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Improving the flexibility of coal-fired power generators: Impact on the composition of a cost-optimal electricity system

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HIGHLIGHTS

- Coal-based technologies can supply flexibility and contribute to lower system costs.
- With CO_2 cap in place, increasing the biomass share in co-firing is advantageous.
- Low-cost flexibility stimulates investments in wind and solar power.

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ABSTRACT

A transformation of the electricity generation system is required to drastically reduce the associated CO_2 emissions. In future systems, variable renewable energy sources (wind and solar) are expected to provide a significant fraction of the electricity supply, increasing the requirement for variation management compared with today's situation. This paper investigates the impacts of measures designed to increase the competitiveness of coal-fired power plants in future energy systems, which are facing restrictions related to CO_2 emissions and variable operation as a consequence of high penetration levels of wind and solar power. We investigate the cost-optimal compositions of three regional electricity generation systems with different conditions for generation using renewables with a linear cost-minimizing investment model. The model is applied in two energy policy scenarios: one with a tight cap on CO_2 emissions, and one with a stringent requirement for generation from renewables.

In a system with a stringent requirement for electricity generation from renewables but without a CO_2 cap, coal-based technologies with improved cycling properties provide variation management, given that the development of measures for ensuring improved flexibility continues and reaches full-scale implementation at moderate cost. The effects of improved cycling properties on the system composition are especially relevant for regions with moderate potential for wind and solar generation, in that they reduce wind curtailment and improve the underlying conditions for investments in solar power. In the system with a tight CO_2 cap, only coal-based technologies with Carbon Capture and Storage (CCS) and co-firing of biomass are feasible. Increasing the share of biomass in co-firing technologies to achieve negative CO_2 emissions increases the competitiveness of these technologies to a greater extent than if simply the cycling properties are improved. A larger co-firing fraction reduces the total system costs, since it facilitates the provision of low-cost flexibility by Natural Gas Combined Cycle (NGCC) plants, and it is especially important in regions where nuclear power is otherwise cost-competitive, as low-cost flexibility stimulates investments in wind and solar power at the expense of nuclear power.

1. Introduction

To limit CO_2 emissions from electricity generation, drastic transformation of the electricity system is required, whereby variable renewable electricity (vRE), i.e., wind- and solar-based generation, provides a considerable fraction of the supply. Other arguments for increasing the vRE share are: (i) increased security of supply (reduced dependency on foreign fuels); and (ii) improved air quality. Up to now, targeting increased vRE rather than the pricing of CO_2 emissions has typically governed the implementation of vRE, which has been promoted with policy instruments, such as feed-in tariffs in Germany [1] and green electricity certificates in Sweden [2].

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Nomenclature

Bio GCC	bio gas combined cycle (–)
C^{cycl}	cycling costs(€)
C^{inv}	annualized investment costs (€/kW)
C^{run}	running costs (€/MWh)
C_{tot}	total system costs (€)
$C^{on}_{p,t}$	start-up costs (€/MW)
$C^{part}_{p,t}$	part load costs (€/MW)
CCS	carbon capture and storage (–)
D_t	electricity demand (MWh/h)
E^{cap}	cap on total CO_2 emissions (kg)
$E^{on}_{p,t}$	start-up emissions (kg/MWh)
$E^{part}_{p,t}$	part-load emissions (kg/MWh)
$E_{p,t}$	emissions from generation (kg/MWh)
FLH	full load hours (–)
$g^{active}_{p,t}$	active capacity available for generation (MWh/h)
$g^{on}_{p,t}$	started capacity (MWh/h)
$g_{p,t}$	electricity generation (MWh/h)
GT	gas turbine (–)
I_p	invested capacity in technology aggregate (kW)
k	time steps in the start-up interval of a capacity (h)
K	time interval for start-up of a capacity (–)
L^{min}_p	minimum load level (%)
NGCC	natural gas combined cycle (–)
O&M	operation and maintenance (–)
p	technology aggregate (–)
P	set of all technology aggregates (–)
PV	photovoltaic (–)
RES	renewable energy sources (–)
t	time step (h)
T	set of all time steps (–)
TT	set of all time steps except for the first time step of the model period (–)
vRE	variable renewable electricity (–)

With increased vRE capacity, the demand for capacity to balance the power generation in the electricity system grows. This capacity may be provided by increased transmission capacity, energy storage, demand-side management, changed dispatch in thermal generation, and the use of electricity in other sectors, such as transportation (electrofuels) and district heating. The operating costs associated with electricity generation from vRE are low relative to those of traditional thermal-based generation. Therefore, when available, vRE generation is positioned early in the dispatch order. Large coal-fired units, which traditionally have been designed to operate as base-load plants with around 8000 full-load hours (FLH) per year, are already experiencing a decrease in FLH, as well as more frequent and longer shut-down periods [3]. The increase in vRE has been most pronounced in European electricity systems, with FLH as low as 3000–4000 h per year already being experienced by thermal plants. An even more drastic decrease in operating hours with long shut-down periods is foreseen (given continued efforts to decrease CO_2 emission from the electricity system) (see [4–6]). This further underlines the necessity to modulate the dispatch of thermal power plants and to explore their potential as providers of variation management. For fossil-based electricity generation, restrictions on CO_2 emissions require fuel switching or the implementation of Carbon Capture and Storage (CCS) technologies, which will further add to the challenge of transitioning from base-load generation to mid-merit operation. The operational flexibility of thermal power plants is influenced by several factors [7,8]:

- Minimum load
- Part-load efficiency
- Start-up times
- Load cycles
- Ramp rates
- Reserve capacity

The cycling properties of thermal plants, i.e., minimum load, part-load efficiency and cost, and start-up time and cost, are all important to consider in modeling electricity generation systems, and they have been shown to influence the cost-optimal composition of future systems [9]. The cycling properties affect the dispatch order and, consequently, the operating hours of thermal power generation units, especially in systems where the thermal capacity is cost-competitive at intermediate utilization times [9,10]. This has been exemplified by Kubik et al. [11] in a dispatch modeling study for Northern Ireland, who showed that retrofitting an existing coal-fired plant to improve its cycling properties with respect to minimum load contributed to reduced system costs, less wind curtailment, and in most cases, reduced CO_2 emissions. In another study, the need for and value of flexibility in two fictional energy systems with a predetermined inflexible and flexible generation mix were investigated [12]. That work showed that an inflexible, nuclear-dominated system values high response capability and low minimum loads, whereas a more flexible gas- and coal-based system assigns a higher value to a short commitment time.

Besides coal-fired plants, gas-based plants and interconnection capacity have also been suggested as cost-effective providers of variation management in the Year 2050 time-frame by Bertsch et al. [13] and Brouwer et al. [14,15]. An improved interconnection capacity could also benefit base-load generators by increasing their capacity factors [15], although creation of the required capacity is complicated and not practically possible in certain areas. Furthermore, the problems of insufficient revenues from thermal power generation and the lack of economic incentives to invest in new generation in the current energy-only market were highlighted in these previous studies, and the need for new or alternative market designs was discussed. In their study, Pudjianto et al. [16] evaluated the potential of grid-scale electricity storage for variation management and identified benefits for generation, transmission and distribution, while also showing potential for real-time balancing support. Furthermore, the value of energy storage, on-shore wind power and power generation equipped with CCS was investigated in a recent study by Heuberger et al. [17]. CCS technologies and on-shore wind was shown to provide a decreasing but consistent system value with increasing capacity deployment. The value of energy storage with first available capacity was shown to be an order magnitude larger compared with CCS and wind power, but rapidly declines as more capacity is deployed.

Given the restrictions foreseen for CO_2 emissions, fuel flexibility and co-firing of biomass are properties that will be valued by the system. The power generation industry is showing increasing interest in improving the competitiveness of thermal power plants through increased flexibility, both with respect to cycling properties and fuel flexibility, including the development of new materials, new control systems/strategies, and new process set-ups, as well as the retrofitting of existing plants with new and/or improved equipment [18,19]. At the same time, revenues from the electricity markets are currently low, and it is difficult to forecast the returns from a future energy system. Therefore, making costly investments in new technologies with long pay-back times is generally problematic. In the absence of a broad understanding of the issues characterizing the future electricity system, it is not straightforward to deduce which properties will be valued by the system. Furthermore, it is not obvious how conditions for generation from renewables, which vary between geographical regions, will influence the value of flexibility measures and the relative