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Assessing the economic feasibility of the gradual decarbonization of a large electric power system

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ABSTRACT

The decarbonization of power systems is among the primary actions to fight air pollution and climate change. In this study, we evaluate the costs of a gradual transition towards a new power system in which the oldest coal plants are replaced with low-carbon power plants. We developed the Wind Energy Integration Cost Advisor Model (WEICAM) to analyze different strategies for this energy transition and determine the most cost-effective roadmap, with and without externalities. The test case is the PJM Interconnection, one of the power systems in the United States with the largest fraction of coal. Different strategies to replace coal plants are evaluated: 1) installing only new, high-efficiency, natural-gas combined-cycle plants (control case), 2) installing new wind farms in combination with natural-gas combined-cycle plants used as spinning reserves (wind case), and 3) same as the wind case but boosting up the production of existing baseload plants that work with a capacity factor between 50% and 60%–80% before installing new wind farms. All three strategies have similar costs (~54 \$/MWh), but the latter is slightly more cost-effective, with a total of 19 GW of coal capacity decommissioned and an increase in the levelized cost of electricity from 49.1 to 53.6 \$/MWh (without externalities). In addition, selecting the windiest sites – even far away from the PJM region – is cheaper than selecting local but less windy sites. When externalities due to human health and environmental pollution are accounted for, the two wind-based strategies become the most advantageous, reducing the levelized cost below 104 \$/MWh from the initial 110 \$/MWh. We conclude that adding new wind farms from the windiest locations, accompanied by a better management of existing plants and a small addition of new natural-gas reserve capacity, is the most economic and the most environmentally responsible pathway to replace retiring coal-fired power plants in PJM.

1. Introduction

Current power systems are among the largest contributors to air pollution and global warming. Conventional electric power generators, fueled by fossil fuels (e.g., coal, natural gas, and oil), emit harmful pollutants – such as sulfur dioxide (SO_2), nitrogen oxides (NO_X) and particulate matter (PM) – into the atmosphere, causing around 6.5 million premature deaths in the world (IEA, 2016a). Moreover, power systems are also one of the main sources of CO_2, thus contributing to the greenhouse effect. According to the International Energy Agency, about 40% of global CO_2 emissions in 2014 were related to electricity and heat production (IEA, 2016b). Among fossil fuels, coal is the most polluting, accounting for most of SO_2, NO_X, and PM emissions (IEA, 2016a) and for about 46% of the total world CO_2 emissions from fuel combustions (IEA, 2016b). Given the impact of conventional power plants on human health, environment and climate change, the gradual decarbonization of the energy sector has been declared as a binding target in the 2015 Paris Climate Conference, where international policy makers agreed to promote actions for shifting to low-carbon power systems. Although coal power will still have an important role to meet the

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List of acronyms

PJM	Pennsylvania-New Jersey-Maryland Interconnection
NGCC	Natural Gas Combined Cycle
PM	Particulate Matter
GHG	Greenhouse Gases
RTO	Regional Transmission Operator
WEICAM	Wind Energy Integration Advisor Model
NREL	National Renewable Energy Laboratory
LCOE	Levelized Cost of Electricity
O&M	Operation and Management
FOM	Fixed Operation and Management costs
VOM	Variable Operation and Management costs
JEDI	Transmission Line Jobs and Economic Development Impact
OMB	Office of Management and Budget
CAP	Capital costs
EXT	Externalities
TC	Additional Transmission costs resulting from the clustering of wind farms
TE	Total Energy delivered by the entire power system during a year

worldwide electricity demand – growing by about 200 GW by 2020 – it is expected that its share in power generation will decrease from the current 41%–37% (IEA, 2015).

China – the largest coal consumer in the world – will play a decisive role in this future mix. Policy actions in energy promoted in the China's Energy Development Strategy Actions Plan (2014–2020) aim at reducing the share of coal in the primary energy consumption to 62% and increasing the share of low-carbon technologies to 15% by 2020. As a result, the share of coal in the energy mix fell to 64.4% in 2015 (Qi et al., 2016). Moreover, coal consumption in the European Union has been decreasing since 2012 as a result of energy policies targeting a reduction of at least 40% in GHG emissions. In addition, current power systems in the U.S. are mainly based on coal burning, with about 33% of the national electricity being generated by coal-fired plants (EIA, 2016). The decarbonization of the U.S. power systems is therefore a priority, as stated in the Clean Power Plan (EPA, 2015). This plan will allow decommissioning of about 50 GW of the 310 GW of total existing coal-fired generation capacity by 2020 (EIA, 2014).

The international scientific community has been concerned about the transition to low-carbon power scenarios. A reference study conducted by Lund and Mathiesen (2009) evaluated the feasibility of a 100% renewable energy scenario in Denmark by 2050 based on the EnergyPLAN model. This model has been also used to assess 100% renewable energy scenarios in Macedonia (Ćosić et al., 2012), Ireland (Connolly et al., 2011) and Portugal (Fernandes and Ferreira, 2014). For this last country, Santos et al. (2016) explored the most cost-effective roadmap to achieve a 100% renewable scenario in 20 years using a model based on a multi-objective mix-integer linear optimization method (described in Pereira et al., 2016). This scenario presented a high share of wind and hydro and the cost of the electricity increased from current 53.6 €/MWh to 162.8 €/MWh. The full transition to a high penetration renewable energy power system has been also evaluated for other European countries, such as France (Krakowski et al., 2016) and Western Europe (Brouwer et al., 2016), Australia (Elliston et al., 2013) and the United States (Jacobson et al., 2015a). In a recent study, Jacobson et al. (2015b) proposed different roadmaps for each of the 50 United States to convert their all-purpose energy systems (for electricity, transportation, heating/cooling and industry) to only with wind, water, and solar power.

These past studies were conducted for a long-term transformation of current power systems, aiming to achieve high-penetration renewable energy scenarios many decades ahead. However, the gradual roadmap towards these future power systems has not been studied in depth. In order to achieve feasible and affordable low-carbon power systems, a correct planning of this transition is crucial, particularly in countries – like the United States – in which other low-emission fuels (i.e., natural gas) may play an important role. Therefore, the first steps in the decarbonization of a power system are essential because new installed power plants have a typical life cycle of 25–30 years, thus conditioning the transition to the desired low-carbon scenario.

This situation is already taking place in the U.S., where coal plants are being replaced by natural gas combined-cycle (NGCC) plants (Davis et al., 2016), partly due to competitive gas prices (Weiss et al., 2015). In a recent study, Pratson et al. (2013) estimated that, based on the production of 304 coal plants and 358 natural gas plants, 9% of the existing coal capacity in the U.S. can be perfectly replaced by natural gas because of its low price. This power source is becoming the dominant fuel in some Regional Transmission Operators (RTOs) – like the PJM Interconnection – as a consequence of the increased availability of natural gas from nearby shale resources and the retirement of coal plants as a result of changing economics and environmental regulation (PJM, 2016a). Among renewables, wind power has also become a potential substitute for coal, especially at locations where this clean technology can economically compete with natural gas (like the U.S. Midwest). As a result, the wind capacity in the country has grown from 2.5 GW in 2000 to almost 74.4 GW at the end of 2015 (GWEC, 2016) and wind energy currently represents more than 20% of the generation in some states and 4.2% nationally (AWEA, 2016). The cost of different 20% wind energy penetration scenarios in the U.S. has been previously evaluated by EnerNex (2011), which projected costs of wind energy between 3.10 and 5.13 $/MWh. However, given that natural gas and wind are low-carbon emission technologies, the next question to address is: what would be the most cost-effective transition to replace coal?

This paper aims at evaluating and quantifying the cost of electricity in a gradual transition to a new energy scenario in which the most aging and polluting coal-fired plants are replaced by new wind farms, new transmission, new NGCC plants, and a better management of the existing peaking and baseload natural gas plants. The proposed analysis focuses on the PJM Interconnection, one of the largest RTOs in the U.S. and characterized by a high fraction of coal generation. A total of 68 GW of coal capacity – which constitutes about 35% of the total installed capacity – was operating in PJM in early 2016 (PJM, 2016b). Given this high share of coal, massive decommissioning of coal plants is expected and therefore this RTO represents a good power system to explore alternatives for its gradual decarbonization. To this end, we developed the Wind Energy Integration Cost Advisor Model (WEICAM), a simulator of the generation mix, load, and transmission of PJM, loosely based on Budischak et al. (2013), to assess the most cost-effective gradual replacement of coal. Different scenarios – depending on the strategy to replace coal – are evaluated in WEICAM, including the use of NGCC plants as the first choice to replace the coal capacity and the installation of wind farms in the Midwest or inside the PJM region.

The rest of the paper is structured as follows: section 2 presents the data and a description of the WEICAM model. Main results from the different proposed analyses are described in section 3 and main