	-408.31	-14193.44	-160950.2
Saudi Arabia	0.016	-368.37	-95975.58	-496249.44
Senegal	0.3328	-2099.96	-60120.3	-156786.49
Serbia and Montenegro	0.2951	-89.55	-2542.17	-73468.05
Singapore	0	-325.02	-79018.67	-542279.19
Slovakia	0.0673	-234.36	-13653.38	-263171.82
Slovenia	0.0581	-37.4	-30508.26	-344146.89
South Africa	0.141	-968.42	-66200.96	-654548.07
Spain	0.0642	-1732.59	-38573.96	-911571.12
Sri Lanka	0	-8416.07	-372768.96	-932003.09
Sweden	0.0136	-298.92	-561.04	0
Switzerland	0	0	-12872.21	0
Syrian Arab Rep	0.2451	-3.5E+14	-3.00083E+16	-2.7441E+17
Tajikistan	0.1119	-159.55	-165208.94	-37278.99
Togo	0.1932	-5616.02	-144208.47	-281604.72
Trinidad and Tobago	0.0504	0	-63178.78	-128738.48
Tunisia	0.0191	-1038.99	-24271.73	-955667.13
Turkey	0.0531	-2610.25	-43293.31	-1274305.9
Turkmenistan	0.0107	-55.54	-42640.41	-81238.51
Ukraine	0.2148	-273.06	-17615.98	-94548.52
United Arab Emirates	0.0844	-108.71	-101232.09	-257916.35
United Kingdom	0.0356	-2572.88	-123905.56	-1278203.2
United States	0	-3397.58	-186550.88	-1544821.74
Uruguay	0.0196	-1793.73	-152010.62	-1199277.24
Uzbekistan	0.0797	-267.59	-41331.68	-170800.48
Venezuela	0.0891	-488.25	-106898.73	-379092.03
Viet Nam	0.0299	-2380.07	-111468.85	-145839.2
Yemen	0.3422	-129.54	-17754.12	-69210.83
Zambia	0.7674	-1546.82	-1162.86	-18084.52
Zimbabwe	0.3225	-2437.89	-150691.44	-536823.55

NONPARAMETRIC ESTIMATION UNDER NIRS ASSUMPTION OF SPECIFICATION I: ESTIMATED VALUES OF INEFFICIEINCIES AND SHADOW PRICES OF POLLUTANTS

Country	ODDF value	Shadow prices, US$/ton		
		CO_2	SO_2	NO_x
Albania	0.5532	-868.35	0.00	-85600.00
Algeria	0.5572	0.00	0.00	-232810.00
Argentina	0.128	0.00	-121730.00	0.00
Armenia	0.6058	-868.35	0.00	-85600.00
Australia	0.3893	-342.91	0.00	0.00
Austria	0.2401	0.00	0.00	0.00
Azerbaijan	0.8991	0.00	0.00	-232810.00
Bangladesh	0.2157	-1341.30	0.00	0.00
Belarus	0.8673	0.00	0.00	-232810.00
Belgium	0.0006	0.00	0.00	0.00
Bosnia and Herzegovina	0.7535	-868.35	0.00	-85600.00
Brazil	0	-346.58	-10746.00	-3196.50
Bulgaria	0.7471	0.00	0.00	-232810.00
Cameroon	0.0878	-1613.40	0.00	0.00
Canada	0.2257	-170.37	0.00	0.00
China	0	-2.22	-268.45	-1865.70
Colombia	0.2067	0.00	0.00	0.00
Congo	0.3954	-1276.10	0.00	0.00
Croatia	0.3783	0.00	0.00	-232810.00
Czech Rep	0.7664	0.00	0.00	-232810.00
Denmark	0.318	0.00	0.00	0.00
Dominican Rep	0.4042	0.00	0.00	-113370.00
Egypt	0.4887	0.00	0.00	-232810.00
El Salvador	0.1469	-1301.80	0.00	0.00
Estonia	0.7227	0.00	0.00	-232810.00
Ethiopia	0.2849	-1613.40	0.00	0.00
Finland	0.5226	-7778.30	0.00	-24028.00
France	0	-446.27	-17923.00	-22234.00
Gabon	0.6075	-1808.80	0.00	0.00
Georgia	0.5633	0.00	-224380.00	-81100.00
Germany	0	-64.11	-10112.00	-102220.00
Ghana	0.188	-1300.20	0.00	0.00
Greece	0.2053	0.00	0.00	0.00
Haiti	0	-975.66	-5815.50	-59469.00
Honduras	0.4265	-1219.80	0.00	0.00
Hong Kong	0	-4142.70	-8740.10	-26186.00
Hungary	0.3928	0.00	0.00	-232810.00
India	0.4199	0.00	0.00	-12028.00
Indonesia	0	-5.74	-3126.10	-6150.40
Iran, Islamic Rep	0.801	0.00	-0.01	-232810.00
Ireland	0.0392	0.00	0.00	0.00
Israel	0.3843	0.00	0.00	0.00
Italy	0.0169	0.00	0.00	0.00
Japan	0	-149.45	-81298.00	-110560.00

Country	ODDF value	Shadow prices, US$/ton		
		CO_2	SO_2	NO_x
Kazakhstan	0.7268	0.00	0.00	-5031.70
Korea, Rep	0	-0.73	-292.39	-1050.90
Kyrgyzstan	0.5134	0.00	0.00	-232810.00
Latvia	0.7038	-868.35	0.00	-85600.00
Lithuania	0.6334	0.00	0.00	-113370.00
Macedonia, FYR	0.6501	0.00	0.00	-232810.00
Malaysia	0.4524	0.00	0.00	0.00
Mexico	0.2597	0.00	0.00	-58503.00
Moldova, Rep	0.8128	0.00	0.00	-232810.00
Morocco	0.3132	0.00	0.00	-232810.00
Namibia	0	-2608.10	-62.49	-2091.00
Nepal	0.0596	-22.12	0.00	0.00
Netherlands	0.0401	0.00	0.00	0.00
New Zealand	0.1765	0.00	0.00	0.00
Norway	0.254	0.00	0.00	0.00
Oman	0	-1.12	-288.03	-11528.00
Panama	0.1341	-1301.80	0.00	0.00
Paraguay	0.1972	-946.82	-98826.00	0.00
Philippines	0.4062	-1341.30	0.00	0.00
Poland	0.4259	0.00	0.00	-58503.00
Portugal	0	-17.49	-9127.60	-24208.00
Romania	0.6089	0.00	0.00	-232810.00
Russian Federation	0.8292	0.00	0.00	-125410.00
Saudi Arabia	0.3968	0.00	0.00	-77628.00
Senegal	0.3152	-1300.20	0.00	0.00
Serbia and Montenegro	0.7616	0.00	0.00	-232810.00
Singapore	0	-2.10	-175.26	-1565.90
Slovakia	0.774	0.00	0.00	-232810.00
Slovenia	0.6724	-1126.30	0.00	-38801.00
South Africa	0.648	0.00	0.00	-77628.00
Spain	0.0825	-448.95	0.00	0.00
Sri Lanka	0.0599	-1300.20	0.00	0.00
Sweden	0.2076	-7767.20	0.00	0.00
Switzerland	0	-112.97	-10595.00	-65459.00
Syrian Arab Rep	0	-10.75	-239.83	-1774.70
Tajikistan	0.2851	0.00	-336680.00	0.00
Togo	0.3573	-2065.00	0.00	0.00
Trinidad and Tobago	0.4483	0.00	-5890.30	0.00
Tunisia	0.4076	-868.35	0.00	-85600.00
Turkey	0.0781	0.00	0.00	-58503.00
Turkmenistan	0.6472	0.00	0.00	-113370.00
Ukraine	0.9589	-1341.30	0.00	-0.21
United Arab Emirates	0.2222	0.00	-32864.00	0.00
United Kingdom	0	-177.70	-6319.60	-21449.00
United States	0	-63.21	-36255.00	-44603.00
Uruguay	0	-799.95	-8225.70	-10705.00
Uzbekistan	0.218	0.00	-2718.40	0.00
Venezuela	0.4716	0.00	0.00	-58503.00
Viet Nam	0.1958	0.00	-2718.40	0.00
Yemen	0.6776	0.00	-224380.00	-81100.00
Zambia	0.5171	-2335.20	0.00	0.00
Zimbabwe	0.5707	-22.12	0.00	0.00

Appendix 7

NONPARAMETRIC ESTIMATION UNDER NIRS ASSUMPTION OF SPECIFICATION II: ESTIMATED VALUES OF INEFFICIEINCIES AND SHADOW PRICES OF POLLUTANTS

Country	ODDF value	Shadow prices, US$/ton		
		CO_2	SO_2	NO_x
Albania	0.0127	0	-0.0033	-3.67E+05
Algeria	0.0753	0	-0.0011	-3.03E+05
Argentina	0	-18.899	-9.94E+04	-73560
Armenia	0.313	0	0.00E+00	-5.31E+05
Australia	0.2257	0	-8930.7	-0.0001
Austria	0.0023	0	-8930.7	0
Azerbaijan	0.5644	0	0	-3.64E+05
Bangladesh	0	-915.6	-12305	-78188
Belarus	0.4683	0	0	-3.64E+05
Belgium	0	-28.947	-2069.7	-95908
Bosnia and Herzegovina	0.6907	0	-0.0004	-5.31E+05
Brazil	0	-300.28	-37087	-32390
Bulgaria	0.2799	0	0	-1.86E+05
Cameroon	0.1038	-7506.5	-58956	0
Canada	0.0834	-271.31	0	0
China	0	-34.221	-21628	-51589
Colombia	0	-25.363	-27915	-38571
Congo	0.726	-7427.8	-38250	0.00E+00
Croatia	0.2372	0	0	-3.69E+05
Czech Rep	0.0992	0	0	-3.69E+05
Denmark	0.1572	0	-0.0048	-0.0006
Dominican Rep	0.0546	-326.2	0	0.00E+00
Egypt	0.1099	0	0	-4.10E+05
El Salvador	0.0316	-1752	-13541	0
Estonia	0.5267	0	-0.0001	-3.64E+05
Ethiopia	0	-5430	-2.0641	-251.72
Finland	0.314	-203.82	-11368	0.00E+00
France	0	-999.2	-34530	-81776
Gabon	0.4567	-2183.2	0	-3.07E+03
Georgia	0	-42.932	-4.54E+04	-5.56E+05
Germany	0	-16.282	-25698	-2.37E+05
Ghana	0	-1261.5	-1.05E+05	-256.72
Greece	0.0815	0	0	0
Haiti	0	-410.66	-2.10E+05	-4.55E+05
Honduras	0.1519	-0.098	-3.91E+04	-0.0024
Hong Kong	0	-1037.9	-17873	-51949
Hungary	0.0594	0	0	-3.64E+05
India	0	-29.453	-36839	-80235
Indonesia	0	-19.018	-43095	-68964
Iran, Islamic Rep	0.1027	0	-0.0001	-4.00E-04
Ireland	0	-14.58	-1.30E+05	-40614
Israel	0.0614	0	0	0
Italy	0	-26.523	-33116	-1.03E+05
Japan	0	-108.89	-1.10E+05	-1.83E+05

Country	ODDF value	Shadow prices, US$/ton		
		CO_2	SO_2	NO_x
Kazakhstan	0.3286	0	0	0
Korea, Rep	0	-5.3557	-3401.2	-15269
Kyrgyzstan	0.1841	0	-0.0001	-5.31E+05
Latvia	0.3657	0	-0.0001	-3.64E+05
Lithuania	0.1142	-235.91	-8727.4	0
Macedonia, FYR	0.4088	0	-0.0001	-3.64E+05
Malaysia	0.1821	0	-31002	0
Mexico	0	-14.429	-11226	-95937
Moldova, Rep	0.5413	0	-0.0009	-3.64E+05
Morocco	0	-17.654	-1322.9	-2.78E+05
Namibia	0	-1405.3	-50.889	-1203.7
Nepal	0	-8028.6	-1996.6	-38118
Netherlands	0	-16.456	-72186	-67006
New Zealand	0.027	-292.87	-1.28E+05	0
Norway	0.0287	-508.55	0	0
Oman	0	-3.4039	-328.26	-2.59E+05
Panama	0.095	-1752	-13541	0
Paraguay	0	-1413.1	-1.22E+05	-2514.1
Philippines	0	-774.93	-155.67	-1.49E+05
Poland	0.2124	0	0	0
Portugal	0	-28.409	-19767	-9579.5
Romania	0	-1.7282	-339.44	-3.86E+03
Russian Federation	0.1138	0	0	0.00E+00
Saudi Arabia	0.0574	0	0	0
Senegal	0.4958	-7506.5	-58956	0
Serbia and Montenegro	0.6568	0	0	-4.04E+05
Singapore	0	-0.2902	-4112.7	-458.72
Slovakia	0.2899	0	0	-3.69E+05
Slovenia	0.2381	-774.6	-0.003	-1.39E+05
South Africa	0.0942	0	-0.0006	-0.0008
Spain	0.0712	-1547.7	0	0
Sri Lanka	0	-128.72	-31771	-3.65E+05
Sweden	0.0787	-1680	0	0
Switzerland	0	-923.4	-69997	-2.57E+05
Syrian Arab Rep	0	-5.7096	-20321	-801.35
Tajikistan	0.2476	0	-8.22E+05	0
Togo	0.2134	-4744.2	0	0
Trinidad and Tobago	0.2551	0	-88516	0.00E+00
Tunisia	0.0476	0	0	-3.64E+05
Turkey	0	-3.2384	-154.11	-1.55E+05
Turkmenistan	0.3314	0	-39133	-0.0001
Ukraine	0.5927	0	-1302.9	-0.0001
United Arab Emirates	0.0753	0	-23702	0
United Kingdom	0	-24.972	-22092	-43936
United States	0	-57.263	-49941	-77226
Uruguay	0	-554.1	-25304	-1.07E+05
Uzbekistan	0.0374	0	0	0
Venezuela	0.3268	0	0	0
Viet Nam	0	-373.28	-18693	-1.47E+05
Yemen	0.6156	0	0.00E+00	-6.11E+05
Zambia	0.7399	-8340.7	0	-47208
Zimbabwe	0.248	-293.25	0	0

A p p e n d i x 8

NONPARAMETRIC ESTIMATION UNDER VRS ASSUMPTION OF SPECIFICATION I: ESTIMATED VALUES OF INEFFICIEINCIES AND SHADOW PRICES OF POLLUTANTS

Country	ODDF value	Shadow prices, US$/ton		
		CO_2	SO_2	NO_x
Albania	0	-62.01	-7245.90	-489540.00
Algeria	0.5488	0.00	0.00	-239160.00
Argentina	0.128	0.00	-121730.00	0.00
Armenia	0.1313	0.00	-253330.00	-104390.00
Australia	0.3893	-342.91	0.00	0.00
Austria	0.2398	0.00	0.00	0.00
Azerbaijan	0.7992	0.00	0.00	-463870.00
Bangladesh	0.2157	-1341.30	0.00	0.00
Belarus	0.8471	0.00	0.00	-239160.00
Belgium	0.0006	0.00	0.00	0.00
Bosnia and Herzegovina	0	-168.11	-1545.40	-207980.00
Brazil	0	-295.35	-13077.00	-11711.00
Bulgaria	0.7203	0.00	0.00	-239160.00
Cameroon	0.0878	-1613.40	0.00	0.00
Canada	0.2257	-170.37	0.00	0.00
China	0	-11.60	-231.72	-603.72
Colombia	0.2067	0.00	0.00	0.00
Congo	0	-502.05	-19711.00	-101210.00
Croatia	0.3047	0.00	0.00	-233490.00
Czech Rep	0.7558	0.00	0.00	-239160.00
Denmark	0.2629	0.00	0.00	0.00
Dominican Rep	0.3897	0.00	0.00	-233490.00
Egypt	0.4857	0.00	0.00	-239160.00
El Salvador	0.1129	-1220.00	0.00	0.00
Estonia	0.0948	0.00	0.00	0.00
Ethiopia	0.2849	-1613.40	0.00	0.00
Finland	0.5101	-6893.20	0.00	-207760.00
France	0	-331.26	-19539.00	-42495.00
Gabon	0	-350.50	-8804.20	-168720.00
Georgia	0	-57.31	-61959.00	-827520.00
Germany	0	-36.24	-16305.00	-109190.00
Ghana	0.188	-1300.20	0.00	0.00
Greece	0.2038	0.00	0.00	0.00
Haiti	0	-77.65	-6985.50	-219500.00
Honduras	0.3333	-118.86	-177230.00	0.00
Hong Kong	0	-57.79	-3790.00	-9892.60
Hungary	0.3828	0.00	0.00	-239160.00
India	0.4199	0.00	0.00	-12028.00
Indonesia	0	-12.92	-4196.30	-8627.80
Iran, Islamic Rep	0.8	0.00	0.00	-239160.00
Ireland	0	-2.94	-48471.00	-628.46
Israel	0.3843	0.00	0.00	0.00
Italy	0.0169	0.00	0.00	0.00
Japan	0	-57.63	-80711.00	-130950.00

Country	ODDF value	Shadow prices, US$/ton		
		CO_2	SO_2	NO_x
Kazakhstan	0.7268	0.00	0.00	-5031.70
Korea, Rep	0	-1.90	-185.30	-889.83
Kyrgyzstan	0.1179	0.00	0.00	-233490.00
Latvia	0.3747	-71.16	-14053.00	-132120.00
Lithuania	0.405	0.00	0.00	-50935.00
Macedonia, FYR	0.054	0.00	-17784.00	-153580.00
Malaysia	0.4524	0.00	0.00	0.00
Mexico	0.2597	0.00	0.00	-58503.00
Moldova, Rep	0.6323	0.00	0.00	-233490.00
Morocco	0.2934	0.00	0.00	-239160.00
Namibia	0	-2626.80	-3.69	-79765.00
Nepal	0.0596	-22.12	0.00	0.00
Netherlands	0.0401	0.00	0.00	0.00
New Zealand	0.0892	-191.27	-72572.00	0.00
Norway	0.134	-72.16	0.00	0.00
Oman	0	-80.31	-1676.80	-156700.00
Panama	0	-625.06	-4509.70	-85043.00
Paraguay	0.1117	-163.80	-227020.00	0.00
Philippines	0.4062	-1341.30	0.00	0.00
Poland	0.4259	0.00	0.00	-58503.00
Portugal	0	-1.37	-8231.80	-54219.00
Romania	0.6013	0.00	0.00	-239160.00
Russian Federation	0.8292	0.00	0.00	-125410.00
Saudi Arabia	0.3968	0.00	0.00	-77628.00
Senegal	0.3152	-1300.20	0.00	0.00
Serbia and Montenegro	0.7289	0.00	0.00	-239160.00
Singapore	0	-1.12	-34.98	-429.47
Slovakia	0.7362	0.00	0.00	-233490.00
Slovenia	0.2761	-3534.10	0.00	-1361800.00
South Africa	0.648	0.00	0.00	-77628.00
Spain	0.0825	-448.95	0.00	0.00
Sri Lanka	0.0599	-1300.20	0.00	0.00
Sweden	0.2076	-7767.20	0.00	0.00
Switzerland	0	-20.80	-6971.60	-103890.00
Syrian Arab Rep	0	-0.19	-28.78	-4222.50
Tajikistan	0	-24.35	-217130.00	-87995.00
Togo	0	-1923.20	-57913.00	-99928.00
Trinidad and Tobago	0	-56.32	-46594.00	-138780.00
Tunisia	0.3773	0.00	0.00	-233490.00
Turkey	0.0781	0.00	0.00	-58503.00
Turkmenistan	0.3887	0.00	-15107.00	-64720.00
Ukraine	0.9589	-1341.30	0.00	0.00
United Arab Emirates	0.1801	0.00	-37719.00	0.00
United Kingdom	0	-151.90	-7280.80	-32657.00
United States	0	-63.02	-39368.00	-45281.00
Uruguay	0	-376.22	-26854.00	-73499.00
Uzbekistan	0.218	0.00	-2718.40	0.00
Venezuela	0.4716	0.00	0.00	-58503.00
Viet Nam	0.1958	0.00	-2718.40	0.00
Yemen	0.5886	0.00	0.00	-239160.00
Zambia	0.5171	-2335.20	0.00	0.00
Zimbabwe	0.5707	-22.12	0.00	0.00

A p p e n d i x 9

NONPARAMETRIC ESTIMATION UNDER VRS ASSUMPTION OF SPECIFICATION II: ESTIMATED VALUES OF INEFFICIEINCIES AND SHADOW PRICES OF POLLUTANTS

Country	ODDF value	Shadow prices, US$/ton		
		CO_2	SO_2	NO_x
Albania	0	-157.98	-5661.7	-3.70E+05
Algeria	0.0726	0	0	-2.25E+05
Argentina	0	-15.55	-1.12E+05	-1.08E+05
Armenia	0.1592	0	-8.19E+23	-1.90E+23
Australia	0.2192	-18.552	-11968	0
Austria	0	-1.1344	-984.72	-232.18
Azerbaijan	0.4836	0	0	-1.39E+05
Bangladesh	0	-1090.8	-26733	-91382
Belarus	0.4648	0	0	-3.69E+05
Belgium	0	-31.633	-2442.4	-91502
Bosnia and Herzegovina	0	-3894.8	-15528	-2.48E+06
Brazil	0	-257.91	-37825	-30862
Bulgaria	0.2275	0	0	-1.06E+05
Cameroon	0.1038	-7506.5	-58956	0
Canada	0.0834	-271.31	0	0
China	0	-39.641	-21637	-50130
Colombia	0	-25.946	-29397	-42804
Congo	0	-1986.1	-2.11E+05	-8.25E+05
Croatia	0.2163	0	0	-3.69E+05
Czech Rep	0.0977	0	0	-3.73E+05
Denmark	0.1292	0	-0.0001	0
Dominican Rep	0	-103.16	-11193	-3.30E+04
Egypt	0.1099	0	0	-4.10E+05
El Salvador	0	-981.03	-45632	-1.07E+05
Estonia	0	-0.9595	-99.78	-3.96E+04
Ethiopia	0	-5314.6	-5.5593	-238
Finland	0.2681	-63.161	-16063	-1.70E-03
France	0	-996.34	-35759	-80916
Gabon	0	-1103.9	-2223.8	-3.92E+05
Georgia	0	-23.546	-3.69E+04	-5.40E+05
Germany	0	-16.334	-25510	-2.39E+05
Ghana	0	-1262.6	-1.19E+05	-1393.5
Greece	0.0815	0	0	0
Haiti	0	-192.76	-2.14E+04	-5.42E+05
Honduras	0	-324.24	-5.41E+04	-1279.4
Hong Kong	0	-851.91	-47433	-29338
Hungary	0.0582	0	0	-3.69E+05
India	0	-31.212	-38688	-80540
Indonesia	0	-20.629	-43565	-70658
Iran, Islamic Rep	0.1027	0	0	0.00E+00
Ireland	0	-18.516	-1.44E+05	-92421
Israel	0.0614	0	0	0
Italy	0	-30.928	-35331	-1.04E+05
Japan	0	-119.13	-1.18E+05	-1.88E+05

Country	ODDF value	Shadow prices, US$/ton		
		CO_2	SO_2	NO_x
Kazakhstan	0.3286	0	0	0
Korea, Rep	0	-5.5745	-4230.5	-17164
Kyrgyzstan	0.153	0	0	-4.76E+05
Latvia	0.1317	-15.476	0	-9.90E+04
Lithuania	0	-3.6647	-9623.8	-70845
Macedonia, FYR	0	-1.8723	-763.25	-1.66E+05
Malaysia	0.1821	0	-31002	-0.0001
Mexico	0	-16.504	-12333	-97454
Moldova, Rep	0.3982	0	-23009	-6.55E+04
Morocco	0	-19.825	-1664.7	-2.99E+05
Namibia	0	-1081.5	-168.26	-36920
Nepal	0	-7303.4	-1022.4	-55214
Netherlands	0	-16.06	-85830	-67380
New Zealand	0	-733.94	-4.80E+04	-113.52
Norway	0	-602.26	-450.13	-5893.1
Oman	0	-4.7249	-15040	-2.43E+05
Panama	0	-840.94	-12457	-94214
Paraguay	0	-1092.5	-3.91E+00	-62385
Philippines	0	-617.47	-280.72	-1.74E+05
Poland	0.2124	0	0	0
Portugal	0	-104.73	-27916	-629.44
Romania	0	-2.7569	-373.46	-5.65E+03
Russian Federation	0.1138	0	0	0.00E+00
Saudi Arabia	0.0574	0	0	0
Senegal	0.4958	-7506.5	-58956	0
Serbia and Montenegro	0.6513	0	0	-4.00E+05
Singapore	0	-1.965	-12143	-22230
Slovakia	0.2811	0	0	-3.69E+05
Slovenia	0.0797	-965.12	0	-1.28E+05
South Africa	0.0942	0	0	0
Spain	0.0712	-1547.7	0	0
Sri Lanka	0	-77.608	-25852	-3.81E+05
Sweden	0.0787	-1680	0	0
Switzerland	0	-683.4	-87188	-2.71E+05
Syrian Arab Rep	0	-26.767	-15101	-32295
Tajikistan	0	-2.1082	-6.66E+05	-13558
Togo	0	-3283.4	-78690	-54726
Trinidad and Tobago	0	-6.9347	-1.37E+05	-1.87E+05
Tunisia	0.0376	0	0	-3.69E+05
Turkey	0	-3.4478	-235.96	-2.39E+05
Turkmenistan	0.0896	0	-7030.7	-13026
Ukraine	0.5927	0	-1302.9	0
United Arab Emirates	0.0724	0	-17301	0
United Kingdom	0	-169.22	-18019	-30569
United States	0	-62.482	-52337	-79219
Uruguay	0	-541.45	-25713	-1.50E+05
Uzbekistan	0.0374	0	0	0
Venezuela	0.3268	0	0	0
Viet Nam	0	-386.69	-10542	-9.01E+04
Yemen	0.6156	0	0.00E+00	-6.11E+05
Zambia	0.7399	-8340.7	0	-47208
Zimbabwe	0.2265	-338.01	0	0

Appendix 10

PARAMETRIC ESTIMATION OF SPECIFICATION I: ESTIMATED VALUES OF ODDF, 95% CONFIDENCE INTERVAL AND BIAS CORRECTED VALUE OF ODDF.

Country	ODDF value	95% confidence interval		Bias-corrected value of ODDF
		Lower bound	Upper bound	
Albania	0.0902	0.0020	0.1218	0.1414
Algeria	0.0418	0.0009	0.0538	0.0629
Argentina	0.0178	0.0006	0.0745	0.0088
Armenia	0.0945	0.0090	0.1203	0.1372
Australia	0.3335	0.1457	0.4317	0.3925
Austria	0.0954	0.0205	0.1112	0.1253
Azerbaijan	0.3187	0.2013	0.4832	0.3037
Bangladesh	0.1029	0.0023	0.1974	0.1485
Belarus	0.1707	0.1359	0.2287	0.1564
Belgium	0.0361	0.0005	0.0551	0.055
Bosnia and Herzegovina	0.26	0.1614	0.3438	0.2724
Brazil	0.141	0.0126	0.2089	0.1779
Bulgaria	0.1344	0.0452	0.1767	0.1634
Cameroon	0.0836	0.0189	0.2429	0.0371
Canada	0.1794	0.0481	0.2350	0.2177
China	0.1633	0.0060	0.2616	0.2318
Colombia	0.1027	0.0068	0.1209	0.1463
Congo	0.5735	0.3373	0.6281	0.6743
Croatia	0	0.0059	0.0518	0
Czech Rep	0.1319	0.0473	0.1428	0.17
Denmark	0.2034	0.0859	0.2554	0.2415
Dominican Rep	0.0409	0.0013	0.0550	0.0582
Egypt	0.0971	0.0091	0.1198	0.1336
El Salvador	0.0166	0.0006	0.0498	0.0135
Estonia	0.1796	0.0485	0.2202	0.2337
Ethiopia	0	0.0700	0.5568	0
Finland	0.1461	0.0496	0.1754	0.1825
France	0.0447	0.0006	0.0573	0.0725
Gabon	0.3084	0.1608	0.3533	0.3616
Georgia	0.1327	0.0068	0.1796	0.1968
Germany	0.0784	0.0010	0.1034	0.1259
Ghana	0.0652	0.0070	0.1470	0.0561
Greece	0.1145	0.0430	0.1370	0.1417
Haiti	0	0.0084	0.1649	0
Honduras	0.2439	0.1304	0.2879	0.2757
Hong Kong	0.0393	0.0007	0.1382	0.044
Hungary	0	0.0085	0.0800	0
India	0	0.0028	0.1263	0
Indonesia	0	0.0085	0.1328	0
Iran, Islamic Rep	0.0888	0.0442	0.1395	0.0868
Ireland	0.0254	0.0005	0.0595	0.0313
Israel	0.1351	0.0799	0.1758	0.1426
Italy	0.1072	0.0295	0.1258	0.1453
Japan	0.1188	0.0018	0.2236	0.1748

Country	ODDF value	95% confidence interval		Bias-corrected value of ODDF
		Lower bound	Upper bound	
Kazakhstan	0.1616	0.0341	0.2488	0.195
Korea, Rep	0.0936	0.0053	0.1394	0.1285
Kyrgyzstan	0.0418	0.0007	0.0619	0.0647
Latvia	0.1162	0.0473	0.1582	0.1339
Lithuania	0	0.0016	0.0691	0
Macedonia, FYR	0.1426	0.0452	0.1759	0.1784
Malaysia	0.1239	0.0562	0.1441	0.15
Mexico	0.0336	0.0006	0.0495	0.0498
Moldova, Rep	0.192	0.1412	0.2556	0.1869
Morocco	0	0.0060	0.1035	0
Namibia	0	0.0099	0.9277	0
Nepal	0.0387	0.0234	0.2953	0
Netherlands	0	0.0031	0.0575	0
New Zealand	0.0279	0.0008	0.0735	0.0304
Norway	0.1393	0.0418	0.1629	0.177
Oman	0	0.0057	0.1108	0
Panama	0.1212	0.0269	0.1214	0.1678
Paraguay	0	0.0055	0.0980	0
Philippines	0.0632	0.0024	0.0884	0.0893
Poland	0.1126	0.0301	0.1247	0.1484
Portugal	0.0297	0.0004	0.0339	0.0484
Romania	0.0008	0.0040	0.0767	0
Russian Federation	0	0.0029	0.1595	0
Saudi Arabia	0.0085	0.0031	0.0797	0
Senegal	0.3331	0.2289	0.4459	0.3367
Serbia and Montenegro	0.2094	0.1500	0.2401	0.2213
Singapore	0	0.0054	0.1700	0
Slovakia	0.1433	0.0958	0.1716	0.1519
Slovenia	0.1279	0.0480	0.1545	0.1528
South Africa	0.1638	0.1147	0.1930	0.1731
Spain	0.1064	0.0268	0.1152	0.1442
Sri Lanka	0	0.0054	0.0828	0
Sweden	0	0.0016	0.0699	0
Switzerland	0	0.0029	0.0664	0
Syrian Arab Rep	0.2762	0.1024	0.3115	0.349
Tajikistan	0.0576	0.0009	0.0702	0.0909
Togo	0.2214	0.1188	0.3956	0.1927
Trinidad and Tobago	0.0842	0.0035	0.1358	0.1147
Tunisia	0.0399	0.0009	0.0538	0.0604
Turkey	0.0065	0.0018	0.0675	0
Turkmenistan	0	0.0094	0.1380	0
Ukraine	0.2692	0.2487	0.4932	0.1614
United Arab Emirates	0.0952	0.0045	0.1535	0.1254
United Kingdom	0.0687	0.0020	0.0848	0.1043
United States	0	0.0068	0.1609	0
Uruguay	0	0.0067	0.1106	0
Uzbekistan	0.1685	0.0056	0.2032	0.2537
Venezuela	0.0784	0.0023	0.0861	0.1207
Viet Nam	0.0739	0.0029	0.1609	0.0881
Yemen	0.1827	0.1002	0.2623	0.1935
Zambia	0.8203	0.9283	1.0000	0.3706
Zimbabwe	0.4416	0.3561	0.5358	0.4375

Appendix 11

PARAMETRIC ESTIMATION OF SPECIFICATION I: ESTIMATED VALUES OF SHADOW PRICES FOR CO_2, 95% CONFIDENCE INTERVAL AND BIAS CORRECTED VALUE OF SHADOW PRICES.

Country	CO_2 shadow price	95% confidence interval		Bias-corrected value of CO_2 shadow price
		Lower bound	Upper bound	
Albania	-58.32	-168.39	0	-76.37
Algeria	-87.79	-141.07	-3.33	-118.85
Argentina	-427.93	-1093	-24.04	-465.68
Armenia	-49.52	-126.31	-6.45	-57.46
Australia	-460.38	-1021	-18.82	-578.38
Austria	-294.99	-3123.8	-142.66	0
Azerbaijan	-23.90	-9.41	0	-46.27
Bangladesh	-816.41	-2376.6	-38.39	-951.73
Belarus	-74.72	-55.91	-1.49	-131.16
Belgium	-1836.00	-3730.6	-153.13	-2201.4
Bosnia and Herzegovina	-70.38	-45.18	0	-130.56
Brazil	-3360.70 E+10	-2.82E+05	-1181.9	-6.7214e+013
Bulgaria	-112.82	-22.92	0	-222.43
Cameroon	-3452.30	-3407.8	-207.45	-5702.5
Canada	-1607.80	-1514.3	-85.11	-2659.2
China	-1636.90	-3814.3	0	-2449.8
Colombia	-971.22	-5491.3	-235.33	-94.47
Congo	0.00	-4300.2	-141.53	0
Croatia	-127.87	-316.22	-24.57	-106.69
Czech Rep	-106.52	-68.51	0	-194.58
Denmark	0.00	-2286.9	-55.38	0
Dominican Rep	-282.99	-491.59	-38.49	-338.04
Egypt	-271.49	-524.41	-22.15	-342.67
El Salvador	-641.28	-1599.1	-147.47	-505.81
Estonia	-38.10	-44.42	0	-63.96
Ethiopia	-2792.80	-1913	-36.41	-5081.2
Finland	-453.17	-995.37	-6.41	-577.22
France	-2213.90	-3903.5	-155.57	-3027.1
Gabon	-91.25	-660.36	-54.55	0
Georgia	-65.12	-135.09	-0.19	-97.07
Germany	-1255.70	-3480.8	-91.02	-1287
Ghana	-1651.60	-1645.2	-82.72	-2695.4
Greece	-411.82	-1600.5	-81.73	-135.17
Haiti	-7870.50	-37410	-170.23	-7610.9
Honduras	-500.84	-757.43	-61.11	-642.46
Hong Kong	0.00	-1.24E+06	-341.44	0
Hungary	-389.69	-170.84	-7.84	-717.75
India	-328.55	-270.66	0	-584.2
Indonesia	-1487.30	-3480.7	-80.43	-2062.4
Iran, Islamic Rep	-109.42	-86	-3.42	-187.27
Ireland	0.00	-1577.6	-42.7	0
Israel	-106.14	-1596.8	-84.39	0
Italy	-1103.20	-4061.4	-192.54	-665.72
Japan	-1519.80	-15402	-359.88	0

Country	CO_2 shadow price	95% confidence interval		Bias-corrected value of CO_2 shadow price
		Lower bound	Upper bound	
Kazakhstan	-98.05	-29.16	0	-190.8
Korea, Rep	-1970.10	-4516.7	-178.95	-2244
Kyrgyzstan	-57.75	-69.94	0	-103.13
Latvia	-79.76	-72.57	0	-137.03
Lithuania	-174.28	-105.56	-3.71	-315.17
Macedonia, FYR	-19.48	-47.64	0	-24.81
Malaysia	-282.19	-761.95	-54.7	-191.44
Mexico	-558.82	-542.35	-34.96	-896.75
Moldova, Rep	-42.71	-41.86	-2.03	-70.59
Morocco	-102.40	-415.76	0	-136.69
Namibia	-15043.00 E+12	-2.61E+06	-19359	-3.0086e+016
Nepal	-6312.60	-3949.7	-0.05	-11676
Netherlands	-796.33	-3149.2	-182	-247.44
New Zealand	-614.63	-1853.3	-139.64	-409.1
Norway	-999.24	-2195.1	-53.24	-1226.3
Oman	-89.30	-612.11	-0.75	0
Panama	-402.40	-2653.7	-224.97	0
Paraguay	-743.70	-1176.1	-106.31	-933.09
Philippines	-574.25	-805.15	-42.46	-833.84
Poland	-285.65	-173.66	-5.24	-504.96
Portugal	-833.37 E+10	-2.15E+06	-1461.1	-1.6667e+013
Romania	-164.77	-67.31	-1.87	-307.32
Russian Federation	-122.97	-65.74	0	-227.76
Saudi Arabia	-218.26	-299.89	-12.18	-302.68
Senegal	-1012.10	-2074.3	-107.74	-1218
Serbia and Montenegro	-73.07	-43.03	-1.72	-132.91
Singapore	-344.51	-1.03E+05	-50.23	0
Slovakia	-118.77	-82.15	-6.12	-202.59
Slovenia	-98.12	-519.19	-37.76	0
South Africa	-198.60	-202.86	-14.25	-304.81
Spain	-1205.60	-2431.9	-142.22	-1437.7
Sri Lanka	-1193.10	-2442.2	-138.63	-1454.2
Sweden	-1790.10	-2508.7	-64.45	-2687.8
Switzerland	-598.46	-9343.8	-407.45	0
Syrian Arab Rep	-656.91	-559.09	0	-1184.7
Tajikistan	-97.97	-192.84	-9.38	-116.72
Togo	-1048.70	-1264	-41.49	-1643.9
Trinidad and Tobago	-15.20	-118.1	-1.38	0
Tunisia	-220.96	-249.32	-11.34	-355.98
Turkey	-756.65	-790.67	-26.36	-1262.3
Turkmenistan	-53.92	-44.89	-0.06	-91.78
Ukraine	-61.31	-34.04	-2.22	-108.85
United Arab Emirates	-78.71	-738.38	-31.37	0
United Kingdom	-2500.70	-6858.6	-302.58	-2498.4
United States	-11161.00	-8189	-114.06	-20147
Uruguay	-171.37	-4159.3	-238.81	0
Uzbekistan	-101.36	-51.95	0	-187.47
Venezuela	-310.88	-524.1	-28.54	-384.46
Viet Nam	-502.23	-473.27	-9.88	-849.29
Yemen	-28.53	-144.32	-1.11	-8.28
Zambia	-3578.50	-1959.5	-23.97	-6650.1
Zimbabwe	-322.23	-294.11	-18.66	-516.96

Appendix 12

PARAMETRIC ESTIMATION OF SPECIFICATION I: ESTIMATED VALUES OF SHADOW PRICES FOR SO_2, 95% CONFIDENCE INTERVAL AND BIAS CORRECTED VALUE OF SHADOW PRICES.

Country	SO_2 shadow price	95% confidence interval		Bias-corrected value of SO_2 shadow price
		Lower bound	Upper bound	
Albania	-9649.50	-29500	-239.89	-7639.8
Algeria	-24406.00	-37112	-2964.2	-30216
Argentina	-77856.00	-2.27E+05	0	-66652
Armenia	-8863.60	-26838	-1438.8	-7553.2
Australia	-66186.00	-1.54E+05	-8580	-75452
Austria	-87287.00	-1.87E+05	-2289.3	-1.1355e+005
Azerbaijan	-969.79	-1567.5	-37.25	-1463.5
Bangladesh	-33756.00	-2.39E+05	-21401	0
Belarus	-4463.30	-6986.4	-676.95	-5778.7
Belgium	-81185.00	-1.56E+05	-4792.2	-1.0443e+005
Bosnia and Herzegovina	-2814.90	-5290.8	-473.98	-3348.3
Brazil	-1685.10 E+12	-3.65E+07	-1.9155e+005	-3.3702e+015
Bulgaria	-2145.80	-2836.3	-213.23	-3164.9
Cameroon	-13391.00	-1.22E+05	-20370	0
Canada	-86064.00	-1.72E+05	-12409	-1.0546e+005
China	-68445.00	-4.84E+05	-2839.2	-11708
Colombia	-162260.00	-7.46E+05	-89608	0
Congo	-49232.00	-4.61E+05	-28222	0
Croatia	-29873.00	-51278	-6706.6	-34329
Czech Rep	-5079.00	-6836.4	0	-8191.5
Denmark	-83348.00	-2.32E+05	0	-1.0301e+005
Dominican Rep	-36825.00	-77738	-13077	-31544
Egypt	-28995.00	-67362	-8815.1	-24464
El Salvador	-51669.00	-2.13E+05	-38659	0
Estonia	-6018.80	-7688.1	-244.11	-8920.5
Ethiopia	0.00	-23354	-3780.2	0
Finland	-24066.00	-50737	0	-36774
France	-61396.00	-2.88E+05	0	-33595
Gabon	-15119.00	-47230	-3998.5	-9215.3
Georgia	0.00	-40441	0	0
Germany	-119040.00	-2.96E+05	0	-1.541e+005
Ghana	-22754.00	-1.62E+05	-25847	0
Greece	-89727.00	-2.12E+05	-13349	-96228
Haiti	-243010.00	-7.05E+06	-1.5546e+005	0
Honduras	-31881.00	-1.17E+05	-20289	-2700.3
Hong Kong	-147840.00	-6.58E+07	-2689.3	0
Hungary	-15261.00	-20765	-1902.6	-21502
India	-12104.00	-35552	-3063.5	-9391.4
Indonesia	-145090.00	-6.00E+05	-41837	-70527
Iran, Islamic Rep	-7989.90	-14041	-949.53	-10146
Ireland	-113940.00	-2.46E+05	-1724.7	-1.4715e+005
Israel	-53850.00	-1.15E+05	-8462.2	-56088
Italy	-138490.00	-3.65E+05	-34817	-1.2059e+005
Japan	-75263.00	-1.56E+06	0	0

Country	SO_2 shadow price	95% confidence interval		Bias-corrected value of SO_2 shadow price
		Lower bound	Upper bound	
Kazakhstan	-4280.00	-4964.1	-380.41	-6543.9
Korea, Rep	-128490.00	-3.33E+05	-24709	-1.2871e+005
Kyrgyzstan	-8062.10	-16919	0	-11226
Latvia	-7081.80	-11545	-1155	-8820.9
Lithuania	-9084.50	-14473	-1980.3	-11196
Macedonia, FYR	-7504.90	-11144	-39.28	-10856
Malaysia	-61253.00	-1.18E+05	-20483	-57538
Mexico	-35324.00	-67420	-9036.3	-37551
Moldova, Rep	-4813.20	-8549.5	-1190.4	-5247
Morocco	-34621.00	-93928	-2611.5	-31145
Namibia	-31622.00	-2.69E+05	-10764	0
Nepal	-22096.00	-94761	-12099	-4598.4
Netherlands	-84247.00	-1.94E+05	-11629	-90873
New Zealand	-61397.00	-2.47E+05	-4457.6	-19296
Norway	-29639.00	-67696	0	-38021
Oman	-21631.00	-41710	0	-30203
Panama	-72862.00	-3.35E+05	-37044	0
Paraguay	-20944.00	-1.82E+05	-18179	0
Philippines	-24666.00	-71365	-10468	-12863
Poland	-16851.00	-21940	-1925.7	-23876
Portugal	-3916.80 E+12	-4.79E+08	-5.746e+005	-7.8337e+015
Romania	-9109.30	-12211	-1105.8	-12964
Russian Federation	-3965.20	-8925.3	0	-5098.2
Saudi Arabia	-36349.00	-54939	-1167.8	-52765
Senegal	-46852.00	-2.03E+05	-27233	-748.05
Serbia and Montenegro	-4687.20	-7139.9	-792.54	-6040.1
Singapore	-112730.00	-4.14E+06	0	0
Slovakia	-4899.00	-7232.6	-816.64	-6672.8
Slovenia	-16439.00	-31577	-688.17	-19187
South Africa	-18459.00	-29460	-3878.1	-22431
Spain	-105160.00	-2.40E+05	-27443	-1.0208e+005
Sri Lanka	-44808.00	-2.40E+05	-36240	0
Sweden	0.00	-85077	0	0
Switzerland	0.00	-2.72E+05	0	0
Syrian Arab Rep	-77669.00	-1.50E+05	-5111.3	-1.1687e+005
Tajikistan	0.00	-1.08E+05	0	0
Togo	-18142.00	-87600	-13622	0
Trinidad and Tobago	-10532.00	-23507	0	-17774
Tunisia	-19122.00	-38229	-3864.7	-20775
Turkey	-58036.00	-1.15E+05	-10311	-64452
Turkmenistan	-7027.30	-15227	0	-10745
Ukraine	-2352.00	-5141.7	-606.84	-2425.3
United Arab Emirates	-27162.00	-84725	0	-26694
United Kingdom	-229150.00	-6.28E+05	-56017	-2.1115e+005
United States	-875500.00	-1.35E+06	-2100.7	-1.413e+006
Uruguay	-120950.00	-7.27E+05	-46478	0
Uzbekistan	-8297.20	-13725	-880.41	-11890
Venezuela	-69125.00	-1.20E+05	-14825	-84139
Viet Nam	-15066.00	-62304	-7201.6	-1297.5
Yemen	-16377.00	-40765	-4686.5	-12313
Zambia	-3382.80	-6755.7	-1020.8	-3616.4
Zimbabwe	-19620.00	-38442	-6714.2	-19334

Appendix 13

PARAMETRIC ESTIMATION OF SPECIFICATION I: ESTIMATED VALUES OF SHADOW PRICES FOR NO_X, 95% CONFIDENCE INTERVAL AND BIAS CORRECTED VALUE OF SHADOW PRICES.

Country	NO_x shadow price	95% confidence interval		Bias-corrected value of NO_x shadow price
		Lower bound	Upper bound	
Albania	-19770.00	-168.78	0	-39489
Algeria	-137990.00	-141.31	-3.33	-2.76E+05
Argentina	-310410.00	-1.09E+03	-24.05	-6.20E+05
Armenia	-24253.00	-126.45	-6.46	-48456
Australia	-395920.00	-1.02E+03	-18.82	-7.91E+05
Austria	-300940.00	-3.13E+03	-142.69	-6.01E+05
Azerbaijan	-13503.00	-9.58	0	-27002
Bangladesh	-157390.00	-2.38E+03	-38.39	-3.14E+05
Belarus	-35361.00	-56.06	-1.49	-70697
Belgium	-1549000.00	-3.74E+03	-153.13	-3.10E+06
Bosnia and Herzegovina	-40534.00	-45.24	0	-81048
Brazil	-9084.60E+12	-2.85E+05	-1182	-1.82E+16
Bulgaria	-66769.00	-23.3	0	-1.34E+05
Cameroon	-117260.00	-3.43E+03	-207.45	-2.33E+05
Canada	-708710.00	-1.52E+03	-85.12	-1.42E+06
China	-1188400.00	-3.84E+03	0	-2.38E+06
Colombia	-881010.00	-5.50E+03	-235.33	-1.76E+06
Congo	-152630.00	-4.33E+03	-141.54	-3.03E+05
Croatia	-176480.00	-316.56	-24.57	-3.53E+05
Czech Rep	-53523.00	-68.52	0	-1.07E+05
Denmark	-284640.00	-2.30E+03	-55.39	-5.68E+05
Dominican Rep	-262710.00	-491.76	-38.49	-5.25E+05
Egypt	-242820.00	-525.31	-22.15	-4.85E+05
El Salvador	-298450.00	-1.60E+03	-147.5	-5.96E+05
Estonia	-76359.00	-44.56	0	-1.53E+05
Ethiopia	-32780.00	-1920.3	-36.41	-65051
Finland	-99620.00	-996.99	-6.42	-1.99E+05
France	-431520.00	-3.90E+03	-155.58	-8.62E+05
Gabon	-116690.00	-661.74	-54.55	-2.33E+05
Georgia	0.00	-135.99	-0.2	0
Germany	-595890.00	-3.49E+03	-91.03	-1.19E+06
Ghana	-175540.00	-1.65E+03	-82.74	-3.50E+05
Greece	-948410.00	-1.60E+03	-81.76	-1.90E+06
Haiti	-1587300.00	-3.77E+04	-170.25	-3.17E+06
Honduras	-138340.00	-7.59E+02	-61.11	-2.76E+05
Hong Kong	-1693700.00	-1.26E+06	-341.81	-3.12E+06
Hungary	-267560.00	-171.5	-7.84	-5.35E+05
India	-102820.00	-271.66	0	-2.06E+05
Indonesia	-855100.00	-3.48E+03	-80.46	-1.71E+06
Iran, Islamic Rep	-66506.00	-86.23	-3.42	-1.33E+05
Ireland	-564770.00	-1.58E+03	-42.71	-1.13E+06
Israel	-486170.00	-1.60E+03	-84.4	-9.72E+05
Italy	-941350.00	-4.07E+03	-192.56	-1.88E+06
Japan	-649040.00	-1.54E+04	-360.01	-1.29E+06

Country	NO_x shadow price	95% confidence interval		Bias-corrected value of NO_x shadow price
		Lower bound	Upper bound	
Kazakhstan	-82194.00	-29.32	0	-1.64E+05
Korea, Rep	-1844800.00	-4.52E+03	-178.99	-3.69E+06
Kyrgyzstan	-18458.00	-70.08	0	-36895
Latvia	-53659.00	-72.67	0	-1.07E+05
Lithuania	-92547.00	-105.74	-3.71	-1.85E+05
Macedonia, FYR	-66154.00	-47.67	0	-1.32E+05
Malaysia	-433430.00	-7.63E+02	-54.71	-8.66E+05
Mexico	-308050.00	-543.36	-34.96	-6.16E+05
Moldova, Rep	-29721.00	-42.02	-2.03	-59420
Morocco	-194310.00	-417.04	0	-3.88E+05
Namibia	-192800. 00	-2.61E+06	-19082	-3.86E+15
Nepal	-285030.00	-3952.8	-0.05	-5.69E+05
Netherlands	-725330.00	-3.16E+03	-182.01	-1.45E+06
New Zealand	-493310.00	-1.86E+03	-139.65	-9.86E+05
Norway	-99324.00	-2204.8	-53.26	-1.98E+05
Oman	-334760.00	-613.05	-0.75	-6.69E+05
Panama	-364790.00	-2.66E+03	-224.99	-7.28E+05
Paraguay	-162950.00	-1.18E+03	-106.32	-3.25E+05
Philippines	-206030.00	-807.31	-42.46	-4.12E+05
Poland	-295640.00	-174.05	-5.24	-5.91E+05
Portugal	-22140.00 E+12	-2.18E+06	-1466.8	-4.43E+16
Romania	-132180.00	-67.43	-1.87	-2.64E+05
Russian Federation	-48157.00	-65.77	0	-96290
Saudi Arabia	-337310.00	-301.22	-12.18	-6.74E+05
Senegal	-194460.00	-2.08E+03	-107.76	-3.88E+05
Serbia and Montenegro	-59786.00	-43.13	-1.72	-1.20E+05
Singapore	-2680400.00	-1.06E+05	-50.26	-5.34E+06
Slovakia	-61941.00	-82.94	-6.12	-1.24E+05
Slovenia	-115050.00	-519.63	-37.77	-2.30E+05
South Africa	-165610.00	-203.34	-14.26	-3.31E+05
Spain	-759170.00	-2.44E+03	-142.22	-1.52E+06
Sri Lanka	-308340.00	-2.45E+03	-138.66	-6.16E+05
Sweden	0.00	-2508.6	-63.41	0
Switzerland	0.00	-9.34E+03	-402.48	0
Syrian Arab Rep	-887980.00	-5.67E+02	0	-1.78E+06
Tajikistan	-72096.00	-1.93E+02	-9.38	-1.44E+05
Togo	-86027.00	-1268.4	-41.49	-1.72E+05
Trinidad and Tobago	-98608.00	-118.52	-1.38	-1.97E+05
Tunisia	-172340.00	-249.6	-11.34	-3.45E+05
Turkey	-611290.00	-7.92E+02	-26.36	-1.22E+06
Turkmenistan	-67664.00	-44.98	-0.06	-1.35E+05
Ukraine	-26170.00	-34.14	-2.22	-52324
United Arab Emirates	-356170.00	-738.51	-31.38	-7.12E+05
United Kingdom	-2183700.00	-6.87E+03	-302.61	-4.36E+06
United States	-7863200.00	-8.21E+03	-114.09	-1.57E+07
Uruguay	-480410.00	-4.19E+03	-238.82	-9.59E+05
Uzbekistan	-107880.00	-52.26	0	-2.16E+05
Venezuela	-511190.00	-5.25E+02	-28.54	-1.02E+06
Viet Nam	-127840.00	-473.31	-9.88	-2.56E+05
Yemen	-67680.00	-144.54	-1.11	-1.35E+05
Zambia	-66157.00	-1969.6	-24.01	-1.32E+05
Zimbabwe	-132180.00	-294.75	-18.67	-2.64E+05

Appendix 14

PARAMETRIC ESTIMATION OF SPECIFICATION II: ESTIMATED VALUES OF ODDF, 95% CONFIDENCE INTERVAL AND BIAS CORRECTED VALUE OF ODDF.

Country	ODDF value	95% confidence interval		Bias-corrected value of ODDF
		Lower bound	Upper bound	
Albania	0.0000	0.0006	0.0272	0.0000
Algeria	0.0428	0.0021	0.0317	0.0691
Argentina	0.0000	0.0006	0.0248	0.0000
Armenia	0.1335	0.0462	0.0737	0.2055
Australia	0.2458	0.0841	0.1595	0.3689
Austria	0.0193	0.0001	0.0157	0.0336
Azerbaijan	0.1827	0.0710	0.1260	0.2669
Bangladesh	0.0912	0.0012	0.1041	0.1460
Belarus	0.1175	0.0485	0.0683	0.1765
Belgium	0.0273	0.0002	0.0235	0.0464
Bosnia and Herzegovina	0.3509	0.1431	0.1948	0.5308
Brazil	0.1044	0.0146	0.0637	0.1679
Bulgaria	0.0854	0.0178	0.0577	0.1308
Cameroon	0.1232	0.0189	0.0810	0.1925
Canada	0.1683	0.0482	0.1087	0.2564
China	0.0384	0.0003	0.0561	0.0610
Colombia	0.0664	0.0084	0.0404	0.1071
Congo	0.6939	0.2700	0.3451	1.0803
Croatia	0.0472	0.0072	0.0305	0.0751
Czech Rep	0.0148	0.0003	0.0162	0.0227
Denmark	0.0931	0.0239	0.0640	0.1449
Dominican Rep	0.0654	0.0120	0.0385	0.1051
Egypt	0.0795	0.0221	0.0497	0.1216
El Salvador	0.0398	0.0006	0.0238	0.0679
Estonia	0.1491	0.0411	0.1008	0.2258
Ethiopia	0.0000	0.0008	0.0607	0.0000
Finland	0.0786	0.0180	0.0569	0.1222
France	0.0000	0.0004	0.0172	0.0000
Gabon	0.2658	0.0964	0.1505	0.4085
Georgia	0.0379	0.0009	0.0274	0.0624
Germany	0.0267	0.0002	0.0252	0.0455
Ghana	0.0320	0.0003	0.0193	0.0566
Greece	0.1070	0.0416	0.0631	0.1622
Haiti	0.0000	0.0005	0.0274	0.0000
Honduras	0.1965	0.0539	0.1004	0.3106
Hong Kong	0.0083	0.0002	0.0652	0.0000
Hungary	0.0000	0.0005	0.0186	0.0000
India	0.0000	0.0006	0.0324	0.0000
Indonesia	0.0000	0.0006	0.0225	0.0000
Iran, Islamic Rep	0.0323	0.0007	0.0212	0.0540
Ireland	0.0000	0.0005	0.0201	0.0000
Israel	0.1079	0.0386	0.0648	0.1633
Italy	0.0392	0.0012	0.0272	0.0661
Japan	0.0384	0.0002	0.0577	0.0603

Country	ODDF value	95% confidence interval		Bias-corrected value of ODDF
		Lower bound	Upper bound	
Kazakhstan	0.1979	0.0532	0.1331	0.3026
Korea, Rep	0.0497	0.0010	0.0382	0.0825
Kyrgyzstan	0.0714	0.0159	0.0471	0.1100
Latvia	0.0625	0.0078	0.0415	0.0993
Lithuania	0.0000	0.0008	0.0330	0.0000
Macedonia, FYR	0.1117	0.0365	0.0794	0.1660
Malaysia	0.1162	0.0351	0.0659	0.1811
Mexico	0.0353	0.0006	0.0209	0.0610
Moldova, Rep	0.1526	0.0562	0.0888	0.2317
Morocco	0.0337	0.0003	0.0452	0.0533
Namibia	0.0000	0.0008	0.0495	0.0000
Nepal	0.0000	0.0007	0.0293	0.0000
Netherlands	0.0000	0.0005	0.0198	0.0000
New Zealand	0.0217	0.0002	0.0205	0.0376
Norway	0.0476	0.0040	0.0379	0.0765
Oman	0.0000	0.0007	0.0397	0.0000
Panama	0.1434	0.0428	0.0793	0.2237
Paraguay	0.0000	0.0007	0.0344	0.0000
Philippines	0.0306	0.0005	0.0211	0.0515
Poland	0.1379	0.0474	0.0767	0.2108
Portugal	0.0651	0.0134	0.0366	0.1044
Romania	0.0000	0.0007	0.0303	0.0000
Russian Federation	0.0158	0.0004	0.0356	0.0185
Saudi Arabia	0.0160	0.0002	0.0211	0.0261
Senegal	0.3328	0.1148	0.1723	0.5217
Serbia and Montenegro	0.2951	0.1328	0.1623	0.4416
Singapore	0.0000	0.0007	0.0479	0.0000
Slovakia	0.0673	0.0188	0.0382	0.1049
Slovenia	0.0581	0.0073	0.0405	0.0918
South Africa	0.1410	0.0522	0.0734	0.2186
Spain	0.0642	0.0147	0.0343	0.1022
Sri Lanka	0.0000	0.0005	0.0237	0.0000
Sweden	0.0136	0.0002	0.0189	0.0207
Switzerland	0.0000	0.0004	0.0176	0.0000
Syrian Arab Rep	0.2451	0.0660	0.1276	0.3873
Tajikistan	0.1119	0.0362	0.0850	0.1608
Togo	0.1932	0.0361	0.1074	0.3126
Trinidad and Tobago	0.0504	0.0016	0.0505	0.0799
Tunisia	0.0191	0.0002	0.0169	0.0319
Turkey	0.0531	0.0042	0.0344	0.0864
Turkmenistan	0.0107	0.0002	0.0485	0.0096
Ukraine	0.2148	0.0844	0.1347	0.3214
United Arab Emirates	0.0844	0.0036	0.0594	0.1406
United Kingdom	0.0356	0.0004	0.0223	0.0623
United States	0.0000	0.0007	0.0354	0.0000
Uruguay	0.0196	0.0002	0.0237	0.0314
Uzbekistan	0.0797	0.0012	0.0965	0.1240
Venezuela	0.0891	0.0173	0.0565	0.1409
Viet Nam	0.0299	0.0008	0.0355	0.0444
Yemen	0.3422	0.1443	0.1909	0.5180
Zambia	0.7674	0.2866	0.3682	1.2037
Zimbabwe	0.3225	0.1123	0.1594	0.5070

Appendix 15

PARAMETRIC ESTIMATION OF SPECIFICATION II: ESTIMATED VALUES OF SHADOW PRICES FOR CO_2, 95% CONFIDENCE INTERVAL AND BIAS CORRECTED VALUE OF SHADOW PRICES.

Country	CO_2 shadow price	95% confidence interval		Bias-corrected value of CO_2 shadow price
		Lower bound	Upper bound	
Albania	-62.824	-1697.7	0	0
Algeria	-980.67	-2187.6	-636.9	-788.59
Argentina	-1363.7	-3452.2	-403.11	-1228.2
Armenia	-13.444	-343.2	-4.0053	0
Australia	-1106.8	-3447.6	-456.96	-908.62
Austria	-183.91	-690.45	-96.504	-82.077
Azerbaijan	-66.149	-131.7	-24.055	-66.654
Bangladesh	-5915.6	-11281	-2150.7	-5760.2
Belarus	-152.78	-239.07	-87.565	-157.39
Belgium	-868.42	-1430.7	-537.86	-804.29
Bosnia and Herzegovina	-37.808	-156.98	-32.118	-3.4704
Brazil	-22858	-196380	-3994.2	0
Bulgaria	-347.23	-540.45	-191.38	-354.43
Cameroon	-4563.9	-4824.2	-2446.7	-5516.9
Canada	-2274.8	-3129.8	-812.18	-2924.6
China	-2963.6	-4386.2	-561.59	-4141.4
Colombia	-49082	-432100	-7674.2	-10026
Congo	-317.92	-708.44	-293.55	-176.79
Croatia	-141.66	-410.58	-126.11	-64.118
Czech Rep	-229.86	-409.66	-143.04	-204.8
Denmark	-59.486	-561.98	0	0
Dominican Rep	-1713.1	-3664.2	-1515.2	-1237.1
Egypt	-1252.6	-1817.7	-714.27	-1274
El Salvador	-2510	-4900.9	-2185.6	-1975.2
Estonia	-41.953	-220.96	-32.541	0
Ethiopia	-6948.1	-6425.8	-2288.6	-9341.1
Finland	-63.502	-201.11	0	-81.391
France	-1122.5	-1412.9	-187.79	-1472
Gabon	-232.21	-1029	-260.98	0
Georgia	-123.58	-1063.9	0	0
Germany	-727.77	-1058.4	-149.55	-861.12
Ghana	-6216	-6921.3	-2878.5	-7550
Greece	-1471.1	-4407.5	-1298.3	-600.72
Haiti	-7866	-13298	-2609	-8903.6
Honduras	-3822.9	-6942.3	-2775.9	-3572
Hong Kong	-3103.9	-74106	-1008	0
Hungary	-932.42	-1537.9	-609.41	-886.27
India	-2207.5	-2962.4	-595.67	-2757.6
Indonesia	-3065.6	-3924	-1074.6	-3778.8
Iran, Islamic Rep	-684.25	-947.44	-336.06	-769.93
Ireland	-134.1	-1066.6	-69.273	0
Israel	-492.44	-1342	-587.15	-85.382
Italy	-2927.7	-5462	-1106.8	-2814.7
Japan	-809.17	-1076	-106.82	-996.29

Country	CO_2 shadow price	95% confidence interval		Bias-corrected value of CO_2 shadow price
		Lower bound	Upper bound	
Kazakhstan	-318.72	-437.28	-145.59	-373.18
Korea, Rep	-1823.9	-2353.6	-867.83	-2130.4
Kyrgyzstan	0	-268.23	0	0
Latvia	-128.38	-445.11	-106.06	-44.064
Lithuania	-448.43	-873.04	-251.14	-437.98
Macedonia, FYR	0	-202.5	-7.9885	0
Malaysia	-986.72	-1321.8	-698.12	-981.15
Mexico	-2625.1	-3873.1	-1020.7	-3004.8
Moldova, Rep	-106.69	-263	-78.757	-76.481
Morocco	-1181.9	-8729.5	-489.72	0
Namibia	-7.7171E+17	-59811000	-421660	-1.5434E+18
Nepal	-10558	-10583	-3488.6	-13902
Netherlands	-439.58	-571.68	-237.92	-471.72
New Zealand	-609.6	-1198.3	-400.6	-562.89
Norway	-145.18	-380.2	-7.154	-155.46
Oman	-64.374	-999.08	0	0
Panama	-2291.8	-8482.7	-2360.9	-407.05
Paraguay	-2527.8	-4448.8	-1776.2	-2355.9
Philippines	-3919.9	-6000	-1819.4	-4065.5
Poland	-581.95	-775.07	-308.68	-648.63
Portugal	-1.5201E+15	-1282300	-43080	-3.0402E+15
Romania	-1332.4	-1780.2	-592.9	-1554.3
Russian Federation	-408.31	-482.94	-140.26	-526.18
Saudi Arabia	-368.37	-535.92	-185.62	-406.95
Senegal	-2100	-3378	-1642.8	-1991.2
Serbia and Montenegro	-89.55	-163.66	-65.139	-77.379
Singapore	-325.02	-2366.7	0	0
Slovakia	-234.36	-414.96	-162.1	-207.93
Slovenia	-37.404	-455.73	-54.8	0
South Africa	-968.42	-1322.7	-514.36	-1086.5
Spain	-1732.6	-2999.8	-738.88	-1754.1
Sri Lanka	-8416.1	-13997	-4796.4	-8351.1
Sweden	-298.92	-383.44	0	-513.8
Switzerland	0	0	0	0
Syrian Arab Rep	-3.5208E+14	-38122	-1476.7	-7.0416E+14
Tajikistan	-159.55	-344.15	-40.943	-165.28
Togo	-5616	-10160	-3682.2	-5466.4
Trinidad and Tobago	0	-146.43	0	0
Tunisia	-1039	-3710.1	-931.83	-372.1
Turkey	-2610.3	-5646.5	-1075.1	-2486.6
Turkmenistan	-55.537	-147.27	-7.9979	-57.31
Ukraine	-273.06	-304.9	-125.39	-338.58
United Arab Emirates	-108.71	-410.5	-29.123	-61.469
United Kingdom	-2572.9	-3367.1	-1116.2	-3025.5
United States	-3397.6	-5184.7	-589.64	-4718.8
Uruguay	-1793.7	-18438	-1655.7	0
Uzbekistan	-267.59	-357.94	-92.32	-324.56
Venezuela	-488.25	-635.46	-274.23	-531.84
Viet Nam	-2380.1	-2648.6	-939.69	-2920.8
Yemen	-129.54	-334.02	-103.03	-83.612
Zambia	-1546.8	-1606.3	-858.88	-1855.2
Zimbabwe	-2437.9	-2923.1	-1271.7	-2866

Appendix 16

PARAMETRIC ESTIMATION OF SPECIFICATION II: ESTIMATED VALUES OF SHADOW PRICES FOR SO_2, 95% CONFIDENCE INTERVAL AND BIAS CORRECTED VALUE OF SHADOW PRICES.

Country	SO_2 shadow price	95% confidence interval		Bias-corrected value of SO_2 shadow price
		Lower bound	Upper bound	
Albania	0	-56270	0	0
Algeria	-1.50E+05	-2.44E+05	-62301	-1.54E+05
Argentina	-73778	-2.06E+05	0	-86134
Armenia	-5799.2	-17150	-1513.5	-4487.3
Australia	-58348	-1.47E+05	-15178	-57576
Austria	-18144	-97278	-6476.6	-3631.3
Azerbaijan	-7024.5	-10433	-2268.6	-7633.4
Bangladesh	-35663	-1.16E+05	0	-42644
Belarus	-11935	-17341	-4598.3	-12694
Belgium	-26563	-65603	-10935	-20461
Bosnia and Herzegovina	-1255.6	-4140.5	-443.21	-690.31
Brazil	-3.90E+05	-2.72E+06	-50677	0
Bulgaria	-6338.3	-11809	-2224.9	-6112.9
Cameroon	-41696	-46792	0	-64857
Canada	-1.29E+05	-1.54E+05	-29076	-1.78E+05
China	-55274	-85704	-8025.8	-74503
Colombia	-4.98E+06	-3.60E+07	-5.06E+05	-2.57E+06
Congo	-22848	-39976	-6862.8	-27015
Croatia	-28542	-47128	-13054	-27955
Czech Rep	-9553.5	-24751	-3996	-6479.7
Denmark	-9075.8	-83948	0	-2112.6
Dominican Rep	-1.43E+05	-2.33E+05	-59823	-1.47E+05
Egypt	-68011	-1.09E+05	-26500	-71544
El Salvador	-2.30E+05	-3.43E+05	-80287	-2.68E+05
Estonia	-10051	-16935	-4304.9	-9603.2
Ethiopia	-20994	-22175	0	-33494
Finland	-4960.7	-17330	-1620.4	-2713.2
France	0	-28580	0	0
Gabon	-14527	-39340	-6319	-11997
Georgia	-23103	-45878	0	-37082
Germany	0	-47289	0	0
Ghana	-2.63E+05	-2.96E+05	-48698	-3.75E+05
Greece	-71115	-2.37E+05	-36329	-36875
Haiti	-1.01E+06	-1.24E+06	-1.42E+05	-1.42E+06
Honduras	-3.27E+05	-4.31E+05	-86277	-4.22E+05
Hong Kong	-3.86E+05	-6.56E+06	-1.14E+05	0
Hungary	-24308	-50926	-9655.8	-21300
India	-32313	-60798	0	-38556
Indonesia	-2.08E+05	-2.70E+05	-47966	-2.75E+05
Iran, Islamic Rep	-52000	-71368	-18782	-59298
Ireland	-1.39E+05	-2.95E+05	-55856	-1.30E+05
Israel	-63801	-1.63E+05	-31807	-45172
Italy	-96455	-2.76E+05	-42714	-66910
Japan	0	-86262	0	0

Country	SO_2 shadow price	95% confidence interval		Bias-corrected value of SO_2 shadow price
		Lower bound	Upper bound	
Kazakhstan	-13095	-16631	-3895.9	-16027
Korea, Rep	-71905	-1.14E+05	-23814	-80929
Kyrgyzstan	-8965.4	-22928	-1629.6	-6754.3
Latvia	-15872	-27971	-6763.3	-14960
Lithuania	-46940	-60283	-15922	-55490
Macedonia, FYR	-7174.5	-17847	-3572.7	-4773.3
Malaysia	-1.44E+05	-1.91E+05	-52793	-1.69E+05
Mexico	-76654	-1.26E+05	-26389	-83515
Moldova, Rep	-21045	-28915	-7895.4	-23647
Morocco	0	-1.49E+05	0	0
Namibia	-8.32E+15	-2.06E+05	0	-1.66E+16
Nepal	-92678	-99967	-17421	-1.33E+05
Netherlands	-64192	-1.01E+05	-28135	-66131
New Zealand	-1.72E+05	-2.38E+05	-33683	-2.16E+05
Norway	-1402.4	-25478	0	0
Oman	-71610	-1.49E+05	-26420	-70981
Panama	-1.83E+05	-4.39E+05	-74640	-1.68E+05
Paraguay	-2.58E+05	-3.70E+05	-3063.8	-3.48E+05
Philippines	-66170	-1.36E+05	-24373	-63406
Poland	-17144	-28134	-6185.4	-17946
Portugal	-2.31E+17	-1.58E+08	-3.46E+06	-4.62E+17
Romania	-71038	-98412	-21885	-84462
Russian Federation	-14193	-20216	-3380.2	-16977
Saudi Arabia	-95976	-1.16E+05	-31650	-1.18E+05
Senegal	-60120	-83229	-17531	-76157
Serbia and Montenegro	-2542.2	-6122.1	-1025.1	-1936.4
Singapore	-79019	-3.01E+05	-22492	-67676
Slovakia	-13653	-23347	-5841.4	-13047
Slovenia	-30508	-62553	-14414	-26366
South Africa	-66201	-87070	-23231	-78014
Spain	-38574	-1.03E+05	-16506	-30791
Sri Lanka	-3.73E+05	-5.57E+05	-1.19E+05	-4.48E+05
Sweden	-561.04	-4919.1	0	-704.2
Switzerland	-12872	-89503	0	-7164.8
Syrian Arab Rep	-3.00E+16	-2.49E+06	-82932	-6.00E+16
Tajikistan	-1.65E+05	-2.08E+05	-1284.5	-2.29E+05
Togo	-1.44E+05	-1.96E+05	-32831	-1.92E+05
Trinidad and Tobago	-63179	-85625	-20076	-74128
Tunisia	-24272	-97099	-12387	-7610
Turkey	-43293	-1.20E+05	-15696	-31984
Turkmenistan	-42640	-53571	-11392	-53444
Ukraine	-17616	-20497	-5130.2	-22751
United Arab Emirates	-1.01E+05	-1.48E+05	-32378	-1.20E+05
United Kingdom	-1.24E+05	-1.91E+05	-44719	-1.39E+05
United States	-1.87E+05	-2.53E+05	-35825	-2.59E+05
Uruguay	-1.52E+05	-8.98E+05	-41627	-69930
Uzbekistan	-41332	-48207	-10718	-53919
Venezuela	-1.07E+05	-1.28E+05	-35016	-1.34E+05
Viet Nam	-1.11E+05	-1.41E+05	-21413	-1.47E+05
Yemen	-17754	-26564	-7562.4	-18882
Zambia	-1162.9	-1435.3	-328.79	-1474.4
Zimbabwe	-1.51E+05	-1.64E+05	-39886	-2.04E+05

Appendix 17

PARAMETRIC ESTIMATION OF SPECIFICATION II: ESTIMATED VALUES OF SHADOW PRICES FOR NO_X, 95% CONFIDENCE INTERVAL AND BIAS CORRECTED VALUE OF SHADOW PRICES.

Country	NO_x shadow price	95% confidence interval		Bias-corrected value of NO_x shadow price
		Lower bound	Upper bound	
Albania	-2.53E+05	-1701.3	0	-5.06E+05
Algeria	-1.09E+06	-2.19E+03	-636.92	-2.18E+06
Argentina	-8.56E+05	-3.46E+03	-403.21	-1.71E+06
Armenia	-47301	-343.8	-4.0056	-94508
Australia	-7.61E+05	-3.46E+03	-456.98	-1.52E+06
Austria	-5.44E+05	-690.88	-96.507	-1.09E+06
Azerbaijan	-62093	-131.93	-24.055	-1.24E+05
Bangladesh	-2.89E+05	-1.13E+04	-2150.8	-5.72E+05
Belarus	-1.21E+05	-239.28	-87.567	-2.41E+05
Belgium	-1.02E+06	-1432.7	-537.86	-2.04E+06
Bosnia and Herzegovina	-51030	-157.21	-32.12	-1.02E+05
Brazil	-2.54E+06	-1.98E+05	-3994.4	-4.96E+06
Bulgaria	-3.43E+05	-540.66	-191.38	-6.86E+05
Cameroon	-77429	-4825.6	-2446.7	-1.51E+05
Canada	-8.12E+05	-3.14E+03	-812.2	-1.62E+06
China	-7.81E+05	-4396.4	-561.6	-1.56E+06
Colombia	-1.52E+07	-4.33E+05	-7.67E+03	-3.03E+07
Congo	-46458	-708.95	-293.57	-92447
Croatia	-2.34E+05	-411.11	-126.11	-4.68E+05
Czech Rep	-4.15E+05	-410.13	-143.04	-8.30E+05
Denmark	-4.01E+05	-563.43	0	-8.01E+05
Dominican Rep	-9.79E+05	-3.67E+03	-1515.2	-1.96E+06
Egypt	-5.01E+05	-1.82E+03	-714.29	-1.00E+06
El Salvador	-6.43E+05	-4.90E+03	-2185.7	-1.28E+06
Estonia	-1.96E+05	-221.17	-32.542	-3.92E+05
Ethiopia	-13126	-6425.8	-2288.7	-21696
Finland	-1.63E+05	-201.5	0	-3.26E+05
France	-2.49E+05	-1414.4	-187.79	-4.97E+05
Gabon	-2.19E+05	-1029.6	-261	-4.37E+05
Georgia	0	-1063.8	0	0
Germany	-3.28E+05	-1059.2	-149.57	-6.56E+05
Ghana	-2.64E+05	-6.92E+03	-2878.5	-5.24E+05
Greece	-1.94E+06	-4.42E+03	-1298.3	-3.87E+06
Haiti	-3.69E+05	-1.33E+04	-2.61E+03	-7.32E+05
Honduras	-5.72E+05	-6.95E+03	-2775.9	-1.14E+06
Hong Kong	-1.77E+06	-7.47E+04	-1.01E+03	-3.52E+06
Hungary	-9.39E+05	-1538.6	-609.41	-1.88E+06
India	-2.55E+05	-2965	-595.68	-5.09E+05
Indonesia	-5.00E+05	-3.93E+03	-1074.6	-9.98E+05
Iran, Islamic Rep	-4.81E+05	-949.38	-336.07	-9.62E+05
Ireland	-9.58E+05	-1.07E+03	-69.277	-1.91E+06
Israel	-1.03E+06	-1.34E+03	-587.15	-2.06E+06
Italy	-1.86E+06	-5.47E+03	-1106.8	-3.71E+06
Japan	0	-1075.9	-106.37	0

Country	NO_x shadow price	95% confidence interval		Bias-corrected value of NO_x shadow price
		Lower bound	Upper bound	
Kazakhstan	-2.63E+05	-437.49	-145.59	-5.25E+05
Korea, Rep	-9.05E+05	-2.35E+03	-867.84	-1.81E+06
Kyrgyzstan	-49132	-268.69	0	-98201
Latvia	-2.18E+05	-445.27	-106.06	-4.35E+05
Lithuania	-3.34E+05	-874.19	-251.15	-6.67E+05
Macedonia, FYR	-1.91E+05	-202.55	-7.9916	-3.82E+05
Malaysia	-6.85E+05	-1.32E+03	-698.13	-1.37E+06
Mexico	-1.03E+06	-3.88E+03	-1020.7	-2.06E+06
Moldova, Rep	-1.02E+05	-263.14	-78.758	-2.03E+05
Morocco	-9.92E+05	-8.75E+03	-489.75	-1.98E+06
Namibia	-8.81E+16	-5.98E+07	-4.20E+05	-1.76E+17
Nepal	-1.55E+05	-10585	-3488.7	-3.02E+05
Netherlands	-3.56E+05	-5.72E+02	-237.92	-7.12E+05
New Zealand	-4.90E+05	-1.20E+03	-400.61	-9.79E+05
Norway	-2.74E+05	-381.17	-7.155	-5.47E+05
Oman	-5.94E+05	-1.00E+03	0	-1.19E+06
Panama	-8.19E+05	-8.53E+03	-2360.9	-1.63E+06
Paraguay	-4.75E+05	-4.45E+03	-1776.2	-9.47E+05
Philippines	-7.57E+05	-6.00E+03	-1819.5	-1.51E+06
Poland	-4.52E+05	-775.24	-308.68	-9.04E+05
Portugal	-1.16E+18	-1.33E+06	-4.31E+04	-2.31E+18
Romania	-1.15E+06	-1781.3	-592.91	-2.31E+06
Russian Federation	-1.61E+05	-483.45	-140.26	-3.22E+05
Saudi Arabia	-4.96E+05	-5.36E+02	-185.62	-9.92E+05
Senegal	-1.57E+05	-3379.9	-1642.8	-3.11E+05
Serbia and Montenegro	-73468	-163.78	-65.14	-1.47E+05
Singapore	-5.42E+05	-2.38E+03	0	-1.08E+06
Slovakia	-2.63E+05	-415.38	-162.1	-5.26E+05
Slovenia	-3.44E+05	-456.05	-54.801	-6.88E+05
South Africa	-6.55E+05	-1324.3	-514.37	-1.31E+06
Spain	-9.12E+05	-3.00E+03	-738.95	-1.82E+06
Sri Lanka	-9.32E+05	-1.40E+04	-4.80E+03	-1.86E+06
Sweden	0	-383.41	0	0
Switzerland	0	0	0	0
Syrian Arab Rep	-2.74E+17	-3.84E+04	-1476.7	-5.49E+17
Tajikistan	-3.73E+04	-3.45E+02	-40.944	-7.44E+04
Togo	-2.82E+05	-1.02E+04	-3682.3	-5.57E+05
Trinidad and Tobago	-1.29E+05	-146.8	0	-2.57E+05
Tunisia	-9.56E+05	-3717	-931.86	-1.91E+06
Turkey	-1.27E+06	-5.65E+03	-1075.3	-2.55E+06
Turkmenistan	-81239	-147.84	-7.9982	-1.62E+05
Ukraine	-94549	-305.16	-125.39	-1.89E+05
United Arab Emirates	-2.58E+05	-4.11E+02	-29.125	-5.16E+05
United Kingdom	-1.28E+06	-3.37E+03	-1116.2	-2.55E+06
United States	-1.54E+06	-5.19E+03	-589.64	-3.09E+06
Uruguay	-1.20E+06	-1.85E+04	-1655.7	-2.39E+06
Uzbekistan	-1.71E+05	-358.53	-92.32	-3.41E+05
Venezuela	-3.79E+05	-6.36E+02	-274.23	-7.58E+05
Viet Nam	-1.46E+05	-2.65E+03	-939.69	-2.90E+05
Yemen	-69211	-334.1	-103.03	-1.38E+05
Zambia	-18085	-1608.1	-858.9	-34928
Zimbabwe	-5.37E+05	-2.92E+03	-1271.7	-1.07E+06

Appendix 18

CORRELATION MATRICES OF ESTIMATES IN SPECIFICATION I ODDF

	Parametric	**DEA NIRS**	**DEA VRS**
Parametric	1.0000		
DEA NIRS	0.3495	1.0000	
DEA VRS	0.2336	0.7864	1.0000

Shadow prices of CO_2

	Parametric	**DEA NIRS**	**DEA VRS**
Parametric	1.0000		
DEA NIRS	-0.1633	1.0000	
DEA VRS	-0.1880	0.8964	1.0000

Shadow prices of SO_2

	Parametric	**DEA NIRS**	**DEA VRS**
Parametric	1.0000		
DEA NIRS	0.0097	1.0000	
DEA VRS	0.0217	0.5127	1.0000

Shadow prices of NO_x

	Parametric	**DEA NIRS**	**DEA VRS**
Parametric	1.0000		
DEA NIRS	0.0748	1.0000	
DEA VRS	0.0499	0.4267	1.0000

Appendix 19

CORRELATION MATRICES OF ESTIMATES IN SPECIFICATION II

ODDF

	Parametric	DEA NIRS	DEA VRS
Parametric	1.0000	0.7644	0.5622
DEA NIRS	0.7644	1.0000	0.7355
DEA VRS	0.5622	0.7355	1.0000

Shadow prices of CO_2

	Parametric	DEA NIRS	DEA VRS
Parametric	1.0000	0.0364	0.0248
DEA NIRS	0.0364	1.0000	0.9200
DEA VRS	0.0248	0.9200	1.0000

Shadow prices of SO_2

	Parametric	DEA NIRS	DEA VRS
Parametric	1.0000	-0.0141	-0.0122
DEA NIRS	-0.0141	1.0000	-0.0343
DEA VRS	-0.0122	-0.0343	1.0000

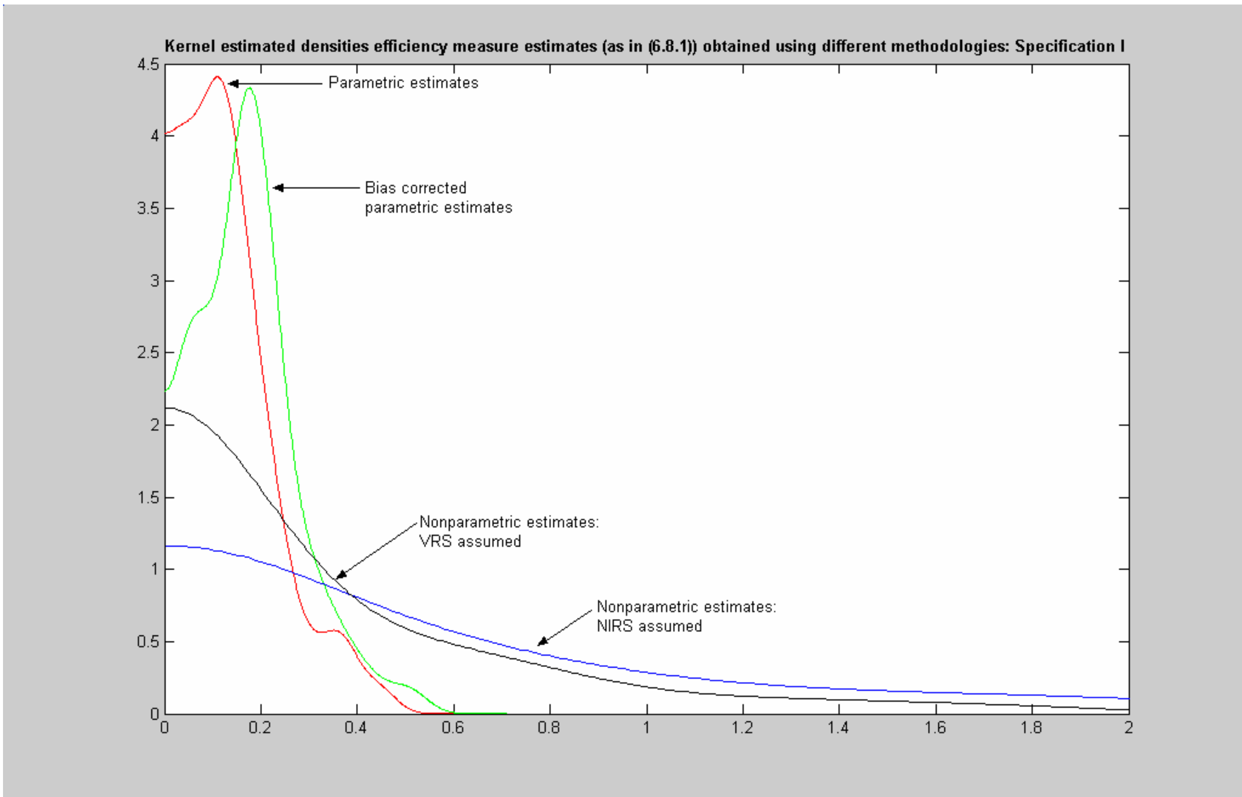
Shadow prices of NO_x

	Parametric	DEA NIRS	DEA VRS
Parametric	1.0000	-0.0931	-0.0135
DEA NIRS	-0.0931	1.0000	0.2411
DEA VRS	-0.0135	0.2411	1.0000

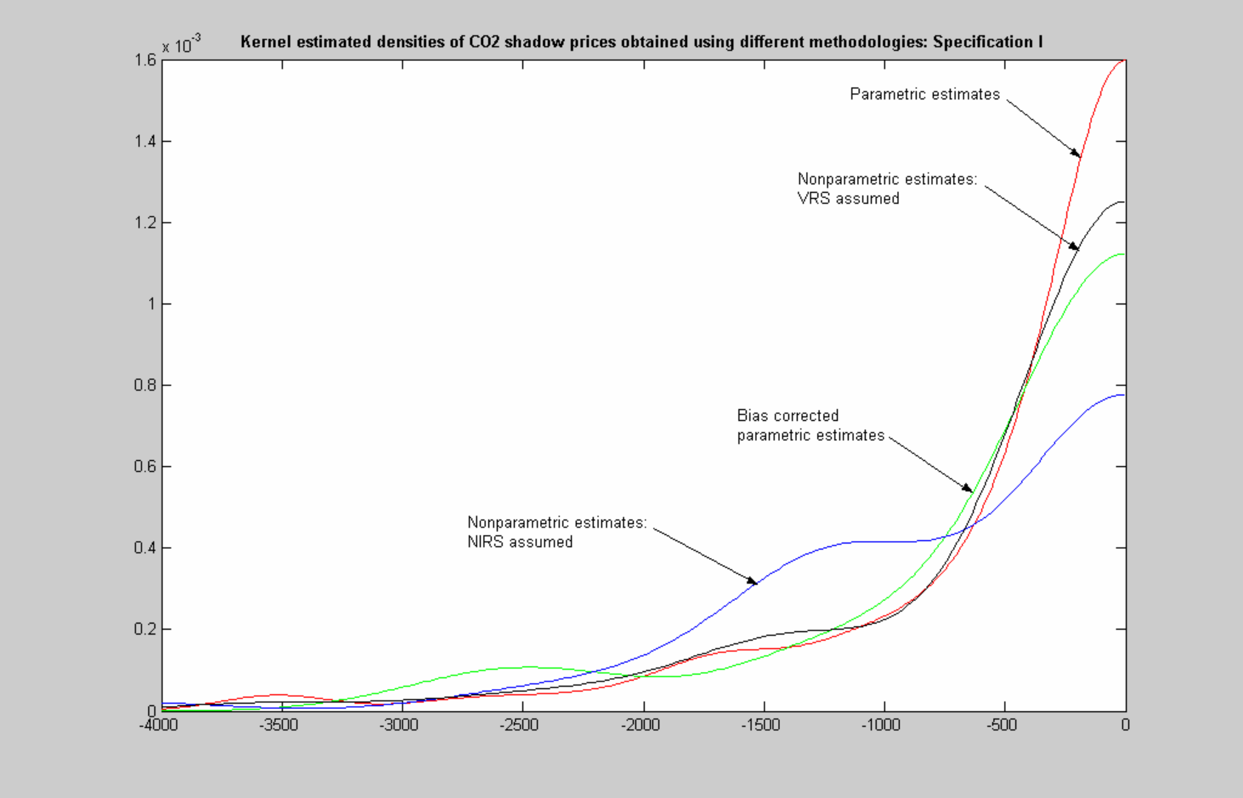
Appendix 20

KERNEL ESTIMATED DENSITIES FOR ESTIMATES: SPECIFICATION I

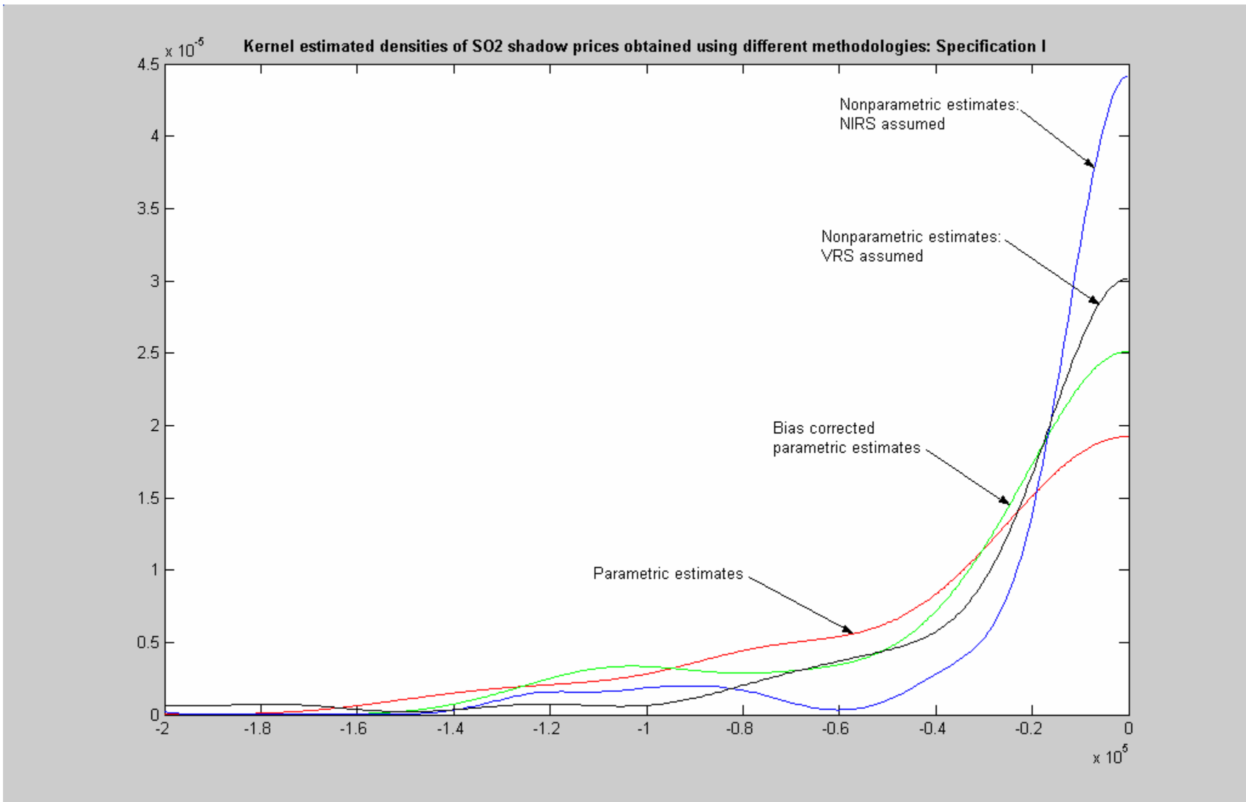
ODDF (monotonically transformed)



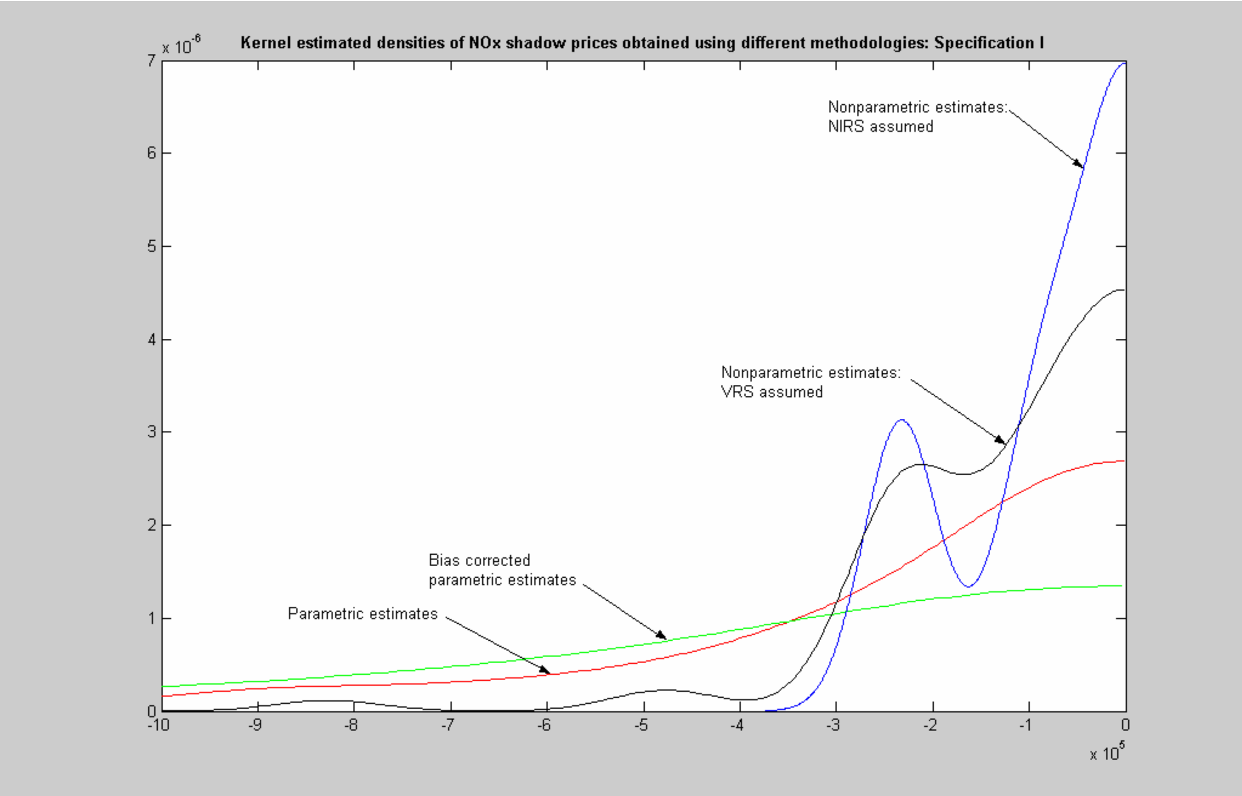
CO_2 shadow prices



SO_2 shadow prices



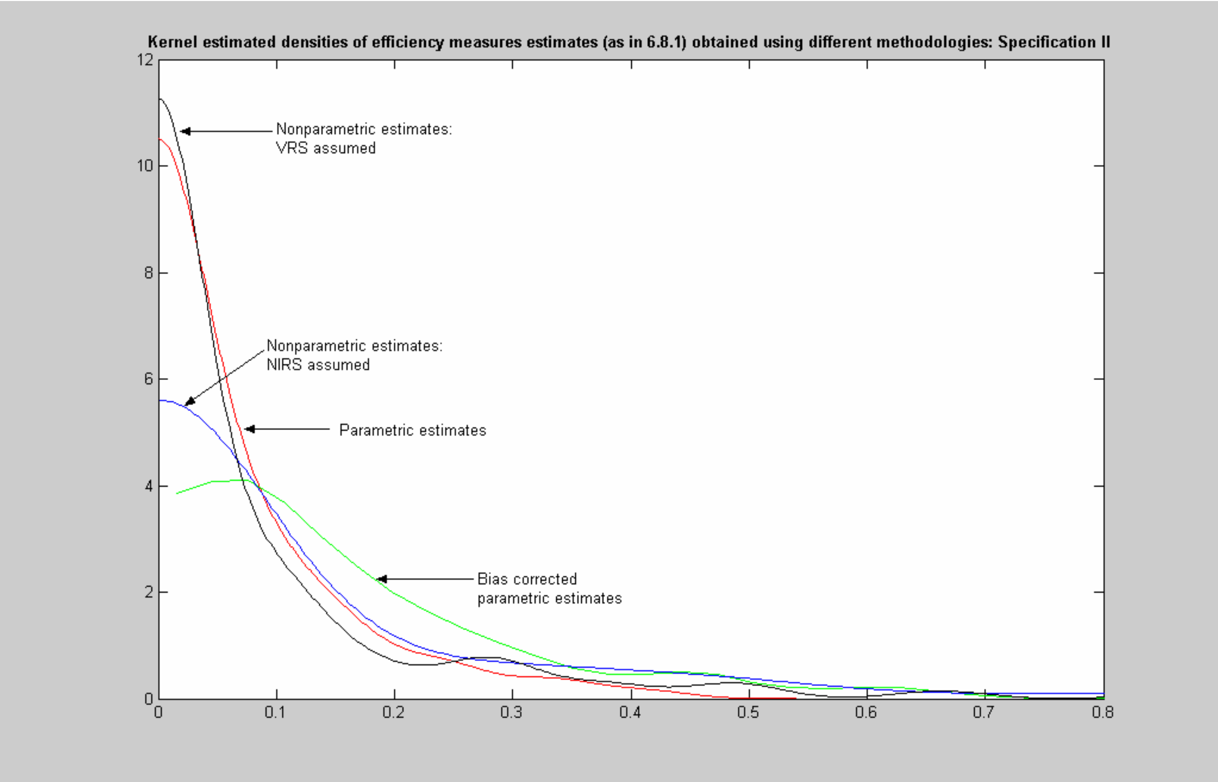
NO_x shadow prices



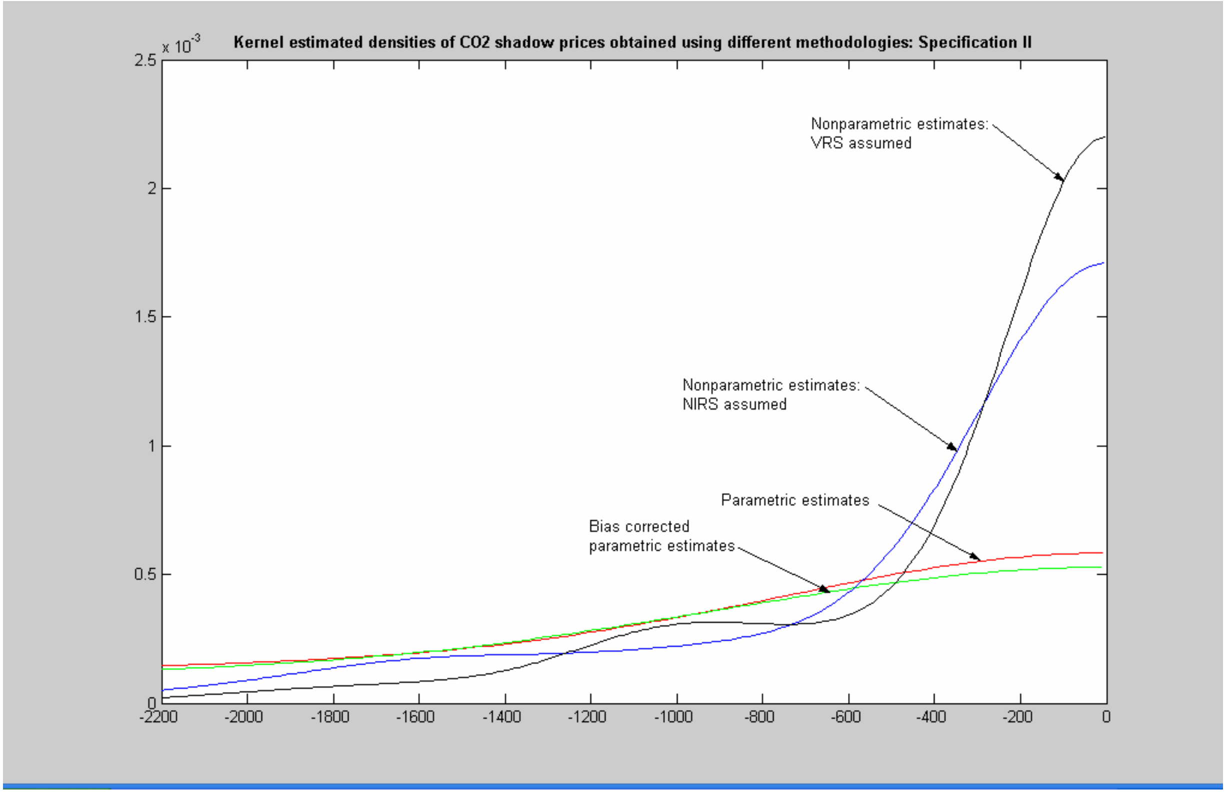
Appendix 21

KERNEL ESTIMATED DENSITIES FOR ESTIMATES: SPECIFICATION II

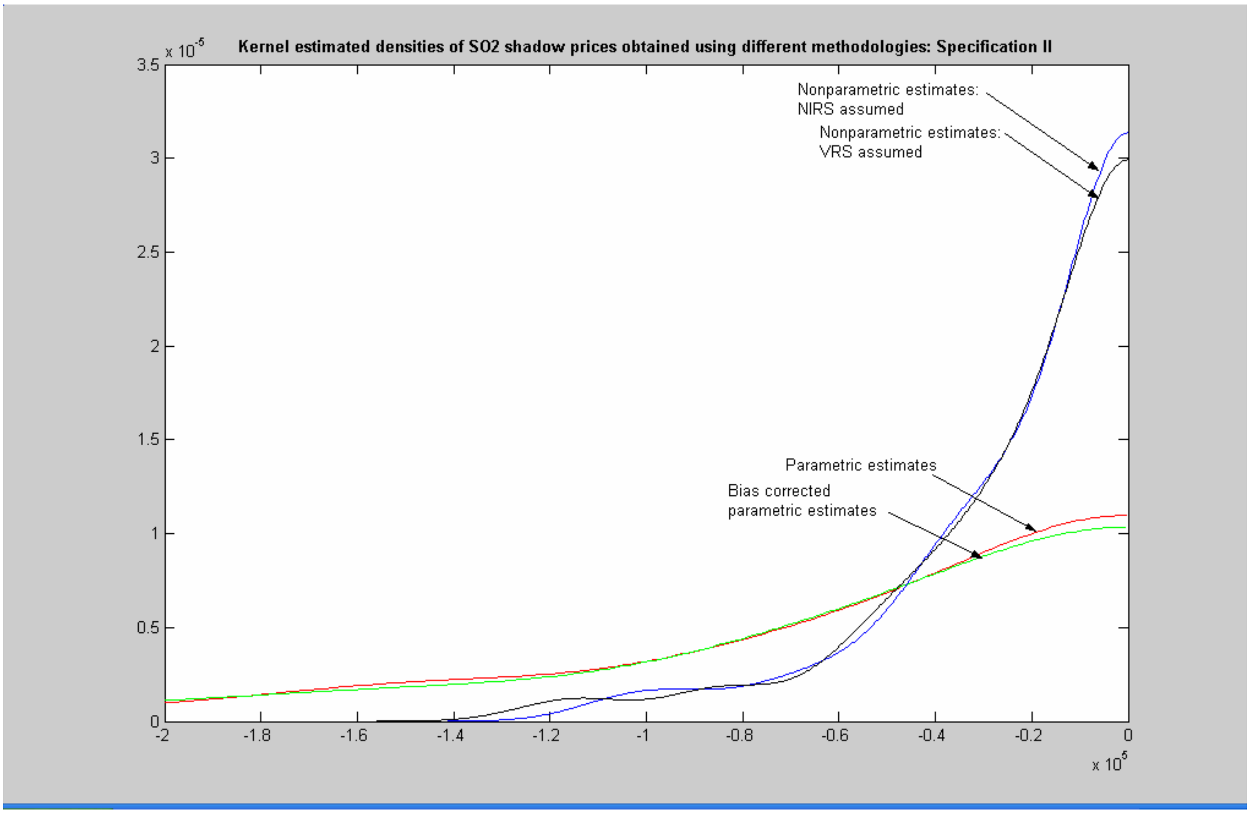
ODDF (monotonically transformed)



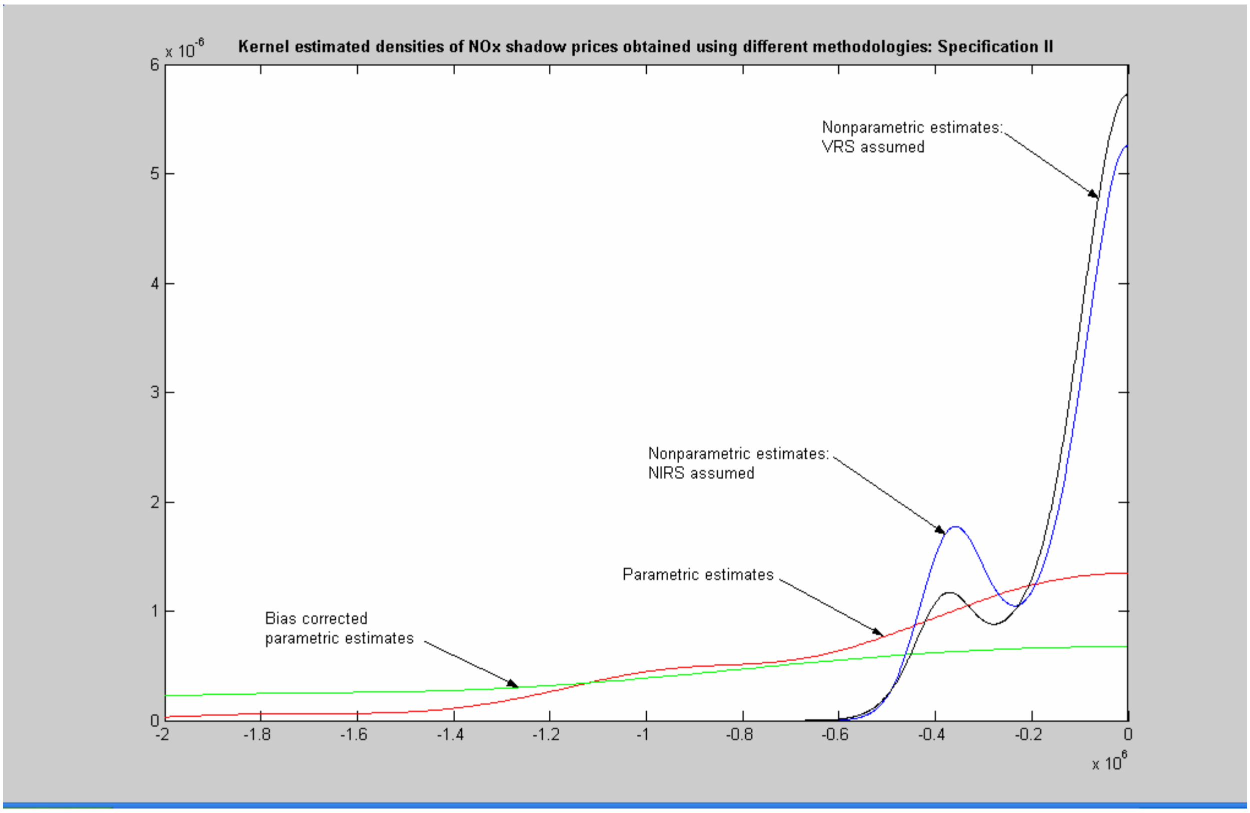
CO_2 shadow prices



SO_2 shadow prices



NO_x shadow prices



A p p e n d i x   2 2

MEAN VALUES OF THE LOWER 95 % OF THE ESTIMATES: SPECIFICATION I

	ODDF	CO_2	SO_2	NO_x
Parametric	0.1241	-478.3852	-34130	-264150
Non-parametric NIRS	0.3851	-259.0728	-868.7803	-42685
Non-parametric VRS	0.2847	-133.8549	-3875.2	-6763.7

Appendix 23

MEAN VALUES OF THE LOWER 95% OF THE ESTIMATES:
SPECIFICATION II

	ODDF	CO_2	SO_2	NO_x
Parametric	0.0927	-1439	-72784	-486486
Non-parametric NIRS	0.1490	-306.75	-14881	-101841
Non-parametric VRS	0.0938	-277.48	-17105	-105757

"ILLARIONOV MAKES HIS CASE ON KYOTO" BY GREG WALTERS FOR *THE MOSCOW TIMES*, DEC., 18, 2003.

Illarionov Makes His Case On Kyoto

By Greg Walters
SPECIAL TO THE MOSCOW TIMES

Andrei Illarionov, President Vladimir Putin's top economic adviser, has fast become Moscow's most consistent and vocal messenger on the Kyoto Protocol, rising above the cacophony of voices emanating from the Kremlin.

Europeans are accusing Russia of "playing poker" with the treaty to limit emissions. But Illarionov's message is clear: Kyoto contradicts Putin's stated goal of doubling gross domestic product by 2010.

Russia's ratification is crucial to the success of the treaty, which the European Union is championing but other key countries like the United States are boycotting.

Without Russia on board, an EU official said this week, it would be "suicide" for Europe to follow the protocol, which calls on signatory countries to limit greenhouse gas emissions.

But Illarionov, who says he speaks for Putin, claims Russia has no choice.

"It will slow down economic growth. Even a 1 percent slowdown in economic growth is a huge amount for us," he said earlier this month.

"The president's position is that the Kyoto Protocol cannot be ratified in its current form, because it is discriminatory, ineffective and not universal," he told reporters Tuesday night.

Illarionov argued that GDP growth and carbon dioxide emissions are fundamentally linked, and that Moscow's targeted economic expansion will soon put Russia above the greenhouse emission limits set by Kyoto.

"In those countries we analyzed, each percent of GDP growth is accompanied by an increase of carbon dioxide emissions by 2 percent," he said. "Starting in 2012, the need for carbon dioxide would exceed those limits set by the Kyoto Protocol, even by the most conservative scenario set by the Economic Development and Trade Ministry."

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KYOTO

Continued from Page 1

But a high-ranking official in the European Commission, who asked not to be named, firmly rejected Illarionov's calculations, calling his 1 percent GDP to 2 percent emissions formula "absolutely counterintuitive."

"That would mean the Russian economy is becoming less energy efficient. These figures contradict the experience of the European Union," the official said.

The Kyoto Protocol calls on signatory countries to cut greenhouse gas emissions to 5.2 percent less than 1990 levels by the year 2012, and for some of them, Russia included, to reduce emissions in years after.

Supporters have argued that Russia could earn money through the treaty: Kyoto provides an opportunity for under-polluting countries to sell their extra emissions quotas to over-producing states, meaning Russia — which produces about a third less greenhouse gases than it did in 1990 — may face a multibillion-dollar bonanza from such deals.

Illarionov disagreed.

"Russia can't earn anything from quota mechanisms," he said. "This is a myth. [Russia] will be in a position where it has to buy quotas to continue economic growth. This is well known to us and to our [negotiating] partners, who do not deny this fact."

But the EU official firmly contradicted Illarionov's account.

"We have all said many times that we are absolutely certain that Russia will benefit economically from the Kyoto Protocol," the official said. "The Russians know this, and they accept it, although they may deny it in public. They are playing poker."

Analysts are split over Illarionov's assertions.

Ksenia Yudayeva of the Carnegie Moscow Center said she finds some of Illarionov's economic arguments quite convincing.

"The Russian economy is growing quite fast," she said. "I would not exclude the possibility that by 2008, Russia would reach the point where the emissions are at 1990 levels."

But Igor Leshukov, director of the Institute of International Affairs in St. Petersburg, said Illarionov's position rests on extremely dubious economics.

"For me this is scientifically and academically groundless," he said. "If we are going to double GDP with the introduction of more efficient technologies, do we necessarily increase energy consumption? If we're going to recreate heavy Russian industry, that being a major source for carbon dioxide emissions, then yes, of course. But there's no market for this industry. And even if this industry reemerged, it would reemerge through more efficient technology.

"So when Mr. Illarionov, who is a fairly good economist, says things that don't make any economic sense, the question is: Why is he saying this?" Leshukov said. "And the answer is, he's acting politically."

Some observers say Russia may be holding out for better terms for entry into the World Trade Organization. Earlier this month, Putin slammed EU bureaucrats for blocking Russia's entry into the WTO over "unfounded and rigid demands" that Russia raise domestic gas and electricity prices as a precondition for accession.

SERGEY PONOMAREV / AP

Illarionov discussing Kyoto on Tuesday.

During a visit to Tokyo this week, Prime Minister Mikhail Kasyanov was quoted as saying that Russia is preparing to ratify the Kyoto treaty.

"If you look at Kasyanov's statements, he is talking about Kyoto in one sentence and the WTO in the next," the EU official said. "And that raises suspicions on our side that there might be a linkage. But we've not received any official proposals to link such issues."

Illarionov flatly denied such speculation.

"I don't see any relation here [with the WTO]," he said on Tuesday. "European Union officials have also said they don't see it."

Illarionov went on to argue that the Kyoto Protocol is also biased against Russia in particular.

"The Kyoto Protocol discriminates against Russia," he said. "The United States is responsible for three times as much [greenhouse gas] as Russia, and China twice as much. Russia is not among the richest countries, but neither the United States nor China have any obligations whatsoever to reduce greenhouse gases."

The exclusion of these countries would lead to an excess of "about 2 billion tons" in carbon dioxide credits, Illarionov said, so Russia's spare quotas, even if they existed, wouldn't even enter the picture.

EU sources called Illarionov's figures unfounded.

"All these numbers are more or less informed estimations," the official said. "It's very difficult to say whether it will be 2 billion or 4 billion. This is not possible, I can't comment on these figures. I don't know where Mr. Illarionov has got them from. There will be big demand, but we cannot quantify it."

On the question of climate change itself, Illarionov said the science simply isn't sufficient. Since global temperatures have changed naturally over centuries, he argues, the very idea that greenhouse gases endanger the Earth's climate remains in doubt.

But Dr. Myles Allen of the atmospheric physics department at Oxford University said that while the science may be inconclusive, most specialists agree the risk is paramount.

"It is of course physically possible that we might be seeing changes as large as those we are seeing now through natural variability," he said. "But the chance of that is low. It all comes down to what sort of risk [Illarionov] is ready to take. To assume that changes of this magnitude and speed will be beneficial for Russia is a very risky strategy."

Illarionov has, however, outlined a way forward: other major polluters, such as the United States and China, must sign on to the treaty; or the terms of the treaty must be softened for Russia.

"Until the largest emitters join in the protocol and make it universal, its ratification would be an illusion of the Europeans that the problems are solved," he said. "One option is for the protocol not to require any reductions in emissions."

The EU official rejected the possibility of changing Russia's commitments. "This is no go," he said. "[Illarionov] is suggesting Russia undo a treaty it has signed. Russia has to think about its political credibility on the world stage."

But without such changes, the treaty is simply inoperable, Illarionov said.

"Someday, although I can't say specifically when, the EU and Japan will thank Russia for its position on the Kyoto Protocol," he said. "We should not make hasty decisions based on uncertain evidence."

Even so, officials from signatory countries have said they remain convinced Russia will ratify the Kyoto Protocol eventually.

"Our assumption is that Mr. Illarionov speaks for himself," the EU official concluded. "We know that he is a critic of the Kyoto Protocol. We are very confident that Russia will ratify."

E D I T O R I A L

Don't Trade Economy For Kyoto

Kremlin fears that ratifying the Kyoto Protocol might put a dent — or worse — in economic growth are well-founded, although not necessarily the way presidential economic adviser Andrei Illarionov explains it.

Illarionov pulled out a dazzling array of charts Tuesday night to explain his case against the treaty and argued that even under his most pessimistic of economic forecasts, Russia would not be able to meet Kyoto restrictions by 2012 and could end up having to buy emissions credits from other countries.

Economic growth is a Kremlin priority, and for good reason. The energy-dependent country is mired in poverty, and President Vladimir Putin has made it clear — in words if not always in deeds — that he will do whatever it takes to double GDP by 2010 and raise dismal living standards.

Clean air, on the other hand, is also a good cause.

European countries and Japan have been trying to coax Russia on board by dangling the possibility of making money off of emissions credits. With industrial output — and, thus, emissions — way down from Soviet levels, at which emissions quotas were set in the treaty, Russia could theoretically sell unused credits to European countries at a potentially handsome profit.

The problem with this is the credits are a gray area that may or may not benefit Russia — should they indeed ever materialize.

One can argue that Russia's less stringent pollution controls provide it with a competitive advantage vis-a-vis more developed countries in the EU and elsewhere.

However, Russian industry is notorious for its profligate energy consumption: More modern technology would provide gains in energy efficiency, meaning that GDP growth would not necessarily result in increased emissions.

Indeed, in this day and age the correlation between economic growth and emissions is not as direct as Illarionov would have us believe. Illarionov himself has called for economic diversification away from the pollution-heavy oil and gas industries, and suggested that information technology could become a driving force of the economy. By his estimates, Russia could become the world's fourth biggest IT producer, after the United States, India and China, over the next few years. Greenhouse gases don't play a role in software development.

Cleaning up the air is an important task, but surely the Kyoto Protocol is not the way to go if it means handcuffing Russia's economic growth.

After all, what good is clean air if people have nothing to eat?