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Environmental impact efficiency of natural gas combined cycle power plants: A combined life cycle assessment and dynamic data envelopment analysis approach

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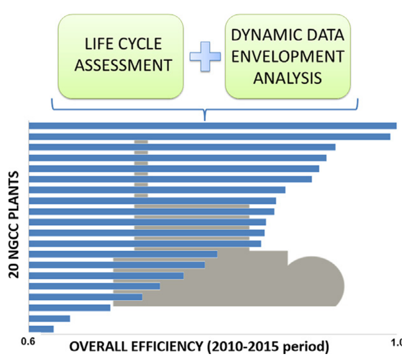
HIGHLIGHTS

- Combined application of life cycle assessment and dynamic data envelopment analysis
- Life-cycle profiles of 20 NGCC plants in Spain in six different years (2010–2015)
- Overall eco-efficiency score above 60% for all power plants
- A high number of operating hours is linked to high environmental impact efficiency.
- Preliminary environmental benchmarking of inefficient power plants

GRAPHICAL ABSTRACT



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ABSTRACT

The energy sector is still dominated by the use of fossil resources. In particular, natural gas represents the third most consumed resource, being a significant source of electricity in many countries. Since electricity production in natural gas combined cycle (NGCC) plants provides some benefits with respect to other non-renewable technologies, it is often seen as a transitional solution towards a future low carbon power generation system. However, given the environmental profile and operational variability of NGCC power plants, their eco-efficiency assessment is required. In this respect, this article uses a novel combined Life Cycle Assessment (LCA) and dynamic Data Envelopment Analysis (DEA) approach in order to estimate –over the period 2010–2015– the environmental impact efficiencies of 20 NGCC power plants located in Spain. A three-step LCA + DEA method is applied, which involves data acquisition, calculation of environmental impacts through LCA, and the novel estimation of environmental impact efficiency (overall- and term-efficiency scores) through dynamic DEA. Although only 1 out of 20 NGCC power plants is found to be environmentally efficient, all plants show a relatively good environmental performance with overall eco-efficiency scores above 60%. Regarding individual periods, 2011 was –on average– the year with the highest environmental impact efficiency (95%), accounting for 5 efficient NGCC plants. In this respect, a link between high number of operating hours and high environmental impact efficiency is observed. Finally, preliminary environmental benchmarks are presented as an additional outcome in order to further support decision-makers in the path towards eco-efficiency in NGCC power plants.

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1. Introduction

Notwithstanding the growing role of renewable technologies in national energy mixes, the current energy context is still dominated by the use of fossil resources, with coal, oil and natural gas accounting for >80% of the world primary energy supply in 2014 (IEA, 2016). After oil and coal, natural gas is the third most consumed fossil fuel, accounting for 24% of the global energy consumption (BP, 2016). Furthermore, the share of natural gas in the global energy mix is increasing. In 2015, with respect to the previous year, world natural gas production and consumption grew by 2.2% and 1.7%, respectively (BP, 2016). In particular, Iran (+6.2%) and China (+4.7%) recorded the highest increment in natural gas consumption, and Norway (+7.7%) and Iran (+5.7%) showed the highest increase in production (BP, 2016). The largest volumes of production and consumption continue to be found in North America and Europe. These regions accounted for >55% of the world consumption of natural gas over the past 10 years (BP, 2016; IEA, 2016).

The significant role of natural gas is associated with advantages in terms of reliability, ease of transport/storage and efficiency, also being considered a more environmentally friendly option than other fossil resources such as coal and oil (Biresselioglu et al., 2015; Faramawy et al., 2016). Its use is widely spread in the industrial, commercial and residential sectors. Regarding power generation, natural gas currently represents a significant source of electricity, especially in OECD countries (25% contribution to the electricity production mix), for which a link between natural gas consumption and economic growth has been identified (Destek, 2016). In particular, natural gas combined cycle (NGCC) power plants involve higher operational flexibility and lower capital costs and emissions than other conventional power plants. In this sense, a shift from coal/oil to natural gas could be a transitional solution towards a low carbon energy system (UNFCCC, 2015), which could be achieved through the combination of NGCC power plants with CO_2 capture and storage systems (de Llano-Paz et al., 2016; Faramawy et al., 2016).

However, despite advantages over other conventional non-renewable technologies (e.g., coal, oil and nuclear power plants), the operation of NGCC power plants does entail the release of harmful pollutants to the environment (Atilgan and Azapagic, 2015; Turconi et al., 2013). In this respect, the environmental performance of NGCC plants should be comprehensively assessed. In particular, Life Cycle Assessment (LCA) is a standardised methodology to evaluate the environmental aspects and potential impacts associated with a product system (ISO, 2006a, 2006b).

In countries with natural gas contribution to the electricity production mix, the associated environmental impacts can vary considerably. This variability is linked to the significant number of NGCC power plants usually found at the national level. For instance, Spain currently accounts for >30 installations in operation (UNESA, 2016). The operational flexibility of NGCC power plants and their use to meet peak electricity demand imply that they do not operate and produce continuously at the same level (intra-year variability). Furthermore, variability is observed not only within the same year of operation but also over a longer period of time (inter-year variability). Hence, measuring NGCC power plants' environmental performance in terms of individualised and period-oriented eco-efficiency arises as a matter of interest (Arabi et al., 2016). In this regard, the traditional eco-efficiency concept refers to the delivery of competitively priced goods that satisfy human needs while progressively reducing environmental impacts of goods and resource intensity throughout the entire life cycle to a level at least in line with the Earth's estimated carrying capacity (Schmidheiny, 1992). Similarly, eco-efficiency today is understood as an aspect of sustainability relating the environmental performance of a product system to its product system value (ISO, 2012).

Unfortunately, while life cycle-based methods alone are highly used to identify and evaluate the relevant sources of environmental impact in a system, their utility as single approaches to eco-efficiency analysis is frail (Vázquez-Rowe and Iribarren, 2015). Thus, the combination of LCA with appropriate operational research tools becomes convenient in order to quantitatively verify the eco-efficiency of entities such as NGCC power plants. Within this context, Data Envelopment Analysis (DEA) arises as a linear programming methodology that quantifies in an empirical manner the relative efficiency of multiple similar entities (Cooper et al., 2007). These resembling entities (e.g., NGCC power plants) are generally called decision making units (DMUs). In the last years, the combined use of LCA and DEA for the identification and quantification of the potential environmental consequences of operational inefficiencies has experienced a pronounced increase (Martín-Gamboa et al., 2017; Vázquez-Rowe and Iribarren, 2015). In this sense, when input and output data are available for multiple similar facilities, the use of the LCA + DEA methodology as an eco-efficiency analysis tool is highly recommended (Lozano et al., 2009; Vázquez-Rowe and Iribarren, 2015). Under these circumstances, in comparison with other life cycle-based approaches (ISO, 2012), LCA + DEA offers an enriched interpretation and communication of eco-efficiency results. This is closely linked to the features of DEA as a tool for multi-criteria decision analysis and benchmarking of key performance indicators.

Given the interest in NGCC power plants as a relevant case study for eco-efficiency analysis, this article uses the LCA + DEA methodology with the aim of determining the environmental impact efficiency of a representative number of NGCC power plants in Spain over an extended period of time.

2. Material and methods

2.1. LCA + DEA framework for the case study of NGCC plants

The goal of this study is to estimate the environmental impact efficiency of a sample of 20 Spanish NGCC power plants over the period 2010–2015. Within the European context, Spain plays a significant role because of its well-established gas infrastructure. The favourable geographical location of Spain and the potential of its network to manage high volumes of gas make this country a suitable candidate to reinforce the European gas interconnections and guarantee the energy supply (Enagás, 2017). Regarding NGCC power generation in Spain, the cumulative capacity was 27.20 GW at the end of 2015. For the evaluated sample of 20 NGCC plants, the corresponding cumulative capacity is 17.09 GW, i.e. above 60% of the total installed capacity in Spain (REE, 2016; UNESA, 2016). Although the NGCC electricity production in Spain significantly decreased in the last years, the contribution of natural gas to the Spanish electricity production mix currently remains above 10% (Enagás, 2017; UNESA, 2016). Moreover, the expected withdrawal of conventional coal and nuclear power plants in the medium term positions NGCC plants as a robust transitional power source in the path towards a highly renewable electricity mix (García-Gusano et al., 2016). Thus, Spanish NGCC power plants constitute a relevant case study for the evaluation of their environmental impact efficiency. In order to perform this eco-efficiency analysis, a three-step LCA + DEA approach is applied as summarised in Fig. 1.

Lozano et al. (2010) established the three steps required for the combined operational and environmental assessment of multiple similar entities in terms of environmental impact efficiency. This approach is selected –rather than other LCA + DEA approaches such as the five step LCA + DEA method (Iribarren et al., 2011, 2013)– due to its suitability for the direct calculation of environmental impact efficiencies (or eco-efficiency ratios) (Lozano et al., 2010; Vázquez-Rowe and Iribarren, 2015). As shown in Fig. 1, the first step involves data collection in order to prepare mainly the life-cycle inventory (LCI) of each NGCC power plant for each of the evaluated years. Detailed information regarding the inputs and outputs considered is provided later in Section 2.2. In the second step, the LCIs are used to perform the life cycle impact assessment (LCIA) of each NGCC plant for each year, thereby obtaining the corresponding environmental profiles. Finally, the