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Upgrading existing coal-fired power plants through heavy-duty and aeroderivative gas turbines

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HIGHLIGHTS

- The feedwater repowering of an existing coal-fired power plant is examined.
- Repowering is operated by adding heavy duty and aeroderivative gas turbines.
- A characteristic plane allows to compare benefits of different repowering options.
- Regenerative gas turbines yield the greatest increase in steam plant performances.
- Aeroderivative gas turbine allows to implement a more flexible part-load strategy.

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ABSTRACT

The need to meet future changes in power demand and current environmental regulations are considered the main driving forces for upgrading existing coal-fired power plants. In this context, repowering by gas-turbine integration is a well-established technique to increase power plant capacity and operational flexibility. Non-negligible benefits are also improvements in efficiency and a decrease in greenhouse gases emissions promoted by the shift to low carbon fuels.

This paper aims to investigate the impact of feedwater heater repowering on a 300 MW coal-fired power plant. Marginal efficiency and power increase, as well as the performance of integrated steam-gas power plants, are evaluated by varying the steam section operating conditions and gas turbine technology. Three main cases are investigated, assuming integration with simple or regenerative heavy-duty gas turbines and aeroderivative gas turbines.

As part of this investigation, a performance plane is defined, allowing to compare repowering options based on different steam turbine overloads and boiler modes of operation. Focusing on repowering configurations with the maximum power increase, the analysis also examines the plant capability to follow potential load variations and their impact on energy and economic performance parameters.

1. Introduction

The power generation sector is faced with a rise in world energy consumptions. Despite increasing penetration of renewable energies, fossil fuels still represent the main source for generating heat and electricity and will continue to dominate the future energy market according to current energy forecasts [1]. Due to increasing stringent environmental regulations and the difficulty in obtaining permits for developing new generating capacity, repowering existing power plants is viewed as a viable option to meet future energy needs or replace units approaching the end of their useful lifetime.

The concept of repowering relies on the use of exhaust gases from an additional gas turbine to improve the productivity of an existing coal-fired power plant. According to the technical solution adopted, power increase can range between 20% and 200%, with a heat rate improvement within the range of 5–40% [2]. Efficiency enhancement, together with the use of low-carbon fuels, offers the opportunity to reduce net emissions of greenhouse gases. Another important aspect is the improved operational flexibility that translates to fast start-up and adaptation to load variations [3–5].

Common approaches to upgrading existing coal-fired power plants include hot windbox repowering, parallel repowering and feedwater repowering [6,7].

In the first option, hot exhaust from a gas turbine replaces the air entering the existing boiler, thus eliminating the need for an

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Nomenclature

Symbols

A	heat exchange surface area, m^2
c	fuel cost, $/GJ
C	repowering cost, M$
E	electricity production, GW h/year
HR	heat rate, kJ/kW h
m	steam flow rate, kg/s
P	power, MW
q	fuel mass flow rate, kg/s
Q	thermal power, MW_t

Greek letters

η	efficiency, %
λ	feedwater deviation, %
φ	regenerator effectiveness, %

Acronyms

CCF	capital charge factor, yr^{-1}
COE	cost of electricity, $/MW h
HR	heat rate, kJ/kW h
IGV	inlet guide vane
LHV	lower heating value, MJ/kg
RG	gas cycle regeneration
TEC	total equipment Cost, M$
TET	turbine exit temperature, °C
TIT	turbine inlet temperature, °C
TOC	total overnight capital, M$

Subscripts

em	emitted
CD	condenser
EXH	exhaust
FR	feedwater repowering
GT	gas turbine
HP	high pressure
HX	heat exchanger
IRP	integrated repowered plant
LP	low pressure
mg	marginal
NG	natural gas
SH	superheated steam
ST	steam turbine
th	thermal

Superscript

O	design condition

air pre-heating system and reducing the boiler fuel requirements. By this integration, generating capacity is increased up to 50% and efficiency by as much as 15%. The main drawback is represented by the need of a new high temperature combustion air system and special high temperature and low O_2 burners [8].

Feedwater heater repowering implies that a gas turbine and gas–water heat exchangers are added in parallel to the existing plant, while the boiler and steam turbine equipments are used in their original configuration. Hence, exhausts from the gas turbine are used to preheat feedwater at the boiler inlet, partially substituting conventional regenerative heaters. Power output could increase by 30–40%, even though the efficiency gain does not exceed 2% points [9–11].

In parallel repowering, the exhaust gases, besides preheating feedwater at the boiler inlet, feed a supplementary heat recovery steam generator (HRSG); hence, additional superheated steam is produced and provided to the unit steam cycle. An evolution of this option is the full repowering, where the original boiler is removed and the overall steam is produced by exhaust heat recovery in the HRSG, whose parameters are selected to maximize the existing steam turbine power output. Hence, this concept enables the maximum efficiency increase (30–40%), with a power boosting up to 200% [2].

Compared to the other options, feedwater repowering benefits from the greater simplicity and lowest additional costs, as it involves only minor modifications to the original power plant design [10,12].

However, feedwater repowering has not been widely investigated in the technical literature. In [13], Szargut modeled energy and environmental benefits of feedwater repowering; in a further study [14], the same author investigated the gas turbine integration, pointing out potential ways to reduce exergy losses related to feedwater–gas heat exchange. Karrelas et al. [15] compared feedwater and parallel repowering of two lignite-fired power plants by means of exergy and economic analysis. Focusing on the same repowering options, Escosa and Romeo [16] investigated the influence of technology and size of additional gas-turbine on CO_2 avoided cost.

Feedwater heating was compared to hotwindbox and full repowering options in [17], analyzing the performance benefits and the associated costs. Focusing on a supercritical steam power plant, Wolowitz [18] evaluated the impact of gas turbine integration on the off-design parameters of steam power plant.

More recently, Grinnan [19] reported the experience in upgrading two existing US steam power plants, by replacing condensers and feedwater heaters; Samanta and Ghosh [20] evaluated the improvement in energy and environmental performances achieved by using the exhaust flue gas from an additional gas turbine to accomplish the preheating of air and feedwater at boiler inlet.

Nevertheless, most of these studies have investigated the potential benefits of repowering intervention for specific steam power plant arrangements. None of these have deepened the influence of boiler and steam turbine operating conditions on energy and economic performances of feedwater repowering. Moreover they did not examined their sensitivity to gas turbine technology or evaluated the behavior of the upgraded power plant at part load operation.

This paper aims to investigate energy and economic benefits of feedwater repowering, varying the maximum allowable condenser overload and the mode of operation of fossil boiler, namely power boosting or coal-saving [21]. As opposed to power boosting, the coal-saving mode of operation requires that boiler operates with a fuel flow rate lower than design value; hence, the reduced superheated steam power production extends the margins for feedwater repowering intervention, thus allowing a higher feedwater deviation with the same condenser overload.

With regard to the additional power unit, three different cases will be investigated, including the integration of simple and regenerative heavy-duty gas turbines or multiple aeroderivative gas turbines.

Hence, findings of energy and economic analysis will allow for construction of a characteristic plane with color maps defining