



Environmental policy design, innovation and efficiency gains in electricity generation



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ABSTRACT

This paper explores the relationship between environmental regulation, innovation, and competitiveness using environmental patent data. The analysis is conducted in two stages. First, a non-parametric frontier analysis is implemented to estimate efficiency scores, including a measure of technological innovation based on patent stocks. Second, econometric methods are applied to analyse the role of policy stringency and policy design on efficiency. Our estimation sample covers thermal power plant sectors in 20 countries from 1990 to 2009. The results show that the stringency of environmental regulations is a significant determinant of productive efficiency with respect to pollutant emissions as well as fuel use. However, these effects turn negative once the level of stringency leaps over a certain threshold. In addition, the paper concludes that the positive effect of regulatory stringency can be diminished by a negative effect of regulatory differentiation with measures which vary in stringency across plant size and age having negative consequences, and these effects are increasing over time. Finally, it is found that integrated approaches to environmental innovation are more likely to bring about efficiency improvements than end-of-pipe technologies.

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1. Introduction

Discovering new ways to decouple economic growth from environmental impacts is a major challenge, and meeting this challenge requires an improved understanding of the effect of policy design on incentives for the efficient realisation of the joint objectives of production of economic outputs and mitigation of environmental outcomes. The two outcomes (economic and environmental) need to be analysed within the same framework, taking into account technological choices.

The literature that has analysed the relationship between environmental regulation, innovation and competitiveness has produced widely divergent findings on many key points (for a recent overview see [Ambec et al., 2013](#); [Lankoski, 2010](#); [Managi et al., 2009](#)). Additionally,

linking regulatory stringency with international market competitiveness has been discussed extensively in literature on productive efficiency analysis ([Costantini and Mazzanti, 2012](#)). For example, while most studies find that environmental regulation generally spurs innovation, there is significant disagreement over the strength of this signal as reflected in terms of policy design characteristics and the nature of the resulting innovation ([Johnstone et al., 2009](#); [Haščič and Johnstone, 2011](#)).

The greatest conflict surrounds how environmental regulation affects competitiveness, normally measured through productivity ([Managi et al., 2005](#)). To summarise, most of the early studies concluded that regulation negatively affected productivity – often significantly ([Palmer et al., 1995](#)). More recent research has produced more mixed results. A growing number of studies find that environmental rules can have a positive effect on productivity if they are designed efficiently ([Berman and Bui, 2001](#); [Lanoie et al., 2008](#)).

It is important to understand why these various studies have reached divergent conclusions. The main focus of this paper is to better understand how differences in policy design can affect the relationship between policy incentives and productive efficiency, and the role that

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different abatement strategies can play in reconciling environmental and economic objectives. While this study focuses on energy generation, and specifically coal-fired power plants, the lessons are of wider relevance.

Depending on their design, environmental regulations can potentially result in increased long-term efficiency in the joint production of market goods (e.g. electricity and heat) and non-market products (e.g. SO_x and NO_x). That is, if there is a decrease in productive efficiency of market outputs, it may be compensated for by increased efficiency in the mitigation of non-market environmental outputs. This implies that when firms are faced with environmental regulations, they might develop innovative means of dealing with them, thereby shifting out the multi-product production frontier.

As discussed above, many previous studies have focused on environmental technologies. However, most of them have not discussed the characteristics of technologies and installed plant type, even though R&D strategies and market needs clearly differ among them. Based on this background, the objective of this study is to investigate the relationship between regulation, innovation and productive efficiency considering technological characteristics. More specifically, we explore how innovation and policy design characteristics affect the production efficiency using data on inputs and outputs, emissions, plant characteristics, patent stocks and policy characteristics. In recent years, the sustainability of the production processes has been analysed, focussing on the role of the efficiency of environmental regulation (Costantini et al., 2016; Franco and Marin, 2015; Green et al., 2012; Hauknes and Knell, 2009).

The novelty of this paper is to take into account the technological characteristics of production and abatement, treating capital stocks in a differentiated manner, and in particular the extent to which they reflect end-of-pipe abatement or more integrated strategies to mitigate emissions. It is hypothesised that the latter strategy will enable the joint realisation of economic and environmental objectives in a more efficient manner.

2. Background and research framework

The effects of air pollution on ecosystems and human health have been documented for more than a century. Environmental regulations such as emission standards seek to reduce these adverse effects. If designed efficiently, the costs of meeting such regulations and standards will be in line with the associated benefits. While there is variation across plant types, coal-fired generation plants are particularly polluting, and are responsible for 40% of electricity generation worldwide. In this section, the determinant factors of air pollution mitigation and emissions are discussed, taking into account the policy design, and distinguishing between types of pollutants, coal types, plant sizes and plant vintages. This analysis draws upon a unique dataset of emission regulations.

2.1. Determinant factors of air pollution mitigation in coal-fired power plants

2.1.1. Measuring the stringency of emission regulations

In principle, environmental objectives can be achieved through a variety of different policy measures, and depending upon design characteristics of equivalent ambition, may have very different implications for economic outcomes (see Costantini et al., 2015; Costantini and Crespi, 2013; Johnstone and Haščič, 2013; Frondel et al., 2010; Nemet, 2009). A general principle of environmental economics is that cost-efficient abatement is realised through the use of measures in which marginal abatement costs are equalised across different sources. For uniformly-mixed global pollutants (such as greenhouse gas emissions) this will also result in economic efficiency if the level of stringency is optimal since marginal abatement costs from all sources will equal marginal benefits. In addition, such measures often provide stronger

incentives for innovation, both because the emitter is given greater flexibility in the choice of abatement option and because there are incentives to identify abatement options across the whole range of possible outcomes. It is for this reason that taxes or tradable permits are frequently advocated.

However, in the case of local and regional air pollutants (e.g. SO_x and NO_x), such as those under analysis in this study, the marginal benefits of abatement will differ by source. In addition, there may be administrative barriers to implementing and enforcing those measures which treat sources in an undifferentiated manner in relation to their damages. For both of these reasons there has been a heavy reliance on the use of performance standards, for air pollutants released into the environment. Most regulations are aimed at limiting the emission of sulphur oxides (SO₂ and SO₃), nitrogen dioxide (NO₂), particulate matter (PM₁₀ and PM_{2.5}) and, to a lesser extent, mercury (Hg) and carbon monoxide (CO). Emission standards of these pollutants are generally expressed in mg/m³, although some countries set their emission limits in different units. The information on the standards was collected from national databases of environmental regulations and the Emission Standards Database of the International Energy Agency's Clean Coal Centre. In order to standardise these limits it has been necessary to apply some assumptions of the heat content of the fuel and the flue gas volume generated in combustion. Following the methodology of the IEA's Clean Coal Centre, conversion into mg/m³ was made assuming a 6% of oxygen content, on a dry gas volume, at 0 °C (273 K) and 101.3 kPa (1 atm). In some cases, regulations are defined using a different percentage of oxygen content (e.g. United States) and in such cases conversions were made using the law of volumes. When the flue gas conditions are not known, the above conditions are assumed.

The dataset covers 34 countries including most OECD member countries and 5 non-OECD countries. The first regulations setting emission standards were introduced in the early 1960s. Japan was the pioneer, setting a national emission standard for stationary sources, with the introduction of the Smoke and Soot Regulation Law in 1962, limiting the emission of particulate matter. In the United States, the 1963 Clean Air Act was the first environmental regulation of air pollution. The 1972 Environmental Action Programme was the first environmental policy adopted across the European Union. The programme set the general framework of objectives and principles for a Community-wide environmental policy. This was followed by national regulations, first introduced in Germany and France in 1974 and 1976, respectively. Since the mid-1980s national emission standards in Europe have been implemented following European Commission's Directives. Non-OECD countries covered in our database such as Brazil, India and the People's Republic of China introduced their emission standards for combustion plants in the early 1990s.

However, in an effort to approximate first-best outcomes regulators often differentiate emission limits across vectors which have implications for marginal abatement costs, namely: fuel (coal type), plant size and plant vintage. The effect of this differentiation on innovation and thus on the efficiency of the production of goods and bads can be significant. If well-designed, such a strategy may be cost-effective in the short-run when the plant stock is fixed since they can reflect abatement costs across different plant characteristics. However, to the extent that they can influence the composition of the portfolio of plants over the medium- and long-term, such differentiation is unlikely to be efficient. Moreover, inefficiencies will also arise over time since the rate of change of technological opportunities for abatement of plants with different characteristics (fuel, size, vintage) is likely to vary. Next, we present the state and characteristics of current environmental regulations directed to coal power plants across these different dimensions.

2.1.2. Differentiating across fuels and plant characteristics

2.1.2.1. Coal types. Coal is created as geological processes apply pressure to dead biotic material. Under some conditions it can be transformed

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