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By **Elena Verdolini**, Fondazione Eni Enrico Mattei

Nick Johnstone, OECD Environment Directorate

Ivan Haščič, OECD Environment Directorate

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Summary

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Keywords: Fossil Fuel Electricity Generation, Energy Efficiency, Carbon Intensity, Technological Change, Patents

JEL Classification: Q40, O33, O13

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Address for correspondence:

Elena Verdolini
Fondazione Eni Enrico Mattei
C.so Magenta 63
20123 Milan
Italy
Phone: +39 02 520 3692
E-mail: elena.verdolini@feem.it

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E. Verdolini,[1] *Fondazione Eni Enrico Mattei*
N. Johnstone, *OECD Environment Directorate*
I. Haščič, *OECD Environment Directorate*

Abstract

This paper provides an empirical analysis of the determinants of energy efficiency in fossil fuel electricity generation across 28 OECD countries over the period 1981-2006, with particular attention to the role played by technological development and the availability of energy efficient technologies in the market. This contribution is novel in three respects: first, empirically assess the effects of different determinants of energy efficiency, which include the input mix in electricity generation, the capacity ratio at which power plants are run, as well as the characteristics of the production technology. Second, we focus on the role of technological availability: using patent data for carefully selected innovations in fossil-fuel technologies, we build an indicator which proxies for technological developments in fuel-efficient electricity generation. Third, by formalizing the relationship between fuel efficiency and carbon intensity, we assess the impact of changes in the input mix and in technological availability on CO_2 emissions in the electricity sector. Results show that input mix, capacity utilization and new investment in capacity play a significant role in increasing energy efficiency. Increasing the stock of available technologies (or stock of knowledge) is also associated with higher efficiency levels. Given the link between increased efficiency and lower CO_2 emissions, we conclude that technological change has a negative and significant effect on carbon intensity, while the changing input mix affects CO_2 intensity both through an increase in efficiency as well as by lowering the input-weighted emission factor.

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[1] Corresponding author: Elena Verdolini, Fondazione Eni Enrico Mattei (FEEM), C.so Magenta 63, 20123 Milan, Italy. Email: elena.verdolini@feem.it. Tel. +39 02 520 3692.
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1. *Introduction*

A number of studies reach the conclusion that unless significant global policy action is taken, anthropogenic CO_2 emissions are bound to growth rapidly, oil and gas prices will be high (relative to coal prices) and energy security concerns will increase. Curbing the rising CO_2 emissions and decoupling economic growth from energy use will not come free of charge. Lower emissions achieved at the cost of reduced economic growth will negatively impact the standards of living, especially in those countries where they are already quite low. In light of this, it is important to target abatement options first in those sectors where the potential for CO_2 emission reductions is higher and the marginal cost of abatement is lower.

The Energy Technology Perspective (ETP) report (IEA 2010) shows that the electricity sector has these characteristics. Policy intervention to reduce CO_2 emissions linked with the production of electricity could account for up to 47% of emissions reductions necessary to meet the BLUE Scenario target, namely a halving of emissions with respect to 2005 levels by 2050. Among the different options to lower CO_2 emissions from electricity generation, energy efficiency in production is claimed to be among the least costly options: together with fuel switching, it could contribute 5% to achieving the BLUE scenario.[2] Moreover, energy efficiency would not only address environmental concerns, but also increase the security of supply by lowering the dependence from imported fossil fuels.

In this paper, we study efficiency of fossil fuel based technologies for the production of electricity. This contribution is important for several reasons: first, given the key role of the electricity sector in the global effort to reduce CO_2 emissions, understanding the dynamics of fuel efficiency and its determinants is important to validate the assumptions made about the rate and direction of its change. Second, a number of factors are commonly indentified as affecting electricity production efficiency from fossil fuel inputs. These include the choice of fossil-fuel employed in production, the capacity ratio at which the power plants are run and the specific technology used for production. The few studies currently available on this topic are either limited to a single country, or include only descriptive analyses without empirically testing the contribution of the different determinants of fuel efficiency.

Last, but not least, we devote particular attention to constructing new indicators to proxy for technological availability, which we include in the empirical estimation. This is to our knowledge the first attempt to link technological change (TC) in the energy sector to actual efficiency improvements (and emission reductions). Most of the literature on TC is focused on innovation and its determinants. However, to significantly reduce anthropogenic CO_2 emissions, technological change needs to affect not only the production of ideas, patents and blueprints, but also the efficiency with which goods and services are produced. We explore this topic focusing on the fossil-based electricity sector. As a result,

[2] Other options to lower CO_2 emissions from the power sector include coupling coal and gas with CCS, co-firing of fossil inputs with biomass, and switching to non-fossil electricity sources such as wind, solar, or nuclear power.

we can examine the importance of technological change as a driver of production efficiency as compared to other important factors such as input mix and capacity utilization. This will shed light on the relative contribution of knowledge and technological availability and will help simulate future efficiency increases.

This paper presents several important conclusions: first, as expected, it shows that fuel efficiency is negatively correlated with increases in the share of coal over total fossil fuel input, but positively correlated with higher capacity utilization levels and with new investments in power plants. Moreover, those countries where technological availability is higher consistently show higher levels of fuel efficiency in electricity generation. The estimated coefficient is however fairly small. This calls for some caution when considering the possibility that TC might significantly increase fuel efficiency in the future.

In addition to analyzing the dynamics of fuel efficiency, we also consider the effect of technological development on carbon intensity. Given the relationship between efficiency and carbon intensity of the electricity sector, technological change has a negative and significant, although small, effect on carbon intensity. Finally, we show that changes in the input mix affects carbon intensity in two ways: on one hand, a lower share of coal over total fossil fuels leads to higher fuel efficiency. On the other hand, it also reduces the input weighted emission factor. In both cases, the effect translates in lower carbon intensity of electricity production.

The paper is organized as follows: Section 2 explains more in detail the potential contribution of the electricity sector to decreased carbon intensity. Section 3 contains a review of the literature on the electricity sector, which points to the abundance of sectoral studies, but to the lack of attention for fuel efficiency dynamics. Section 4 defines fuel efficiency, provides descriptive statistics for the 28 countries included in the analysis and identifies the determinants of efficiency as well as the relationship between efficiency and carbon intensity. Section 5 describes the data and methodology used to build the indicator of technological change. Section 6 presents the result of the empirical estimation on fuel efficiency and describes emission intensity dynamics. Section 7 concludes.

2. The Electricity Sector and Fuel Efficiency

This section summarizes recent results both on the role of the electricity sector in increasing future CO_2 emissions in a "no policy scenario" and on its potential for CO_2 reductions under appropriate policy. The ETP report (IEA 2010) shows that in a Business as Usual (BAU) scenario, CO_2 emissions by 2050 will nearly double. Higher emissions are the result of economic growth and continued reliance on coal and gas both for electricity production and on oil for transportation. Without policy intervention to address climate change concerns, by 2050 not only will primary energy use rise by 84%, but its carbon intensity will also increase by 7%, indicating that decoupling of economic activity from energy use will not take place.

Currently, the electricity sector accounts for 32% of total fossil fuel use and 41% of energy related CO_2 emissions. Until 2050, electricity will be the one of the fastest-growing component of total demand and will reach levels 134% higher than in 2007 (IEA 2010). The expected rise in electricity demand is the result of rapid electrification of households in developing countries and of industrial processes around the world. Two thirds of the increased electricity demand will be met with fossil fuels.[3] As a result, emissions from the electricity sector will increases and the increase in fossil fuel based generation capacity will most likely lock the world into a highly carbon intensive path.

Significant global policy action is called for to counter these trends. With appropriate incentives in place, this sector can turn from one of the largest contributor to rising emissions into a sector that would achieve 44% of emissions reductions necessary to meet reduce emissions by 50% in 2050 with respect to 2007 levels. Means envisioned to achieve the reduction in CO_2 emissions from electricity production include (1) improving the energy efficiency of the energy-intensive industrial sectors and of consumer appliances, (2) reducing the emission intensity of electricity generation (de-carbonization) through either substitution of fossil fuels with nuclear and renewable energy sources or the deployment of carbon capture and storage (CCS), and (3) increasing the fuel efficiency of electricity production from fossil fuels.

The first two of these options face significant challenges. First, increased efficiency of the energy intensive sectors and of household appliances might not reduce overall electricity demand, as rebound effects can increase the overall electricity demand as a result of increased efficiency. Second, a drastic decarbonization of the energy sector and fast shift towards renewable and nuclear electricity production seems unlikely: fossil-fuels are currently the main input for electricity generation, with coal accounting for more than half of their share (IEA 2010). The life of capital stock (fossil fuel power plants) is very long. Other significant barriers to the widespread deployment of non-fossil energy sources are plant safety, radioactive waste disposal and proliferation concerns for nuclear power, and the restructuring of distribution systems necessary to integrate large amounts of electricity coming from intermittent renewable sources. In many cases, the deployment of renewable energy plants also meets the resistance of local communities (e.g. wind power).

Given that fossil fuels are likely to remain a main input in electricity production, an important component of any CO_2 emissions reduction strategy will be the ability to increase the efficiency of fossil-fuel plants. This is an attractive option also to improve energy security. In addition, energy efficiency is particularly relevant for the deployment of CCS: capturing and storing carbon is an energy-intensive process that reduces the net output of power plants. The application of this technology to plants with low efficiency is not economically viable.

[3] Coal-based electricity generation is predicted to increase by 149% above 2007 levels, and will account for 44% of all electricity generation.

It is thus extremely important to fully understand its dynamics and determinants. Fture scenarios presented so far are based on the assumptions of optimal behavior on the side of the economic agents. In some cases, such as the widespread deployment of renewable technologies or nuclear, these assumptions cannot be tested, as data on past performance is still limited. In the case of increased efficiency of the electricity sector, on the other hand, such an analysis is indeed possible: fossil-fuel technologies have not only been used for many years, but their efficiency also increased significantly over time. In addition, there is a good availability of data that allows studying fuel efficiency for electricity generation in a cross-country setting. A clear understanding of fuel-efficient dynamics will help designing sound policies to address the issue of raising CO_2 emissions.

The recent literature recognizes the importance of fossil fuel efficiency in electricity generation, and a few recent studies on this topic are available. These contributions are however of a descriptive nature: even if fuel efficiency in fossil-fuel generation is compared across countries, these differences are not quantitatively explained and the effects of those determinants that are traditionally indicated as driving the dynamics of fuel-efficiency in fossil-fuel electricity generation are not assessed. The next section summarizes the literature focusing on the electricity sector and points to this lack of empirical evidence.

3. Literature Review

Measuring technological change and efficiency improvements in the process of thermal power production has been the focus of economic research since the 1960s. This sector represents an ideal case study. First of all, technological change in the sector has been fast and made possible by developments in metallurgy which increased the size of generating units, their pressure and temperature, and introduced the use of reheat cycles in boilers (Belinfante 1978). Secondly, electricity production has the perfect characteristics to study technological change: the output of the production process is homogenous, and measurable in physical amounts, limiting the need to control for product quality in empirical studies.

Since the 1960s, most of the studies on the productivity of the electric industry focused on the generation stage, due to larger data availability and to its high share in the total costs of production. Initially, most of the research was carried out using data for the electricity sector in the USA. Subsequently, the focus shifted from the USA to other countries, Britain and Australia first, and the rest of Europe later. Two main approaches can be distinguished in the empirical literature: studies focusing on total factor productivity and those based on measures of partial productivity, such as GWh per unit of labor or per unit of capital. Most econometric studies of the power sector were primarily aimed at investigating input substitution possibilities, scale economies and technological change. Other relevant topics for the literature on the electricity sector were the impact of rate of return regulation and of environmental controls on the productivity and efficiency of electricity production. Subsequently, changes in the market structure of the electricity sector and in the ownership of utilities allowed the comparison of the efficiency and productivity of government versus privately owned utilities (see Abbott

2005 for a review of the literature). More recently, interest in the energy transformation sector was spurred by its relevance with respect to greenhouse gas emissions and climate change issues.

The first attempt to measure productivity in the electricity industry was set out by Kendrik (1961), who related electricity output measures to labor and capital inputs. He estimated that in the USA total factor productivity increased by 5.5% a year between 1904 and 1953. Barzel (1964) and Galatin (1968) modified the set of input demand functions to incorporate TC. Barzel (1964) introduced the capacity observed load factor as a regressor in his analysis, and tried to capture the contribution of technological change using dummy variables for different vintages. Galatin (1964) formulated a model in which he took explicit account of the mix of technologies and the degree of capacity utilization. Along these lines, Nelson and Wohar (1983) estimate total factor productivity growth in steam-electric generation for a sample of 50 privately owned utilities over the period 1950-1978. They decompose changes in TFP into components attributable to technical change, scale economies and regulatory biases to assess their relative contribution.

Among the multi-countries studies, Söderholm (1995; 2001) estimates short run interfuel substitution in West European power plants. He shows that although most of the substitution options between fossil inputs is *ex-ante* (before plants are built), there are also several possibilities for *ex-post* substitution. First of all, utilities own plants fuelled by different inputs and therefore can decide which input to burn (if capital utilization is less than 100%). In addition, at the plant level, multi-fired plants allow for burning of different fuels to produce electricity. It is in fact possible to modify a power plant based on coal so that it can burn also gas or oil in the short term and with low capital costs.[4] Thus a cost-minimizing electricity generating firm does have the ability to change its fuel input usage in response to changes in relative fuel prices in the short run.

The studies presented so far are very different from the one proposed here: first of all, they are mostly single country studies as opposed to having a multi-country focus. In addition, the production and productivity dynamics are studied at the micro level, with the unit of observation being either the single firm or the single plant. Moreover, they often employ different definitions of efficiency in electricity production, such as TFP or efficiency measures based on capital or labor inputs. Finally, these studies simply characterize technological development with the use of a trend or time dummies.

The studies that more closely related to this one are some recent analyses of fuel efficiency in OECD countries such as Graus et al. (2007), Taylor et al. (2008) and Graus and Worrell (2009). All these papers build indicators of fuel efficiency in fossil fuel electricity generation, present descriptive analysis of the development of efficiency over time across countries, and calculate the potential CO_2 emission

[4] Belinfante (1978) points out that plants are built to burn alternative fuels interchangeably upon short notice. The adaptation of coal plant to handle gas or oil is rather inexpensive, but the adaptation of a gas or oil plant to burn coal is on the other hand rather expensive and requires more time. Coal burning plant requires generally 10-15% more capital investment, primarily in coal ash handling equipment and more expensive design. See also Söderholm (1997; 1998; 2000; 2001).

reduction if electricity production plants in all countries operated at the higher levels of efficiency observed. In particular, Graus et al. (2007) compare fossil-fired electricity generation for Australia, China, France, Germany, India, Japan, the Nordic countries, South Korea, United Kingdom and Ireland, and United States. Taylor et al. (2008) perform a similar analysis for all OECD countries, while Graus and Worrell (2009) look at fuel efficiency in electricity generation in the EU-27 with particular attention to the age of fossil fuel power plants. In addition, they describe the changes in energy intensity of the sector over time in their sample.

In a similar vein, this contribution looks at the efficiency of electricity production across 24 countries in the period 1981-2007.[5] Compared to the analyses of Graus et al. (2007), Taylor et al. (2008) and Graus and Worrell (2009), this anlaysis is novel in three respects. First, we assess empirically the contribution of different determinants of fuel-efficiency. Second, we devote particular attention to the issue of technical change and technological availability. Using patent data for carefully selected innovative fossil-fuel technologies for electricity generation, we build an indicator which proxies for technological development in the field of electricity production. Therefore, we do not need to resort to a time trend (or time dummies) to measure technological changes. Third, by formalizing the relationship between fuel efficiency and carbon intensity of the electricity sector, we assess the impact of technological availability and changes in the input mix on CO_2 emissions of the electricity sector.

4. *Efficiency in Fossil-Fuel Electricity Generation: Definitions and Trends*

Measurement of fuel-efficiency in electricity production is less problematic than in the case of other industrial sectors. This is because both inputs (fossil fuels) and outputs (electricity) of the production process are highly homogenous compared to other industrial processes.[6] As a result, it is easier to compare performance of different power plants or countries since there is less concern about the issue of controlling for output quality.

In this paper, we define fuel efficiency in line with previous literature on the topic, namely Graus et al. (2007) and Taylor et al. (2008). In particular, fuel efficiency (E^{el}) is defined as the ratio between output of the power plants (P) and the amount of fossil fuel inputs (I) that are required to produce electricity.

$$E^{el} = \frac{P}{I} = \frac{EL + (H * s)}{I} \qquad (1)$$

[5] Countries included in this analysis are: Australia, Austria, Belgium, Canada, Czech Republic, Denmark, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Japan, Korea, Mexico, Netherlands, New Zealand, Norway, Poland, Portugal, Slovak Republic, Spain, Sweden, Switzerland, Turkey, United Kingdom, and the United States.

[6] Although there is variation in the calorific value both between fossil fuels (coal as opposed to gas) and within fossil fuel (hard coal as opposed to brown coal), fossil fuel inputs are still rather homogenous as compared to other production processes.

Note that electricity (*EL*) can be produced either in traditional power plants or in combined heat and power (CHP) plants, where heat (*H*) is produced alongside electricity. While the combined production of electricity and heat is more efficient in terms of primary energy than separate production of the two[7], the extraction of heat causes efficiency losses in the electricity production, which depend on the temperature at which the heat is extracted. We follow the literature and apply a correction facto (*s*) to account for such losses, as shown in equation (1)[8] where *EL* and *H* denote respectively electricity production and heat production from fossil-fuel inputs and *s* is the above-mentioned correction factor set equal to 1.75.[9]

Data on electricity and heat production as well as on fossil fuel inputs for the 24 countries included in this study are taken from the IEA Electricity Information database (IEA 2009). Figure 1 that there are widespread differences in efficiency of electricity production from fossil fuels across the countries in our sample. Moreover, fuel efficiency generally rose with the passing of time, being lower at the beginning of the observation period and higher at the end.

To identify the determinants of fuel efficiency in electricity generation, we take into consideration all those factors that are traditionally indicated in the literature. The first important factor that influences fuel efficiency is the composition of the fossil-fuel input mix: gas-fired plants achieve higher efficiencies than coal-fired plants due to the ability of the respective technology to extract the heat content of the fossil input (IEA 2010). As a result, the different levels of efficiency across countries can be in part attributed to different input mixes, and the increases in efficiency of power plants over time related to changes in the input mix of each country. Figure 2 shows how the input mix changed between 1975 and 2006 in the sample considered in our analysis. Over time oil has been displaced by gas as input for electricity production, while coal maintained its predominant role, accounting for the biggest share of fossil fuel input. Changes in the input mix are determined both by changes in the prices of various inputs as well as by the portfolio of electricity producing technologies, which include non-fossil sources. In our analysis, the share of coal over total fossil fuel inputs reflects these choices regarding energy inputs in a given economy.

Capacity utilization, measured as the ratio of actual to maximum potential output produced, is also one of the most important determinants of electricity production efficiency. Most plants achieve optimal fuel heat rates at capacity utilization ratios of around 80-90%, with a substantial deterioration of the heat rate for capacity utilization ratios of below 50%. Studies based on plant level data show that capacity utilization is higher for base-load plants (more commonly coal-fired) and lower for peak-load plants (more commonly gas-fired) that are turned on quickly in periods of high demand (Belinfante 1978).

[7] According to Ko and Dahl (2001), combining gas turbines with a series of steam generating units (combined cycle), although more capital intensive, can raise efficiency of gas over 50% because of reuse of waste heat. Coal has higher capital costs and needs to be stored and crushed. Moreover, particulate matters need to be removed.

[8] Electricity, heat and fossil fuel inputs are measured in TJ.

[9] We test the results with correction factors between 1.5 and 2.

Figure 1: Fuel Efficiency of Fossil-Fuel Electricity Production

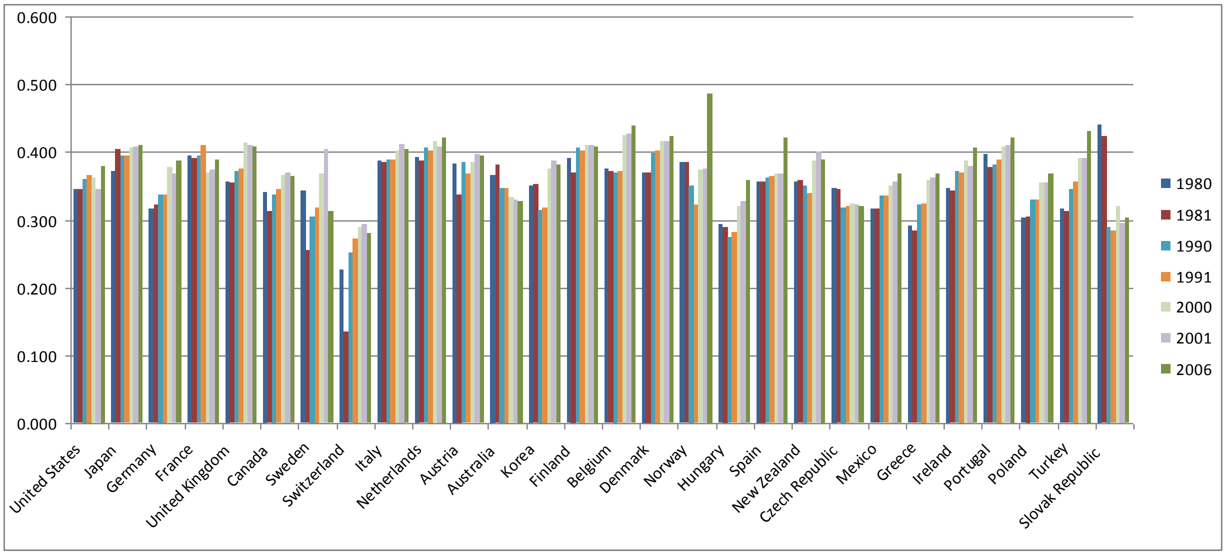
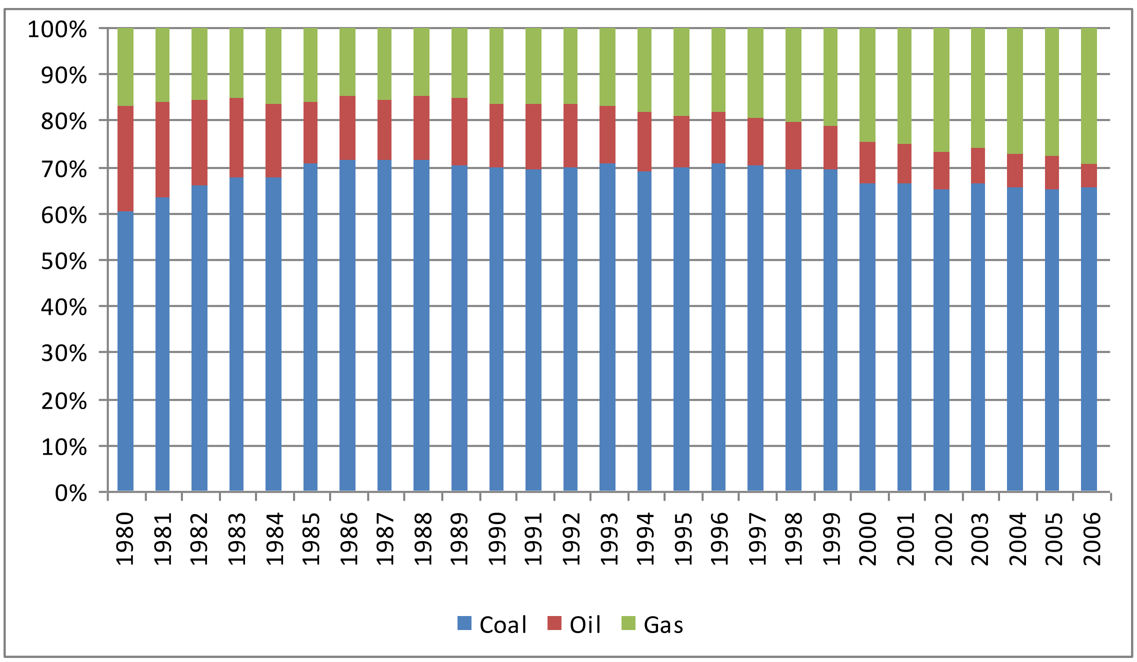


Figure 2: Global Input Mix, 1975-2006



At plant level, there is a clear positive relationship between utilization and efficiency since switching on a plant requires a lot of fuel. However, in an aggregate country level study such as the one presented here, we do not have the ability to control for the differences between capacity utilization at the plant level, for example between base-load and peak-load plants: We therefore need to resort to national aggregates. We define aggregate capacity utilization as the ratio between the electricity produced in a given year and the potential for fossil-fuel-based electricity production if all plants were operating at maximum capacity. This indicator measures a number of changes. First, low capacity utilization of fossil fuel plants at a country level may reflect reliance on other generation technologies, with implications for efficiency. Capacity utilization is lower for those countries, such as France and the Nordic countries, which rely more heavily than others on alternative fuel sources (respectively nuclear and hydro) for the base load, with coal-fired plants used as peak-load sources.[10] Aggregate capacity utilization also measures the fluctuations of demand for electricity over time: often relying on peak-load plants to meet highly fluctuating demand will result in lower aggregate capacity utilization, *ceteris paribus*.

A further important determinant of increases in fuel efficiency is technological change, or the availability of more efficient technologies on the market. Thermal efficiency improves over time as technology advances and firms invest in new capital or modify existing boilers (Considine 1999). In particular, plants of different vintages will achieve different efficiency levels, with newer plants being more efficient, for two reasons: on one hand, newer plants embody the latest available technology and will more likely have higher fuel efficiency; on the other hand, older plants have been used for longer periods of time and therefore their capital has in part deteriorated (Nelson 1984). Retrofitting can also significantly improve power plant performance and is especially convenient if the plant stock is relatively young: for instance, the case of Japan and China, where many plants are around 15 years old and, given a lifespan of 40 to 60 years, they will be in operation for another 25 to 45 years (IEA 2010).

To account for the improvements in technologies for electricity production, we include two proxies for technological development in our analysis. First, we use selected patent data to build several indicators of technological availability at the country level (see Section 4). Second, we account for improvements in fossil fuel technologies for electricity production by constructing a proxy for the capital stock in the electricity sector.

Based on the discussion of the determinants of fuel efficiency, we formulate the following log-log specification:

$$\ln E_i^{el} = \ln \frac{P_c + P_o + P_g}{I_c + I_c + I_g} = \alpha_1 + \alpha_{ShC} \ln IM_i + \alpha_{KS} \ln KS_i + \alpha_{CR} \ln CR_i + \alpha_V \ln V_i + \alpha_i \tag{4}$$

where *i* indicates a given country and the time suffix is suppressed for convenience. Fuel efficiency of electricity generation (E^{el}) is defined as in (1), and is a function of a function of the input mix (IM), vintage effects (*V*), the level of average national capacity utilization (*CR*) and the indicator of technological change (*KS*). Country fixed effects are included to control for any remaining country-

[10] For example, average capacity ratio for France over in the period 1981-2006 is 0.20 versus a 0.43 average capacity in the overall sample.

specific characteristics. Our expectations are that the share of coal over total fossil fuel will be negatively correlated with the level of fuel efficiency in a country, since coal based technologies are less efficient than gas based electricity generation. In addition, increases in installed capacity, higher levels of capacity utilization and greater availability of technology on the market should positively affect the level of fuel efficiency.

As said, data regarding electricity generation, fossil fuel inputs and capacity utilization are taken from the IEA Electricity Information database (2009). Capacity utilization (CR) is defined as (MWh/Mwe*8766) where MWh is electricity produced, Mwe is capacity installed and 8766 is the number of hours in a year. Wishing to control for the vintage effects of power plants in an aggregate analysis, we calculate the average age of a Mwe installed in any given country. The construction of the knowledge stock to proxy for technological development is explained in detail in the next section. To proxy for investment in capital stock in the electricity sector, we calculate the three year moving average in capacity increase.

Given the definition of fuel efficiency and the previous discussion on its determinants, it is important to point out two limitations of the present contribution. First, we cannot take into consideration some important determinants of fuel efficiency at the plant level, such as the cooling method or the outside temperature, which affect fuel efficiency of energy production. However, in the empirical analysis this is captured through the inclusion of country fixed effects. Second, we abstract from the contribution of labor to changes in fuel efficiency in power plants. This is dictated by the lack of appropriate data. However, in the fossil-fuel electricity sector, fuel efficiency improvements are less likely to come from learning-by-doing and from disembodied technical change than from embodied technical change and improvements in metallurgy and combustion. In addition, as pointed out in the literature, capital and fuel inputs make up the majority of the costs of electricity production.[11]

5. *Technological Availability of Fuel-Efficient Innovations*

To build an index proxying for technological availability we use information on patent applications relative to fossil fuel based efficient technologies for electricity production. Patents are a set of exclusionary rights (territorial) granted by a state to a patentee for a fixed period of time (usually 20 years) in exchange for the disclosure of the details of a given invention. Patents are granted by national patent offices on invention (devices, processes) that are judged to be new (not known before the application of the patent), involving a non-obvious inventive step and that are considered useful or industrially applicable. The use of patent data as proxy for innovation has a long history in the field of innovation economics. Griliches (1990) argues that patents are imperfect but useful indicators of inventive activity. Their main limitation is linked to the facts that not all innovations are patented, not

[11] For example, Cowing (1974) suggests that in a usual plant fuel, capital and labor proportions in total costs are respectively 50%, 40% and 10%. According to Belinfante (1978), for the USA the average shares of total cost of production are 49% fuel, 39% capital, operation labor 7% and maintenance 5%. Fuel cost for a typical firm is about 80% of total variable generation costs, including expenditures on coal, natural gas and petroleum products.

all patented innovations have the same economic value and that propensity to patent may vary across countries and technological fields.

For the present study of fuel efficiency in fossil fuel electricity generation, the use of patents as indicators of the supply of fuel-efficient technologies in the market is justified by the fact that patenting is a costly procedure that is undertaken by firms which have the intention of marketing a patented good and benefiting from the temporary monopoly power granted by the patent itself. Patented innovations, therefore, are those for which the inventor is determined to find a market.

The identification of patents that are relevant to fossil-fuel electricity generation technologies is explained in detail in Lanzi et al (2011). As in Lanzi et al (2011) we exploit the differences between inventor country and patenting office and we build three different indexes using patent applications from the PATSTAT database. First, we build a global indicator of technologies in the market by considering all patent applications (claimed priorities and singulars) in fossil based efficient technologies for the production of electricity, independent of the countries where they are protected. This indicator in not country-specific, and it is meant to simply measure the increased availability of better technologies over time. Second, we use information on singular and claimed priorities applications by national inventors. Third, we build market-specific indicators by taking into account all the patent applications (claimed priorities, singulars and duplicates) at the national application authority.[12]

The three indexes are built using patent counts and following previous studies such as Popp (2002) and Bottazzi and Peri (2005) and Verdolini and Galeotti (2011). We use the perpetual inventory method to construct a measure of knowledge stock for each time *t*:

$$KS_t = Pat_t + (1-\delta)KS_{t-1} \tag{5}$$

where the initial stock ($t=t_0$) is calculated as follows:

$$KS_0 = \frac{Pat_0}{\bar{g}+\delta} \tag{6}$$

In all cases, t_0=1958, $\bar{g}$ equals the average growth rate in patenting during the three years preceding the analysis (1955-1957), and δ is a 10% discount rate.[13] Figure 3 shows the trend of these two indicators over time for the countries under analysis.

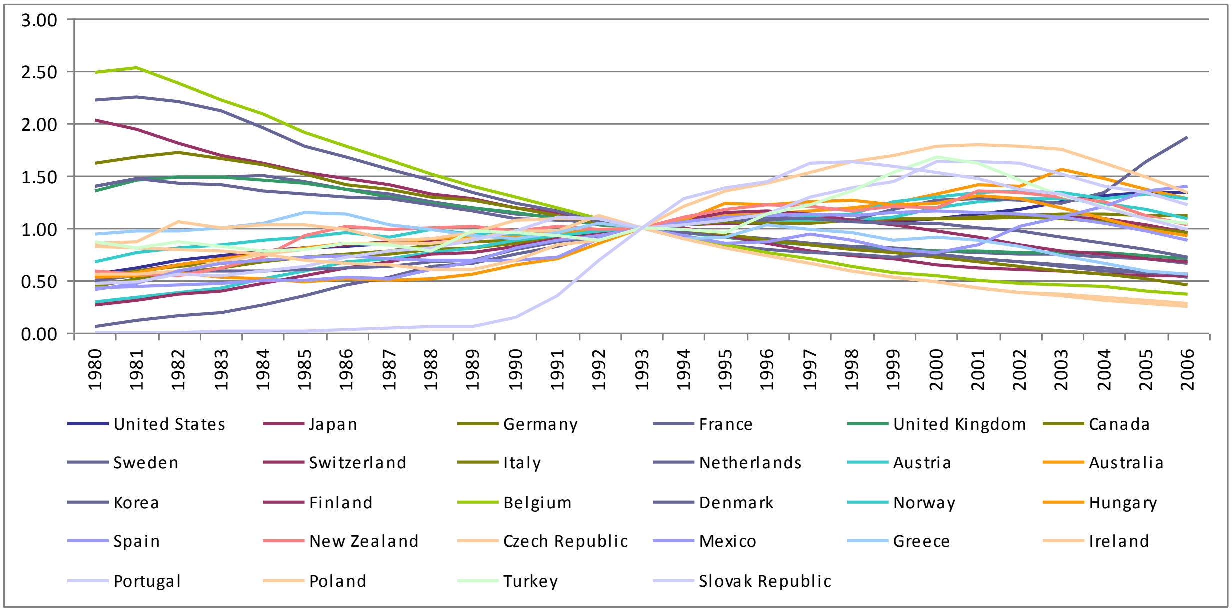
In the empirical analysis, the discounted stream of knowledge is lagged by five years to account for temporal differences between invention and deployment. We carried out a sensitivity analysis of the technological availability indexes by using different lags (from 3 to 10 years) and found that this did not

[12] For details on patenting procedures and on different patents, see Paper 4.

[13] This is in line with the literature, see e.g. Bottazzi e Peri (2005).

qualitatively effect the empirical results. In the next section, we turn to presenting the empirical results of the estimation of equation (1).

Figure 3: Market-specific and global index of technological availability, 1980-2006



6. *Estimation Results*

The empirical analysis is carried out using a panel covering the period 1980-2006 (27 years) and 28 OECD countries, Australia, Austria, Belgium, Canada, Czech Republic, Denmark, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Japan, Korea, Mexico, Netherlands, New Zealand, Norway, Poland, Portugal, Slovak Republic, Spain, Sweden, Switzerland, Turkey, United Kingdom, and the United States.[14] Table 1 presents descriptive statistics. The estimation method is pooled OLS with heteroskedasticity-robust standard errors.

[14] This sample contains a total of 28*27=756 observations. However, in 13 cases the share of coal over fossil fuel equals zero and in 39 cases there is not information about installed capacity. The total number of observations are thus 704. In addition, there is 1 missing observation due to lack of information specifically with respect to the capital stock variable.

Table 1: Descriptive Statistics

Variable	Obs	Mean	Std. Dev.	Min	Max
Efficiency	756	0.360	0.045	0.129	0.523
Share of Coal In Fossil Inputs	756	0.562	0.280	0	0.995
Capacity Ratio	717	0.889	1.001	0.026	8.906
Technological Availability (Global)	756	16612.96	4307.88	7659.79	20788
Technological Availability (Local Inventor)	756	144.819	384.715	0.282	2277
Technological Availability (Local Application Authority)	756	536.654	851.467	0.500	4568
3-years Capacity Increase	643	0.021	0.092	-0.358	0.423

Table 2: Regression Results. Dependent variable: Log of Fuel Efficiency

	(I)	(II)	(III)	(IV)	(V)	(VI)
Share of Coal	-0.0403***	-0.0261**	-0.0311***	-0.0514***	-0.0288***	-0.0471***
In Fossil Inputs	(0.0100)	(0.0104)	(0.0110)	(0.00921)	(0.00966)	(0.0114)
Capacity	0.0611***	0.0751***	0.0773***	0.0461***	0.0648***	0.0568***
Ratio	(0.0106)	(0.0130)	(0.0141)	(0.0117)	(0.0148)	(0.0151)
Index of Technological	0.128***			0.125***		
Availability (Global)	(0.00921)			(0.0133)		
Index of Technological		0.0308***			0.0208***	
Availability (Own)		(0.00423)			(0.00481)	
Index of Technological			0.0226***			0.0377***
Availability (Market)			(0.00781)			(0.00827)
Capacity Increase				0.00485**	0.00518**	0.00599**
3-years				(0.00217)	(0.00263)	(0.00277)
Country FE	yes	yes	yes	yes	yes	yes
Constant	-2.249***	-1.225***	-1.181***	-2.206***	-1.129***	-1.287***
	(0.0897)	(0.0324)	(0.0657)	(0.133)	(0.0413)	(0.0716)
Nr of Cases	704.000	704.000	704.000	406.000	406.000	406.000
R-Square	0.802	0.758	0.740	0.835	0.789	0.792

The empirical results of the estimation of (4) are shown in Table 2. Specifications I through III include the input mix, the level of capacity utilization and different indexes of technological availability, respectively global (specification I), own innovators (specification II) and own patent office (specification III). Specifications IV through VI also include the variable proxying for the capital stock in fossil fuel generation.

The estimated coefficients are in line with expectations outlined above. In all specification, the elasticity of fuel efficiency with respect to the coal share is estimated between 0.026 (specification II) and 0.051 (specification IV). A 1% decrease in the share of coal over total fossil input translated in efficiency levels that are between 0.026% and 0.051% higher.

Conversely, higher capacity utilization is associated with higher levels of fuel efficiency in electricity production: a 1% increase in average capacity utilization at the country level is associated with an increase in fuel efficiency between 0.061% (specification I) and 0.077% (specification III), depending on the specification employed. This suggests that efficiency gains can be achieved in countries where electricity production is lower than the maximum installed capacity. However, such efficiency gains may not be easy to achieve, if the lower capacity utilization is a sign that fossil electricity generation is used as peak load, for example to compensate for the fluctuation of intermittent renewable sources. This result also points to the possibility of increasing efficiency through demand-side policies aimed at smoothing electricity consumption and demand over time.

Particularly interesting are the results related to technological availability indexes, which perform rather differently in the estimation. The first index, indicating the global availability of more efficient technologies, indicates that a 1% increase in the knowledge stock is associated with an increase of around 0.12% in combustion efficiency. The second index, indicating the stock of innovation produced by home inventors, associates a 1% increase in technological availability with an increase of efficiency between 0.0221% and 0.031%. The third index, indicating all the innovation available in any national market for technology, shows that a 1% increase in the stock of innovation is associated with an increase of between 0.023% and 0.038%.

It is to be noticed that the explanatory power of the first indicator of technological availability (global knowledge) seems to be the highest, while the other two perform equally well but the associated coefficients are lower. This is an interesting finding. The global knowledge stocks works exactly as a time trend in the equation, since it is increasing over time and common to all countries. Conversely, the market specific indicators show that the impact of technological availability over time is much lower. This can be due to the fact that the global index picks up additional effects rather than only the ones linked with technological availability. As such, a global index or a time trend will probably overestimate the effect of technological availability over time.

Specifications IV through VI include the 3 year average increase in capital stock of fossil generation electricity. The estimated coefficient shows that the higher the stock of capital (thus, the higher the investment in new generation capacity), the higher combustion efficiency.

7. Efficiency Determinants and Carbon Intensity

This Section relates changes in energy efficiency of fossil fuel electricity production with trends in the carbon intensity of electricity generation. Increasing the efficiency of fossil fuels based electricity also results in decreased CO_2 emissions. Using the emission factors associated with the fossil fuel input (see the Appendix) we calculate the CO_2 emissions associated with the production of electricity in out sample during the period 1991-2006.[15]

Figure 4 shows the growth rate of $C0_2$ emissions together with that of electricity production, with 2000 as the base year. Between 1991 and 2006, electricity and heat output increased by almost 40% in our sample, with an average annual increase of around 2.5%. Conversely, CO_2 emissions increased over the same period by about 29%, with an annual average increase of almost 2%. Therefore, electricity and heat production have been rising faster than the associated CO_2 emissions, leading to a decrease in emission intensity of fossil fuel electricity production. This trend indicates that in a capital intensive sector technological change only happens slowly over time. In addition, it clearly points to the necessity to significantly increase investment in more efficient technologies if the goal to be reached is higher efficiency and reduced emissions from fossil fuel based electricity.

The link between fuel efficiency and carbon intensity is straightforward. In particular, given 3 inputs in the production of electricity, namely coal, oil and gas, CO_2 intensity (*CI*) indicates the emissions per GWh of electricity production and can be defined as follow:

$$CI = \frac{F_c * I_c + F_o * I_o + F_g * I_g}{P_c + P_o + P_g} \tag{7}$$

where *I* is the input of fossil fuel, *F* is the corresponding emission factor and *P* is production of both electricity and heat. The relationship between fuel efficiency and carbon intensity becomes apparent transforming the above equation as follows:

Figure 4: CO_2 Emissions from Fossil Fuel Electricity Production, 1991-2007

[Figure 4 from excel around here]

$$CI = \frac{F_c * I_c + F_o * I_o + F_g * I_g}{P_c + P_o + P_g} \frac{I_c + I_o + I_g}{I_c + I_o + I_g} = \bar{F} * \frac{I_c + I_o + I_g}{P_c + P_o + P_g} = \bar{F} * \frac{I}{E^{el}} \tag{8}$$

Carbon intensity can be thought of as the product of the inverse of fuel efficiency and $\bar{F}$, the input weighted emission factor. As a result, by empirically assessing the impact of the determinants of fuel efficiency, we are also able to comment on the effect of the carbon intensity of the electricity production process. For example, the coefficient associated with the knowledge stock variable in the

[15] Since 1991, the IEA (2009) provides detailed data on the breakdown of coal, gas and oil inputs for electricity production. Limiting the analysis to 1991-2006, we avoid having to make assumptions about the breakdown of coal, oil and gas inputs for the period before 1991 for which only data at the aggregate level is available.

fuel efficiency equation speaks the impact of knowledge stock on fuel efficiency, but also the impact of increased technological availability on the carbon intensity of the electricity industry:

$$\frac{\partial \ln CI}{\partial \ln KS} = \frac{\partial \ln CI}{\partial \ln E^{el}} * \frac{\partial \ln E^{el}}{\partial \ln KS} = -\frac{\partial \ln E^{el}}{\partial \ln KS} = -\alpha_{KS} \tag{9}$$

Conversely, the input mix affects carbon intensity in two ways: on the one hand, it has an indirect effect through changes in fuel efficiency; on the other hand, the input mix has a direct effect on the input weighted emission factor.

8. Conclusion

In this empirical analysis, we estimated the impact of the input mix, the level of capacity utilization, the quality of the fossil-fuel power plant stock and sevaral indicators of technological availability on the level of fuel efficiency of fossil-fuel power plants in 28 OECD countries over the period 1981-2006. We show that, while higher coal shares in the input mix are associated with lower fuel efficiency levels, higher capacity utilization, newer power plants and higher levels of technological availability are associated with higher levels of efficiency. Given the relationship between fuel efficiency and power plant CO_2 intensity, this empirical analysis also points to the contribution of technical change in reducing carbon intensity.

The results presented in this paper shed some light on the relative importance of all the options currently presented as ways to reduce CO_2 emissions associated with fossil-fuel electricity production. In particular, while the impact of the knowledge stock on fuel efficiency is positive and significant, its coefficient is not very high in magnitude. Moreover, a decrease in carbon intensity has not lead to overall CO_2 emissions reductions. Therefore, it is important to keep in mind that, unless significant changes will happen either on the demand side (energy conservation) or on the supply side (production of electricity from alternative sources), increases in the available stock of knowledge will not be sufficient to both reduce carbon intensity and the overall level of CO_2 emissions.

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Appendix A

Table A. 1: Emission Factors (tonne of CO2/TJ)

Input	Emission Factor
Crude Oil	73.30
Orimulsion	77.00
Natural Gas Liquids	64.20
Motor Gasoline	69.30
Aviation Gasoline	70.00
Jet Gasoline	70.00
Jet Kerosene	71.50
Other Kerosene	71.90
Shale Oil	73.30
Gas/Diesel Oil	74.10
Residual Fuel Oil	77.40
Liquefied Petroleum Gas	63.10
Ethane	61.60
Naphtha	73.30
Bitumen	80.70
Lubricants	73.30
Petroleum Coke	97.50
Refinery Gas	57.60
Other Petroleum Products	73.30
Anthracite	98.30
Coking Coal	94.60
Other Bituminous Coal	94.60
Sub-Bituminous Coal	96.10
Lignite	101.00
Oil Shale and Tar Sands	107.00
Brown Coal Briquette	97.50
Patent Fuel	97.50
Coke Oven Coke and Lignite Coke	107.00
Gas Coke	107.00
Coal Tar	80.70
Gas Work Gas	44.40
Coke Oven Gas	44.40
Blast Furnace Gas	260.00
Oxygen Steel Furnace Gas	182.00
Natural Gas	56.10
Peat	106.00
Charcoal	112.00

Source: http://www.ipcc-nggip.iges.or.jp/public/2006gl/pdf/2_Volume2/V2_2_Ch2_Stationary_Combustion.pdf

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