Energy Efficiency and Firm Performance
Evidence from Swedish Industry

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Abstract

This thesis sheds light on different aspects of the performance of Swedish industrial firms. To this end, the analysis defines and measures energy efficiency in an economic context, as well as investigating the implicit relationships between energy efficiency and other firm performance metrics – productivity and environmental performance. Paper I estimates energy efficiency using a "true" random effects stochastic frontier model. The presence of energy inefficiency indicates the potential for energy consumption reduction. Paper II includes undesirable outputs when measuring energy efficiency in a non-parametric model approach. To assess the impacts of efficiency determinants, a double bootstrap procedure is adopted for the second-stage regression analysis. Paper III investigates firm performance in three dimensions – productivity, energy efficiency, and environmental performance. A panel vector auto-regression model is utilized to examine the causal and dynamic relationships between the three dimensions of firm performance and the environmental investment. The overarching conclusion from the thesis is that there is considerable potential to improve energy efficiency in Swedish industrial firms. It is very likely that the permit price of the EU emissions trading system for CO_2 and the Swedish CO_2 tax rate were too low to create incentives to improve energy efficiency. A firm strategy that emphasizes energy efficiency improvements is also likely to save costs and be beneficial for overall productivity in later periods. Environmental performance comes at a cost in terms of lower productivity, and thus the results cannot corroborate the win-win outcome postulated by the so-called Porter Hypothesis.

Keywords: energy efficiency, firm performance, stochastic frontier analysis, data envelopment analysis, panel vector auto-regression, Swedish industrial firms

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Dedication

To my morfar, who is my role model, and wrote these words for me on the day I went to college:

路漫漫其修远兮，吾将上下而求索。

The way ahead is long; I see no ending, yet high and low I'll search with my will unbending.

-- 屈原, 公元前340年,《离骚》

Qu Yuan, 340 BC, 《*Li Sao*》

I follow up the quest despite of day and night and death and hell.

-- Alfred Lord Tennyson (1872) Gareth and Lynette, line 865.

Contents

List of Publications

This thesis is based on the work contained in the following papers, referred to by Roman numerals in the text:

I Lundgren, T., Marklund, P.-O., Zhang, S.S. (2016). Industrial energy demand and energy efficiency – Evidence from Sweden. *Resource and Energy Economics* 43, 130-152.

II Zhang, S.S., Lundgren, T., Zhou, W.C. (2016). Energy efficiency in Swedish industry: A firm-level data envelopment analysis. *Energy Economics* 55, 42-51.

III Zhang, S.S., Lundgren, T., Zhou, W.C. (2016). Environmental investment and firm performance: A panel VAR approach. (*Submitted*)

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Abbreviations

CCPI	Climate Change Performance Index
DEA	Data Envelopment Analysis
DMUs	Decision Making Units
EC	European Commission
EU	European Union
EU ETS	European Union Emission Trading System
GHGs	Greenhouse Gases
IEA	International Energy Agency
SEK	Svensk Krona (Swedish Krona)
SFA	Stochastic Frontier Analysis
TRE	True Random Effects
TWh	Terawatt hour
pVAR	Panel Vector Auto-regression

1 Introduction

Energy efficiency reveals a firm's operating ability to use and allocate energy input efficiently in a production process. The efficient use of energy is important for improving the competitiveness of industrial firms: it helps to reduce energy consumption and energy costs, and to reduce carbon emissions. As stated by the IEA (2014), energy efficiency is widely recognized as the most cost-effective approach to addressing energy-related issues and increases in competitiveness. The Swedish energy and climate policies set ambitious energy efficiency and carbon emissions reduction targets, and they set improvements in energy efficiency as a strategic priority. The topic of this thesis focuses on issues related to energy efficiency, environmental performance, and productivity in Swedish industrial firms.

Swedish industry is important to the nation's economic growth (Nauclér, Tyreman, & Roxburgh, 2012). In 2012 it contributed about 15% of the GDP, while industry also accounts for about 40% of Swedish final energy consumption (Swedish Energy Agency, 2013). The greatest use of energy in Swedish industry (more than 160 TWh) occurred in 1974, but subsequently the energy consumption has not reached these levels and the consumption has been relatively stable. Electricity (mainly generated by hydro and nuclear power) and biomass are the main sources of energy for Swedish industry, and their consumption levels have increased considerably over the years. The proportion of electricity consumed has increased from 21% (in 1971) to 35% (in 2013), whereas the percentage of energy generated from biomass has increased from 21% (in 1971) to 38% (in 2013). District heating, on average, accounts for about 3% of the total energy consumption. After the oil crisis of the 1970s, the proportion of energy from petroleum products gradually decreased, from 48% in 1971 to 7% in 2013. The total consumption of petroleum products, coal, and gas still accounted for about 23% of the total energy consumption in 2013 and this consumption is the major contributor (contributing about 80%) to the country's carbon emissions (Swedish Energy Agency, 2015).

According to the Germanwatch Climate Change Performance Index (CCPI) 2016, Sweden ranked sixth among the 58 top CO_2-emitting nations that take actions on climate protection (Germanwatch, 2016). This can mostly be attributed to Sweden's advanced technology, a properly designed climate and energy policy scheme and a well-developed awareness of energy and environmental issues. The Swedish climate and energy policies are more ambitious than the EU triple 20 targets:[1] 1) reduce greenhouse gas (GHGs) emissions by 40% compared with the 1990 level; 2) increase the share of renewable energy to at least 50%; and 3) improve energy efficiency by 20% with respect to the 2008 level.

Sweden has a long history of levying energy and emissions taxes. The Swedish energy tax was initiated in the 1950s. Later on, in 1991, a carbon dioxide tax was introduced and Sweden became one of the first countries to impose a tax on carbon (Marchal et al., 2012). The rates of energy tax vary according to the type of fossil fuel, and the statutory carbon dioxide tax rate was initially 0.25 SEK/kg CO_2 emitted. Swedish industrial firms were exempted from the energy tax and they were only charged at 50% of the statutory carbon dioxide tax level. Energy-intensive firms were charged at an even lower carbon dioxide tax rate. In the subsequent 1993 tax reform, both energy and carbon tax rates were raised considerably, but industrial firms were still exempted from the energy tax, and they paid only 25% of the general carbon dioxide tax. The tax system was reformed again in 1997, and industrial firms then paid 50% of the general carbon dioxide tax. Since then, the statutory carbon dioxide tax rate has been increased, from 0.37 SEK/kg CO_2 emitted in 2000 to 1.01 SEK/kg CO_2 emitted in 2008. However, the taxes for Swedish industry were reduced to 20% of the statutory tax rate (Swedish Energy Agency, 2012). Additionally, industrial firms can apply for a tax refund if their tax bill exceeds 0.5% of their value added tax. Energy-intensive industrial firms were exempt from the carbon tax if their tax payment would exceed 0.8% of their value added tax (Brännlund et al., 2014). In 2009 the Swedish Parliament approved Bill 2009/10:41 on the carbon dioxide tax for the years 2010, 2011, 2013 and 2015. Under this new taxation scheme, sectors that do not participate in the EU ETS (e.g., agriculture, forestry, etc.) are subject to the full statutory carbon dioxide tax rate, and the number of tax exemptions for domestic industry sectors has been reduced considerably (IEA, 2013).

In 2004, the energy tax exemption on electricity was removed. A levy of 0.005 SEK per kilowatt-hour electricity consumption was made on energy-intensive industrial firms, which is in accordance with the EU's Energy Tax Directive. According to the Council Directive No. 2003/96/EC, these industrial firms can be exempted from paying the energy tax on electricity consumption if they can provide evidence of energy efficiency improvements. Correspondingly, an energy efficiency improvement program (PFE) targeting Swedish energy-intensive industrial firms was launched in 2005. The program is voluntary and firms participating in it receive a full rebate of their energy tax

[1] The EU triple 20 targets aim to increase energy efficiency by 20% and reduce greenhouse gases emissions by 20%, compared to the 1990 levels. The targets also intend to increase the share of renewable energy to at least 20% of the total energy consumption.

on electricity consumption. The program is intended to generate the same effect as the energy tax, through improving the efficiency of electricity consumption. The program was set up with a five-year cycle mechanism. Firms that wish to continue their participation must apply all the energy efficiency improvement measures that have been identified and that have a payback time of less than three years (Swedish Energy Agency, 2012). This program is currently in its last five-year period, and will end in 2017.

In the sample period of this study, 2000-2008, the main change in policy in this area at the EU level was the introduction of the EU ETS in 2005. In principle all energy-intensive industry sectors are covered by the EU ETS. These energy-intensive businesses include oil refineries, steel works and the producers of iron, aluminum, metals, cement, lime, glass, ceramics, pulp, paper, cardboard, acids, bulk organic chemicals, etc. Some small installations can be excluded from the system if they can use other measures to reduce their emissions by the same amount. The EU ETS aims to reduce emissions from the included sectors before 2030 by 43% from the 2005 level.

The EU ETS works with a 'cap and trade' approach. This unique approach provides firms with the opportunity and flexibility to cut their emissions in the most cost-effective way (European Commission, 2013). A cap, or limit, is placed on the overall number of emission allowances at the Member State level according to national allocation plans. Within the cap, firms can buy and sell emission allowances as needed. One emission allowance is equivalent to one ton of CO_2. At the end of each year, if a firm cannot show it has enough allowances to cover all its emissions it is heavily fined. Alternatively, if a firm has spare allowances because it has reduced its emissions, it can keep the allowances to cover future needs or it can sell them to another firm that needs extra allowances. The cap is reduced annually, so that the total amount of emissions should also decline each year. Currently, the cap is being decreased by 1.74% per year. From 2021, it is expected to be decreased by 2.2% annually, in order to attain the goal of a 43% reduction in carbon emissions by 2030 at the EU level (European Commission, 2014).

In the first trading period (2005-2007), only power plants and energy-intensive industries were included in the system. The emission allowances were distributed by free allocation. In the second period (2008-2012) the total number of emission allowances was reduced by 6.5% from the 2005 level. For the third trading period (2013-2020), the system has been significantly changed. A single EU-wide cap replaces the national caps of the previous system. The mechanism for the free allocation of emission allowances will be progressively replaced by an auction system. Furthermore, the system will cover more sectors and some other types of GHGs.

2 Objectives

This thesis consists of three papers that deal with issues related to energy efficiency and firm performance. It attempts to seek empirical answers to the following questions:

1) How can energy efficiency be appropriately defined and measured on a foundation of economic theory? What is the potential for energy efficiency improvement in Swedish industrial firms?
2) What factors influence energy efficiency? In particular, what are the impacts of the EU ETS and the Swedish carbon dioxide and energy taxes on energy efficiency?
3) How do three dimensions of firm performance – productivity, energy efficiency and environmental performance – affect each other, and how do they interact with environmental investment?

3 Methodology

This section describes the methodology used in this thesis. Section 3.1 briefly introduces the concepts of energy efficiency and firm performance. The measurements of energy efficiency and firm performance are presented in section 3.2 and section 3.3 respectively. Section 3.4 describes the data.

3.1 Energy efficiency and firm performance

Energy intensity has been widely used as a proxy for energy efficiency. For industrial firms, energy intensity is the ratio of energy input to value added produced (see, e.g., Bhattacharyya, 2011).[2] Using this concept, improvements in energy efficiency can be achieved by lowering energy intensity. Using energy intensity as a proxy for energy efficiency may be misleading, as energy intensity depends on factors not related to efficiency, such as different weather conditions, management culture etc. Further, energy intensity may be a bad proxy for the variation in energy efficiency across industries/firms, since energy demand (input) in production may vary as a result of different factors such as what exactly is produced, what restrictions the firms are facing, different technologies, etc. In an attempt to overcome these issues, energy efficiency in this thesis is defined using production economics, as advocated by, for example, Evans, Filippini, and Hunt (2013).

In production theory, the word “efficiency” often refers to productive efficiency, which can be measured from two aspects: input-oriented and output-oriented efficiency. In the input-oriented case, inefficiency implies how

[2] Patterson (1996) proposes multiple ways to calculate the energy intensity: energy intensity could be a thermodynamic indicator (energy inputs and outputs measured in thermodynamic units), a thermodynamic–physical indicator (energy inputs and outputs measured in thermodynamic and physical units respectively), a thermodynamic–economic indicator (energy inputs and outputs measured in thermodynamic and economic units respectively), or an economic indicator (energy inputs and outputs measured in economic units).

much inputs could be reduced given the output level and technology (energy efficiency in this thesis is defined in this context). In the output-oriented case, inefficiency indicates how much more output can be produced given the input quantities and technology (productivity in paper III is defined in this context). Moreover, if prices are known, the concept of productive efficiency can be extended to revenue, profit or cost efficiency (see details in, e.g., Kumbhakar and Lovell, 2000).

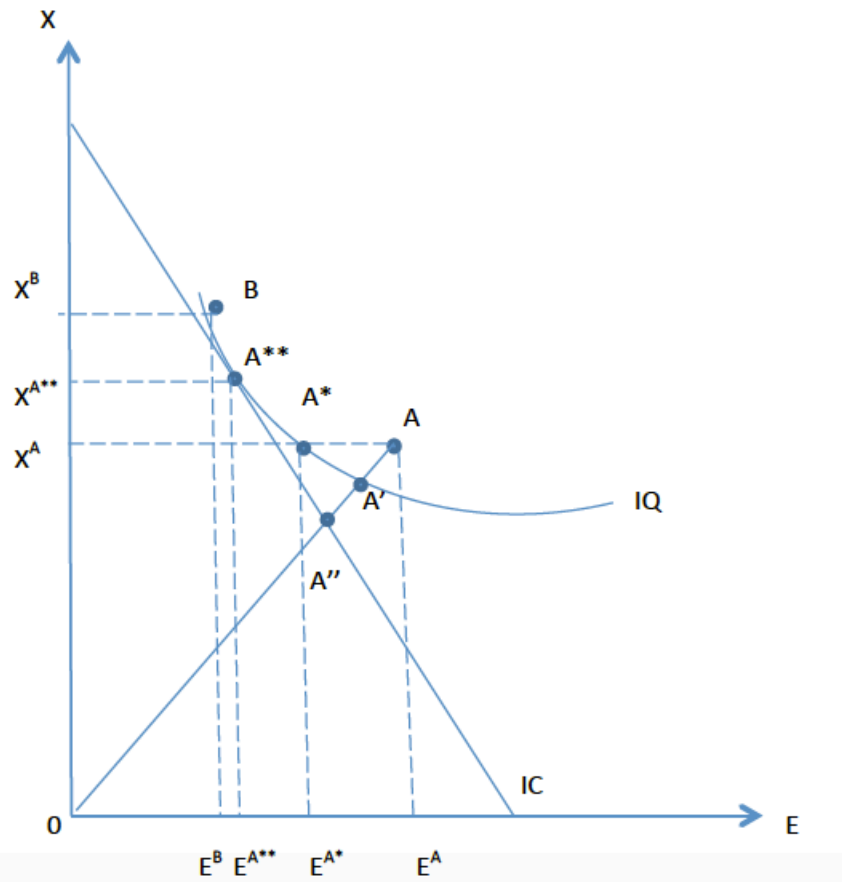

Figure 1. Illustration of energy efficiency

An intuitive definition of input-oriented energy efficiency can be traced back to Farrell (1957)'s radial efficiency. As shown in Figure 1, a firm utilizes energy input (E) and non-energy input[3] (X) to produce output. The output isoquant curve (IQ) defines a benchmarking frontier: firms located on the IQ line are technically efficient and produce Q_0 units of output. Assume there is a

[3] Non-energy inputs could be capital, labor, material, etc.

firm A that uses an amount E^A of energy input and an amount X^A of non-energy input and produces an amount Q_0 of output. Firm A is technically inefficient because it lies above the IQ curve. According to Farrell (1957), the technical efficiency of firm A is calculated as 0A'/0A.

When considering production costs, the measurement of efficiency is slightly different. The isocost line (IC) is introduced on this occasion. Assume there is another representative firm A** that is located on the IQ line and that the IC line is tangential to the IQ line at point A**.[4] Thus, firm A** can produce an amount Q_0 of output by using the minimum cost or, in other words, firm A** is technically and allocatively efficient. Firm A has both technical and allocative inefficiencies. The overall productive efficiency of firm A is calculated as 0A''/0A, where 0A'/0A is the technical efficiency and 0A''/0A' is the allocative efficiency.[5] Improving the overall productive efficiency of firm A is equivalent to moving from point A to point A**: the consumption of energy input will decrease from E^A to E^{A**} whereas the consumption of non-energy input will increase from X^A to X^{A**}.[6]

The discussion above is about Farrell's (1957) radial measurement of technical and allocative efficiency. In this context, the measurement of efficiency is based on a proportional reduction of energy and other inputs. Kopp (1981) introduces the concept of non-radial input specific efficiency. Using this concept, energy specific efficiency measures the potential reduction of energy consumption when output and non-energy inputs are fixed. In Figure 1, the non-radial energy specific efficiency of firm A is calculated as the ratio $0E^{A*}/0E^A$. It denotes the distance from the energy consumption level of firm A to the technically efficient energy consumption level. The definition of energy efficiency in paper II and paper III is grounded in this concept.

Schmidt and Lovell (1979) and Kumbhakar and Lovell (2000) further develop this concept of non-radial input specific efficiency to take costs into account. In this context, the optimal energy demand is derived from a given technology subject to a cost minimization constraint. The presence of energy inefficiency is denoted by the gap between the observed energy consumption and the derived optimal energy demand. Energy efficiency in paper I is defined according to this concept.

Combs, Crook, and Shook (2005) review 238 articles in the Strategic Management Journal published during the period 1980 to 2004 and find that nearly 82% of them use some type of financial indicator to represent firm performance. A financial indicator, such as return over assets or stock price, depicts only a part of firm performance. Paul and Siegel (2006) argue that the measurement of firm performance lacks a theoretical foundation in economics.

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[4] The slope of the isocost line is determined by the ratio of input prices.

[5] This implies a relationship: overall productive efficiency = technical efficiency*allocative efficiency.

[6] This may happen when firm A installs a new device that optimizes energy consumption as well as improving production.

In the light of these arguments, paper III investigates firm performance over three dimensions – productivity, energy efficiency, and environmental performance – and grounds the metrics in production theory.

The metrics of firm performance are defined using the Malmquist index of Färe, Grosskopf, Lindgren and Roos (1989). They are the geometric mean of two Caves et al.'s (1982a, 1982b) indexes, and they represent changes of productivity/energy efficiency/environmental performance between two periods. The index of Caves et al. (1982a, 1982b) is the ratio of within period and cross period distance functions. The distance function is defined according to Shephard (1970), and is the reciprocal of Farrell (1957)'s radial measurement. For instance, for productivity, the within period distance function measures the radial distance of an output observation for time period t to the best practice technology frontier for the same time period, whereas the cross period distance function measures the radial distance of an output observation for time period t to the best practice technology frontier for the time period t+1. In this context, the productivity indicates the potential increase of outputs, given the level of inputs. Likewise, energy efficiency indicates the potential reduction of energy inputs, given the level of outputs and non-energy inputs. Environmental performance indicates the potential reduction of undesirable outputs, given the level of outputs and inputs.

3.2 Measurement of energy efficiency

In the energy efficiency literature there are two widely used approaches. One is stochastic frontier analysis (SFA), which uses econometric models to estimate a frontier and measure efficiency. The other is data envelopment analysis (DEA), which calculates efficiency by solving mathematical programming models. The following sections will discuss these two approaches further.

3.2.1 Stochastic Frontier Analysis

Paper I uses the SFA method to carry out the analysis. SFA originated in two seminal papers: Meeusen and van den Broeck (1977) and Aigner, Lovell and Schmidt (1977). The main advantage of using SFA is that statistical noise and energy efficiency can be distinguished. Hence, for example, omitted variables are more likely to be captured by the statistical noise term, and the estimated efficiency would potentially be close to the "real" level. Most commonly, the statistical noise is assumed to have normal distribution, whereas the inefficiency component is assumed to be a one-sided, non-negative distribution. The half normal and exponential distributions are usually assigned to the inefficiency component, since they are single-parameter distributions and can be easily estimated using the maximum likelihood estimation (MLE) procedure. There are a few studies that adopt more flexible but complex distribution assumptions. For instance, Stevenson (1980) proposes a gamma and a truncated normal distribution, and Lee (1983) proposes the four-parameter Pearson family of distributions. In paper I, the statistical noise term is assumed to have normal distribution and the energy inefficiency component is assumed to have truncated normal distribution.

When using a panel dataset in the empirical analysis, it is necessary to consider issues such as heterogeneity. Paper I therefore adopts Greene's (2005a, 2005b) 'true' random effects (TRE) model. This is a stochastic frontier model with a firm-specific random term that captures time-invariant cross-firm heterogeneity. A crucial assumption is that the time-invariant term is not correlated with any other term in the model. One issue with the TRE model is that any time-invariant (energy) inefficiency will be captured by the "heterogeneity" term rather than the time-variant inefficiency term.[7] Nevertheless, as explained by Greene (2005a, 2005b), this is an empirical question, and whether the time-invariant effects really belong to the inefficiency is debatable. Another issue is the parameter identification of the three-part disturbance. A maximum simulated likelihood estimation is therefore utilized: averaging the likelihood function over sufficient draws from the distribution of the time-invariant term will generate an adequately accurate estimate of the integral form of the likelihood function and allow for identification of the parameters. Paper I adopts this algorithm.

Energy efficiency in paper I is obtained by estimating a single energy demand frontier (see, e.g., Filippini and Hunt, 2011).[8] In this case the estimated energy efficiency potentially includes both technical and allocative inefficiencies. However, as discussed by Schmidt and Lovell (1979), the sign of allocative inefficiency can be either positive or negative, which corresponds to whether the observed input is overused or underused. Thus, if the allocative inefficiency is negative and its absolute value is larger than the positive-definite technical inefficiency, this would imply that the observed energy

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[7] The TRE model is very similar to Kumbhakar and Hjalmarsson's (1993) random effects model. In their paper, Kumbhakar and Hjalmarsson obtain the estimator in two steps. First, the parameters of the variables in the frontier are estimated using within groups OLS or feasible two-step GLS. Second, the MLE is adopted to estimate the variances of the statistical noise and inefficiency. According to Kumbhakar and Lovell (2000), the advantage of this procedure is that there is no need to impose the distribution assumption until the MLE step. One issue with this method, similar to the issues with Greene's (2005a, 2005b) method, is that any time-invariant component of technical inefficiency is captured by the fixed effects rather than the real inefficiency term. See the detailed discussions in Heshmati and Kumbhakar (1994) and Kumbhakar and Heshmati (1995).

[8] Schmidt and Lovell (1979) and Kumbhakar and Lovell (2000) obtain the input-specific technical and allocative efficiencies separately by estimating the cost frontier together with all the input demand frontiers. This approach satisfies the theoretical restriction imposed by production theory, i.e., it measures the technical and allocative efficiencies of firm A** in Figure 1. Additionally, the estimation of the system equations (cost frontier and input demand frontier) allows the allocative efficiency to be different for each input.

consumption is underused, or in other words that the actual energy consumption level is even lower than the optimal energy demand level. This can be illustrated in Figure 1. Assume there is an inefficient firm B that consumes an amount E^B of energy. Obviously, E^B is smaller than E^{A**} (the optimal energy demand level). Improvement in the energy efficiency of firm B requires a reduction in the non-energy input, but an increase in the energy input. This result is somehow counterintuitive, since the intention of energy efficiency measurement is to identify the potential energy saving possibilities. Nevertheless, the case mentioned above will be identified as "wrong-skewness" in the empirical estimation, since the energy inefficiency component[9] in the model of paper I is always positive-definite. That is, if there is a valid estimate of the inefficiency components, this indicates that the energy inefficiency is either merely technical inefficiency, or contains both technical and allocative inefficiencies but with the former being dominant. Thus, the interpretation of the potential improvement in energy efficiency (indicated by the estimated energy efficiency) in paper I would stay in line with the notion of energy conservation; that is, improving energy efficiency would imply reducing energy consumption.

3.2.2 Data Envelopment Analysis

DEA, introduced by Charnes, Copper, and Rhodes (1978), utilizes the linear programming technique to measure the relative efficiency of a set of Decision Making Units (DMUs). A main advantage of using the DEA approach is that it does not require a particular functional form for the technology frontier to be specified. Thus, the model misspecification problem could be avoided. Additionally, there is no need to impose any distributional assumptions on a DEA model. This property highlights a disadvantage of the DEA approach compared with the SFA method: the estimated efficiency potentially includes statistical noise.

There are quite a number of studies that use DEA to estimate energy efficiency: see, for example, Ramanathan (2000), Hu and Wang (2006), Azadeh, Amalnick, Ghaderi, and Asadzadeh (2007), Mukherjee (2008a, 2008b), Shi, Bi, and Wang (2010), and Bloomberg, Henriksson, and Lundmark (2012). However, none of these studies takes into account undesirable outputs. Undesirable outputs are the by-products of desirable outputs in a production process. Paper II therefore adopts the joint production framework of Färe, Grosskopf, and Pasurka (1986) and Färe et al. (1989), which includes both desirable and undesirable outputs, to estimate energy efficiency. Most of the previous studies that consider the undesirable outputs, however, focus on the estimation of overall productivity. The work by Zhou and Ang (2008) is

[9] The energy inefficiency component includes both technical and allocative inefficiencies.

probably the first to use a joint production DEA model to estimate energy efficiency.[10]

The issue regarding the so-called weak disposability assumption of the joint production framework is worth noting. The weak disposability assumption applies to desirable and undesirable outputs, meaning that it is costly to dispose of undesirable outputs and that desirable and undesirable outputs can only be reduced proportionally (Färe et al., 1986, 1989). Nevertheless, Coelli, Lauwers, and van Huylenbroeck (2007), Førsund (2009) and Murty, Russell, and Levkoff (2012), for example, have pointed out that the weak disposability assumption seems to be inconsistent with the material balance principle. The weak disposable technology allows decrease of both desirable and undesirable outputs while keeping the input constant, which is not compatible with the material balance principle.

However, as Coelli et al. (2007) mentioned, the violation issue does not exist if the desirable outputs contains zero bad material. For example, if the electricity is generated using coal, the desirable output (i.e., electricity) contains no bad material (such as sulfur). Another exceptional condition that satisfies the material balance principle is that the abatements are made on undesirable outputs (see e.g., Førsund, 2009; Murty et al., 2012). In papers II and III, where the weak disposability assumption has been imposed, the desirable output does not contain any SO_2 or NO_X. Further, the SO_2 and NO_X are measured after abatement. Therefore, the weak disposability assumption in this thesis does not violate the material balance principle.

3.3 Measurement of firm performance

Productivity measurement is an important research topic in DEA. A commonly adopted productivity measurement in the DEA literature is the Malmquist productivity index, which was introduced by Caves et al. (1982a, 1982b). This index was further developed in the context of performance assessment by Färe et al. (1989). It measures the productivity change over time and can be multiplicatively decomposed into technological change and efficiency change components. Färe et al. (1989) integrated Farrell (1957)'s efficiency measurement into Caves et al.'s (1982b) productivity measurement to construct a Malmquist productivity index based on DEA.

The metrics of firm performance in paper III are calculated using Färe et al. (1989)'s Malmquist type of indexes of productivity, energy efficiency and environmental performance. DEA models are utilized to calculate the distance functions that make up the Malmquist indexes. The distance functions for

[10] In their model, however, each energy input is reduced at different proportion. Hence the substitutability between energy inputs would also be captured in the energy efficiency estimation. In paper II, the reduction proportion of the reduction of each energy input is the same, which guarantees a pure technical energy efficiency estimate.

productivity and energy efficiency are constructed according to Shephard (1970), and the distance function for environmental performance is constructed according to Tyteca (1997), who adopts Färe et al.'s (1986, 1989) joint production framework.[11] The distance functions are calculated within and across periods. The within period distance function estimates the productivity/energy efficiency/environmental performance in time period *t* (or *t*+1) using the technology of time period *t* (or *t*+1); whereas the across period distance function estimates the productivity/energy efficiency/environmental efficiency in time period *t* (or *t*+1) using the technology of time period *t*+1 (or *t*). According to Färe et al. (1989), a Malmquist index that is greater than, less than or equal to 1 indicates, respectively, progress, regress or no change in productivity/energy efficiency/environmental performance.

The Malmquist index can be calculated in other ways. For instances, the index can be calculated using Aigner and Chu (1968)'s parametric linear programming approach, or Fecher and Perelman (1989)'s econometric approach. It would be of interest to apply these methods in future research.

3.4 Data overview

The empirical analyses in this thesis are carried out using a firm-level panel dataset that includes 14 Swedish industrial sectors and covers the years 2000 to 2008. The 14 sectors are pulp and paper, iron and steel, chemical, stone and mineral, mining, machinery, fabricated metal products, rubber and plastic, electro, motor vehicles, printing, wood products, textiles, and food. The three largest energy-consuming sectors in Swedish industry are the pulp and paper, iron and steel, and chemical sectors. By 2013, they consumed 51%, 16% and 9% of the industry's final energy, respectively (Swedish Energy Agency, 2015). The data for the variables used in the empirical analyses are collected and offered by Statistics Sweden (Swedish: Statistiska centralbyrån, SCB). All monetary values are in 2008 SEK.

The dataset contains information about non-energy inputs (labor and capital), energy inputs (electricity, coal, oil, gaseous fuel, biofuel, district heating), produced output (indexed), and undesirable outputs (CO_2, SO_2, NO_X). The capital stocks are calculated using gross investment data (excluding investments in buildings) and the perpetual inventory method.[12] The wood and the pulp and paper sectors use a considerable amount of biofuel, but for most

[11] Kumbhakar and Tsionas (2016) propose a novel approach that uses a SFA method to estimate environmental efficiency. A by-production framework, which comprises both desirable and undesirable production technologies, is utilized to analyze an environmental production process. Thus, the environmental efficiency measurement is well grounded in production theory. Additionally, there is no need to impose the weak disposability assumption.

[12] The capital depreciation rate is assumed to be 0.087 for all firms and sectors in manufacturing, as suggested in King and Fullerton (1984) and Bergman (1996).

sectors this fuel is insignificant or not used at all. Produced output is derived from sales data, and is calculated as sales divided by a sector-specific Producer Price Index (PPI). The dataset also contains information about policy and policy-related measures: Swedish carbon dioxide and energy taxes; the EU ETS (identification of participation); R&D; and environmental investment in air pollution. The dataset covers the first trading period and the first year of the second trading period of the EU ETS (2005-2008). The carbon tax for Swedish industrial firms that are included in the EU ETS has been gradually phased out since 2008. In the first trading period, however, the carbon tax was still functional.

The empirical analyses in papers I to III, however, are carried out using different sample periods for the dataset. Paper I uses the period from 2000 to 2008, which contains data on 4,297 firms. Paper II utilizes the sample that covers the years 2001-2008, which contains data on 3,066 firms. The reason for choosing these sample periods is that the R&D variable, which is considered as an energy efficiency determinant factor in the regression analysis, only has observations from 2001 onwards. Paper III uses the dataset covering the years 2002-2008, which contains data on 517 firms. The reason for choosing this sample period is that the environmental investment data have been collected since the year 2002. The rather small number of observations in the sample is due to the “two consecutive years” selection criterion for the Malmquist index calculation.

4 Conclusion and future research

The main result is that there is considerable potential to improve the energy efficiency of Swedish industrial firms over the sample period studied. The EU ETS and the Swedish carbon dioxide tax do not seem to create any significant energy-saving incentives. This is partly due to the relatively low permit price in the period of study. Also, the effective carbon dioxide tax rate, after exemptions and other special rules, may have been too low to incentivize energy conservation. The Swedish energy tax, on the other hand, significantly motivated energy efficiency improvements. The results also show that sectors that consume a relatively small amount of energy tend to have lower energy efficiency, which suggests that the relevant policies should not ignore these sectors. Finally, it is found that a managerial strategy that emphasizes energy efficiency improvements is likely to start a positive chain of events: it facilitates productivity growth, reduces the environmental burden, and leads to environmental investments. However, for the environment–productivity relationship, it is hard to achieve the "win-win" outcome that has been suggested by Porter and van der Linde (1995). The analysis shows that being more environmentally efficient comes at the cost of lower productivity in the next period.

Measuring energy efficiency has been the core of this thesis. Another interesting topic in the energy efficiency area is the rebound effect. The rebound effect is the phenomenon of the expected energy saving targets eventually being partially or fully offset. It occurs because the energy efficiency improvements make energy relatively cheap, and therefore create incentives to consume more energy. In this context, the energy saving targets would be challenged by improved energy efficiency. Future research could be carried out to measure the magnitude of the rebound effect in Swedish industry, and the results would be expected to allow some policy implications to be drawn, such as whether the energy efficiency policy is effective.

5 Summary of the papers

This thesis contributes to the literature on energy efficiency and firm performance. It is the first study to measure firm-level energy efficiency across the whole Swedish industry and to assess the impacts of climate and energy policies such as the EU ETS, the Swedish carbon dioxide and energy taxes, etc. It is also the first study to provide a comprehensive Swedish industrial firm performance measurement, and to examine the causal and dynamic relationships between firm performance and environmental investment. A summary of the papers is presented below.

5.1 Industrial energy demand and energy efficiency – Evidence from Sweden (Paper I)

The main objectives of this paper are: 1) measuring energy efficiency; and 2) assessing the impacts of efficiency determinants. The concept of an input demand frontier suggested by Schmidt and Lovell (1979) and further described in Kumbhakar and Lovell (2000) is utilized to represent the energy demand at the firm level. Accordingly, energy demand frontiers for fuel and electricity are derived from a Cobb-Douglas (C-D) production frontier by minimizing the cost. The derived frontiers therefore define an optimal fuel/electricity demand at the least cost of a best-practice technology. In this framework, energy efficiency is encompassed in the demand frontier, and the estimated energy efficiency indicates how far energy can be further reduced for the given levels of output and non-energy inputs. The empirical demand frontier is formulated following Filippini and Hunt (2011). It is a conditional energy demand function that defines the minimum levels of energy input required to produce a certain amount of output, given a C-D technology and input quantities and prices. The derived energy demand frontier inherits the properties of a C-D production frontier. The rationale for specifying a C-D production frontier is the ease of tractability and of the interpretation of estimates. Also, the C-D specification has the merit of simplicity in deriving the demand frontier

(Kumbhakar & Lovell, 2000). A time trend term is included to capture the Hicks-neutral technological change.

A conditional energy inefficiency component of the demand frontier describes the impacts of energy efficiency determinants. The Battese and Coelli (1995) single-stage approach is utilized to obtain the estimates of energy efficiency and the efficiency determinants simultaneously.

The empirical analysis is carried out using a firm-level, industry-wide panel dataset containing 4,297 Swedish industrial firms for the period 2000 to 2008. Given the technical heterogeneity across sectors, the analysis is carried out in each sector separately. Greene's (2005a, 2005b) "true" random effects SFA model is adopted to capture time-invariant heterogeneity across firms. Thus, the estimated energy efficiency is time-variant and firm-specific. This is the first study in the SFA literature to analyze firm-level, industry-wide energy efficiency and the impacts of efficiency determinants.

The energy efficiency estimates for Swedish industrial firms indicate that there is considerable potential to improve fuel/electricity efficiency, and particularly fuel efficiency. This implies that energy conservation policy has had a larger impact on electricity use, and leaves fewer possibilities for further improvement. The results for the efficiency determinants show that the EU ETS has had a positive but not significant impact on energy efficiency (especially on fuel efficiency) in many sectors. One possible explanation for this non-significant impact could be that the ETS permit price was too low to motivate energy-saving efforts during the period of the study. The results also indicate that firm size matters. Middle- and large-sized firms, compared to small-sized ones, tend to use fuel/electricity more efficiently.

A correlation test between energy efficiency and energy intensity suggests that the latter is not a good proxy for the former, which is consistent with the conclusions in Filippini and Hunt (2011, 2012) and Filippini, Hunt, and Zoric (2014). In fact, the correlation test results imply that decreases in energy intensity can be at best be related to small increases in energy efficiency.

5.2 Energy efficiency in Swedish industry: A firm-level data envelopment analysis (Paper II)

The main purpose of this article is (again) to measure energy efficiency in Swedish industrial firms. A non-parametric approach that considers both desirable and undesirable outputs is adopted to estimate energy efficiency. In addition, the study, as for paper I, also focuses on investigating the impacts of energy efficiency determinants.

The empirical analysis is carried out in two steps. In the first step, firm-level energy efficiency is estimated by sector and by year using DEA techniques. The measurement of energy efficiency is grounded in Farrell (1957), who estimates the maximum possible proportional reduction of energy inputs to produce the given level of outputs without requiring any additional amount of other inputs. To take into account undesirable outputs, the DEA model is formulated according to the joint production framework proposed by Färe et al. (1986, 1989). In the second step, the impacts of efficiency determinants are evaluated by regressing the DEA efficiency scores on a set of explanatory variables. Since the efficiency scores are calculated rather than observed, and moreover there is a serial correlation issue in relation to the calculated scores, a modified input-oriented double bootstrap procedure based on that of Simar and Wilson (2007) is employed to yield consistent regression estimates and provide valid inferences.

With a panel dataset consisting of 3,066 firms in 14 Swedish industry sectors for the period 2001-2008, it is possible to assess firm-specific energy efficiency for the whole industry. The energy efficiency is calculated based on separate frontiers for each sector and for each year. The regression analysis is carried out at the industrial level. There are two reasons for having a single regression model. The first is that for some sectors such as textiles, there are no ETS firms at all. The second reason is that if the regressions were carried out separately, the coefficient estimates might have opposite signs in different sectors, thereby increasing the complexity of explaining the effect of policy measures (this is a different approach to that followed in paper I). In the single regression model, sector and year dummy variables are included to capture the heterogeneity across sectors and years.

The contributions of this paper can be described from two aspects. One is that it is the first study to measure firm-level industry-wide energy efficiency by using a joint production framework DEA model. The other is that it is the first study to evaluate the impacts of energy efficiency determinants in the second-stage regression analysis by utilizing a modified, input-oriented version of Simar and Wilson's (2007) double bootstrap procedure. Estimates of energy efficiency show that there is considerable potential to improve energy efficiency in Swedish industry, as is also shown in paper I. It is noteworthy that the industries that consume less energy have lower energy efficiency. To achieve the ambitious Swedish energy efficiency improvement target, a policy implication would be that some attention should be paid to the less energy-dependent industrial sectors. The results of the regression analysis show that the EU ETS and the Swedish carbon dioxide tax have had a positive impact on energy efficiency, but not a significant one. The moderate impact is likely to have been due to the fairly low ETS permit price and carbon dioxide tax rate, and the small share of fossil fuel (about 30%) used for energy in industry. This result indicates that if the EU ETS or the carbon tax (or both) are to be used as an instrument to motivate industrial firms to improve energy efficiency, the actual price that is placed on the fossil energy must be sufficiently high for incentives to be created. The insignificant impact of the EU ETS corroborates the finding in Lundgren et al. (2016) (paper I). Last but not least, large-sized firms, compared with small-sized ones, tend to have higher energy efficiency, as was also found in paper I.

5.3 Environmental investment and firm performance: A panel VAR approach (Paper III)

This paper seeks empirical answers to the question of how three dimensions of firm performance – productivity, energy efficiency and environmental performance – interact with environmental investment. More specifically, would improvement in energy efficiency foster productivity growth? Are energy efficiency enhancement and environmental performance improvement positively associated? Do environmental investments – driven by regulation and/or corporate social responsibility (CSR) – facilitate productivity growth?

To answer these questions, the analysis assesses firm performance using Malmquist-type indexes. Thus, metrics of firm performance are well grounded in production theory, and represent changes in productivity, energy efficiency and environmental performance. In the second step, a panel vector auto-regression (pVAR) model is utilized to examine the causal and dynamic relationships. The estimated Malmquist indexes are corrected using Simar and Wilson's (1999) bootstrap procedure, and then used in the regression analysis. This paper is the first study to investigate causal and dynamic linkages between three dimensions of firm performance and environmental investment, at firm-level and across all industry sectors.

The empirical analysis is carried out using a panel dataset for Swedish industry that contains 1,966 observations for 517 firms for the period 2002-2008.

Regarding the firm performance measurements, the results show that during the periods studied, on average, the productivity of Swedish industrial firms improved in many consecutive years but that the growth rates were moderate. Variations in energy efficiency and environmental performance were relatively small. Regarding the estimation results of the regression analysis, one finding is that environmental performance and energy efficiency are positively associated. Another finding is that a previous increase in environmental investment induces a current energy efficiency improvement, signifying that such investment may primarily be directed towards conserving energy. What is more, energy efficiency and productivity are also positively associated. In particular, energy efficiency in the previous period seems to facilitate current productivity growth, emphasizing the potential cost-saving value of energy conservation.

Furthermore, the results show that improving environmental performance and/or increasing environmental investment – which could be driven either by environmental regulation or by CSR – is not free, and will, at the very least, generate a burden for productivity growth in the next period. In particular, if this improvement in environmental performance and/or increase in environmental investment is induced by environmental regulation, the result does not support the Porter Hypothesis. Finally, an increase in environmental investment in the previous period improves current energy efficiency, and, in turn, the improved energy efficiency will tend to boost productivity, environmental performance and investment in the next period. As a consequence, it is possible to plan an effective environmental investment strategy that could facilitate productivity if channeled via cost-saving energy efficiency improvements.

The main conclusions are, from a management perspective, that a managerial strategy that emphasizes improvements in energy efficiency is likely to start a positive chain of events; and, from a policy perspective, that the anticipated "win-win" outcome posited by Porter and van der Linde (1995) cannot be validated by the results.

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