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Power generation and pollutant emissions in the European Union: A mean-variance model

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In this work, portfolio theory is applied to efficient electricity generation from both an economic and environmental point of view. The proposed model includes all the generation costs for different technologies, including externalities; the risk derived from them, and a set of constraints on the emission of pollutant gases, such as carbon dioxide, sulphur dioxide, nitrogen oxides and particulate matter. Our results show that the EU technology portfolio, as proposed by the International Energy Agency for the 2030 horizon, is far from efficient. The joint cost-risk-environmental perspective confirms the need to increase the share of renewable energy technologies in the European energy mix, including photovoltaic energy, and to promote wind power as much as possible, to reduce the environmental impact. It is also necessary to continue to rely on hydro, CCS and nuclear technologies, in order to optimize the cost-risk tradeoff and the security of supply. In addition, it is concluded that restrictions on other pollutant gases should be also imposed, because they would contribute to reducing the environmental impact, with a relatively small increase in terms of cost-risk.

1. Introduction: energy planning, portfolio theory and the importance of carbon emission reduction

The power generation challenge in each territory must be characterized by safety, cost efficiency, environmental protection and system reliability. Altogether, this will allow for the maintenance of competitiveness and ensure the sustainability of a key process in the economic and social development of the territory in question. In this line, the future portfolio design of power generation technologies would determine a country's role in terms of dependence on outside resources, the energy security level of the territory, and the social and environmental impact derived from the use of the different technologies in the power portfolio. The definition of the power generation technologies portfolio is therefore one of the most relevant decisions within strategic future energy and environmental planning.

A great many authors have used the initial proposal suggested by Bar-Lev and Katz (1976) and have developed and been inspired by other authors, such as Awerbuch (Awerbuch and Berger, 2003; Awerbuch and Yang, 2007) and Delarue (Delarue et al., 2011) to study the energy problem posed by power generation. This approach considers energy planning as a problem of long-term investment selection. Within this approach, the opportunity arises to use quadratic optimization methodology from Markowitz's portfolio theory (1952), which is based on the performance-risk tradeoff. In the energy context, it is usually based on the cost-risk tradeoff, thus making it possible to estimate the power production cost of the available technologies, as well as their risk,

ABBREVIATIONS: CCS, Carbon dioxide Capture and Storage; CO_2, Carbon dioxide; EU, European Union; EU-ETS, European Emission Trading System; GHEH, Gases Harmful to the Environment and Human Health; MWh, Megawatts per hour; IEA, International Energy Agency; NP, New Policies Scenario; CP, Current Policies Scenario; 450, 450 Scenario; IPTS, Institute for Prospective Technological Studies; NOx, Nitric oxide and nitrogen dioxide; O&M, Operation and Maintenance; RES-E, Renewable Energy Sources for Electricity; PV, Photovoltaic; SO2, Sulphur dioxide.

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understood in terms of cost variability.

One relevant factor when determining the generation technologies lies in the consideration of externalities. This work follows the lines initiated by several previous studies on portfolio theory and energy planning (Humphreys and McClain, 1998; Krey and Zweifel, 2006; Arnesano et al., 2012; De-Llano et al., 2014; DeLlano-Paz et al., 2015) with regard to the inclusion of the externality costs derived from power production in the cost structure of the technologies. It is a matter of adding in those costs not taken into account by the integrated power companies (except for those related to CO_2 emissions), including potential damages to ecosystems and society, which have a negative effect on well-being and public health (Liu et al., 2016; Garg et al., 2016). The intent of this is to partially correct the possible market error derived from not considering these costs, which are borne by society and the environment (Eyre, 1997; Schultman et al., 2001). As a result, the costs of pollutant technologies increase, and the difference between them and renewable energies decreases, thus improving their competitiveness. In addition, observation is made of the interest on the part of authors who use portfolio theory models to include CO_2 emissions market cost (Peerapat Vithayasrichareon and MacGill, 2012; Lynch et al., 2013; Cuixia et al., 2014; Marrero et al., 2015; Jano-Ito and Crawford-Brown, 2017; Guerrero-Lemus et al., 2012; Lucheroni and Mari, 2017) and to study the impact of CO_2 cost variability in the composition of efficient portfolios (Peerapat Vithayasrichareon and MacGill, 2012; Lynch et al., 2013; Kumar et al., 2015; Lucheroni and Mari, 2017).

The emission and concentration of pollutant gases have a negative and harmful impact on human life and the environment (DeLlano-Paz et al., 2015; Ghaith and Epplin, 2017; Cucchiella et al., 2017). The deforestation (Shen et al., 2016) and the use of fossil fuels in association with industry, transport and the generation of electricity represents the main cause of pollutant gas emissions (Wang et al., 2016; Chen et al., 2017; Kopidou and Diakoulaki, 2017). Recently, in 2015, the global carbon emission atmosphere concentration rose to 401 ppm, up from 312 ppm in 1950 (Ghaith and Epplin, 2017). This has resulted in a 1.02 °C increase in the average global temperature between 1900 and 2015 (Zeng et al., 2017b). There are numerous negative effects of this concentration: the global warming of the earth's surface, the rising sea level, air pollution, acid precipitation, pollution of the oceans and ozone depletion (Omer, 2008; Panwar et al., 2011; Hernández-Escobedo et al., 2010; DeLlano-Paz et al., 2015; Marron et al., 2015; Zeng et al., 2017b).

In order to reduce these negative processes, territories can establish efficient measures that mitigate the negative externalities of climate change (Cretí and Joëts, 2017): national/regional emission reduction targets (Marcantonini and Valero, 2017), carbon trading mechanisms (Zeng et al., 2017a; Marcantonini and Valero, 2017) or a specific carbon tax per consumed kWh on household electricity (Ghaith and Epplin, 2017), among other energy policy measures. As a matter of fact, since 1990 greater environmental sensitivity has been observed by different countries. This takes shape based on the development of environmental policies and the creation of institutions that oversee environmental protection (Botta and Kozluk, 2014; Andersson, 2018). It constitutes the greatest challenge faced by the current generation (Zeng et al., 2017a; Damsø et al., 2017). From an economic perspective, there is talk of a low carbon economy (Cao et al., 2017), which takes advantage of the business opportunity presented by the current environmental trend (Piecyk and McKinnon, 2010; Wu et al., 2017; Yang et al., 2017).

There are, however, negative effects derived from the imposition of climate change policies. Among them is the so-called carbon leakage effect (Antimiani et al., 2013; 2016), which occurs as the result of possible distorting effects in the economy caused by the delocalization of companies to countries with more relaxed or non-existing environmental regulations in terms of emissions (Antimiani et al., 2013, 2016; Andersson, 2018). However, authors like Wu et al. (2017) present their doubts about the evidence of this relationship.

Considering the environmental objective sought by the low carbon economy, there are two key elements to consider in the analysis: the carbon intensity of the economy and energy savings (Wu et al., 2013; Renner, 2014; Zeng et al., 2017a). For this reason, analysis based on energy utilization and energy efficiency indexes has become more relevant (Meng et al., 2016). Along these lines, we see the work by Zeng et al. (2017b), who analyze the development of renewable energies in the BRICS countries through the study of the financing models used and the perspective of the theory of technological innovation systems. These authors indicate that the net increase of 1 percentage point in the level of electricity production using renewable energies (excluding hydroelectric technology) reduces carbon emission intensity by 0.16 points. Likewise, it should be noted the study of Wang et al. (2016), who review the GHG emissions derived from industrial sectors in China, particularly for the pulp and paper sector, which is highly intensive in terms of pollutant emissions.

Other authors such as Zeng et al. (2017a) enrich the analysis by using a structural vector autor regresive model (SVAR) to study the influence of the different factors conditioning carbon emissions trading and prices: policy factors, internal and international energy prices, macroeconomic variables, etc. Examples of these factors would be on a macro level (economic activities, economic recession, and energy, renewables and environmental policies) or on a micro level (different energy sources and power prices in particular emission trading markets). These authors also conduct an exhaustive and interesting review of the different methods used to study the effects and factors related to carbon emissions. Another methodology that is widely used in this field is Data Envelopment Analysis (DEA). In Meng et al. (2016), we find an exhaustive revision of employing Data Envelopment Analysis (DEA) in order to measure regional energy and environmental efficiency in China. The authors propose a series of recommendations from a methodological and empirical perspective related to the use of the DEA methodology.

From the perspective of portfolio theory applied to real electricity generation assets, a greater diversification level of the energy portfolio of a territory —in terms of sources and suppliers- and the introduction of a higher RES share in energy mix would permit the achievement of emission reduction targets, due to the absence of using fossil fuels in RES (Awerbuch and Berger, 2003; Jansen et al., 2006; Awerbuch and Yang, 2007; Zhu and Fan, 2010; DeLlano-Paz et al., 2015, 2017; Zeng et al., 2017a, 2017b). In addition, RES allows regions to reduce the energy dependence thanks to their autochthonous character (Panwar et al., 2011; Escribano et al., 2013; Cansino et al., 2015) and increase their power supply security level in terms of reducing a supply breakdown produced by geopolitical reasons (Chuang and Ma, 2013; Escribano et al., 2013).

For all these reasons, the establishment of emission reduction objectives facilitates the achievement of a solution for challenge presented by the energy and environmental problem. As a result, energy security, economic development, technological innovation and environmental protection, as parts of the energy challenge, are benefited by the consideration of emissions reduction target (Chuang and Ma, 2013).

Some recent studies employing portfolio theory (Kumar et al., 2015; DeLlano-Paz et al., 2015; Jano-Ito and Crawford-Brown, 2017; Cucchiella et al., 2017) indicate the need to include data