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Energy, economic and environmental assessments for gas-turbine integration into an existing coal-fired power plant

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Abstract

The concept of repowering existing power plants has been recently revalued, in the light of the increasing energy needs, combined with the cost and the difficulty in developing new generating capacity. Among technologies for existing steam power plants, feedwater repowering is considered one of the less-intrusive and cost-effective option to expand capacity, improve efficiency and reduce the pollutants emissions. This paper aims to evaluate the effects of feedwater repowering operating conditions on energy, environmental and economic system performances. Considering a 600 MW coal fired power plant as a study case, two feedwater repowering configurations are investigated. In the first case, a simple throttling of high pressure regenerative steam extractions is operated; in the second configuration, the feedwater upstream the boiler inlet is partially preheated using the waste heat of an additional gas turbine. In both cases, a characteristic plane is introduced for comparing energy, economic and environmental performances of feedwater repowering options, at different condenser overloads and fossil boiler modes of operation.

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Keywords: Feedwater Repowering, Gas Turbine, CO_2 Emissions, Off-Design, Coal Saving, Marginal Efficiency, COE

1. Introduction

The growth of world energy consumptions and the need to meet the increasingly stringent environmental regulations make the repowering of existing coal-fired power plants an attractive option for boosting the generating capacity at competitive cost [1-3]. As well known, in the feedwater repowering the exhaust gases of an additional

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gas turbine are used to preheat a fraction of feedwater upstream the boiler inlet. This leads to a reduction of regenerative steam bleedings and a corresponding rise of steam passing across turbine blades. As a result, the capacity of the existing coal fired power plant boosts, even more than 20%, with a less pronounced efficiency gain [4-6]. Additional benefits of feedwater repowering include the reduction of the electricity generation cost and the carbon dioxide emissions, due to the improved efficiency and to the partial fuel shift from coal to natural gas.

Feedwater repowering of an existing coal-fired power plant has been addressed only in a few studies. In [7] Szargut developed a model to quantify energy and environmental benefits arising from the gas turbine integration. A further study of the same author [8] examined different strategies to reduce the exergy losses related to feedwater-gas heat exchange process. Escosa and Romeo [9] evaluated the CO_2 avoided cost of feedwater repowering, varying the technology and rated capacity of the additional gas turbine. Karellas et al. [10] investigated parallel and feedwater repowering solutions by means of exergy and economic analysis.

The goal of this paper is to evaluate the effects of a feedwater repowering intervention on the energy, economic and environmental performances of an existing steam power plant, considering various condenser overloads and boiler modes of operation (power boosting or coal saving). In the case of power boosting, the boiler operates with a fossil fuel flow higher than or at least equal to design conditions and the corresponding gain of steam power plant capacity is constrained by the maximum permitted overload at low pressure steam turbine and condenser (15-20% of the nominal load) [5,11], in order to avoid the adaptation or the replacement of these equipments. In the case of coal saving, the boiler operates with a fuel flow rate lower than the nominal value, in order to manage the condenser overload, due to partial throttling of steam bleedings. The reduction of the superheated steam flow allows to increase the feedwater deviation with the same condenser overload, thus determining an efficiency enhancement and a reduction of CO_2 emissions.

Two different repowering configurations are investigated in this study. In the first case, steam power plant undergoes a simple throttling of high pressure steam bleedings, thus allowing an increase of steam turbines capacity together with an efficiency penalty, due to lowering of feedwater temperature at boiler inlet. In the second configuration, feedwater is partly deviated from high and low pressure regenerative heaters and preheated by the exhaust gases of an additional gas turbine. The energy analysis of feedwater repowering options, carried out with the commercial General Electric software GateCycle [12], aims to evaluate the power increase and the marginal efficiency, as well as the effects on the specific CO_2 emissions. Moreover, the economic analysis assesses the unit cost of electricity produced by the repowered plant, as well as the unit cost of the additional electricity generated.

In both configurations examined, a characteristic plane is defined: it allows to compare energy, economic and environmental performances of feedwater repowering options, considering different condenser overloads and fossil boiler modes of operation.

Nomenclature

Symbols

C	Fuel cost, \$/GJ
C_{FR}	Feedwater repowering cost, M\$
$CO_{2,\,em}$	Specific CO_2 emissions, kg/MWh
E	Electricity production, GWh
HR	Heat rate, kJ/kWh
M	Steam flow rate, kg/s
P	Power, MW
Q	Fuel mass flow rate, kg/s

Greek letters

γ	Degree of closing of HP steam bleedings, %
η	Efficiency, %
λ	Feedwater deviation, %

Superscripts

O	Design conditions

Subscripts

CD	Condenser
EXH	Exhaust
GT	Gas turbine
HX	Heat exchanger
HP	High pressure
IRP	Integrated repowered plant
LP	Low pressure
mg	Marginal
SH	Superheated
ST	Steam power plant
th	Thermal

Acronyms

BOP	Balance of plant, M\$
COE	Cost of electricity, \$/MWh
TEC	Total Equipment Cost, M\$

2. Description of feedwater repowering options for an existing coal fired power plant

A 600 MW coal-fired power plant is selected as study case to examine the effects of a feedwater repowering intervention. At design conditions, the superheated steam flow produced by a subcritical fossil boiler (486.1 kg/s at 180 bar and 540°C) expands across the steam turbine, including high, intermediate and low pressure sections connected to a single-shaft generator. The feedwater extracted from the condenser is preheated at 242.4°C upstream the fossil-boiler economizer, using six surface heat exchangers and a deaerator supplied by bleedings from steam turbines. The LHV net efficiency of the power plant is 40.8%, while the specific CO_2 emissions are 772.5 kg/MWh. Based on NETL methodology [13] and assuming a TEC of 1600 $/kW [14], the cost of electricity of the steam power plant at design conditions is 75.8 $/MWh, the main contribution being the capital charge, accounting for about 45%. Energy and economic performances of the baseline steam power plant are summarized in Table 1.

In this study the feedwater repowering of an existing coal fired power plant is operated into two different ways: (a) by throttling steam bleedings of the high pressure steam turbine, (b) by-passing partly high and low pressure regenerative feedwater heaters with surface heat exchangers fed by flue gas from an additional gas turbine.

In the first case, the throttling of steam bleedings increases the steam flow expanding through high, intermediate and low pressure steam turbines, thus increasing the power plant capacity. At the same time, efficiency reduces due to the lower feedwater temperature at the boiler inlet, thus leading to a corresponding increase of fuel flow with respect to design conditions.

In the second configuration, a portion of the feedwater is preheated by the exhaust heat of an additional gas turbine. As outlined in Fig. 1, representing the plant layout after the repowering intervention, the gas-water heat-exchanger HX3 is fed by exhaust gases to preheat up to 250°C a fraction of feedwater diverted from the deaerator outlet (λ_{HP}); the gas-water heat exchanger HX2 preheats up to 140°C a fraction of feedwater diverted from the condenser outlet (λ_{LP}). The resulting reduction of steam extractions for preheating the feedwater increases the electricity production and the efficiency of the steam power plant, also due to the heat recovery from the added gas turbine.

Table 1. Design performance of baseline coal-fired steam power plant

Operating parameters and main performance	
Net power output, MW	600
Net efficiency, %	40.8
Condenser operating pressure, bar	0.05
Coal lower heating value, MJ/kg	25.4
Fuel mass flow rate, kg/s	57.9
Steam mass flow rate at condenser inlet, kg/s	335.2
Water mass flow rate at deaerator inlet, kg/s	397.7
Superheated steam mass flow rate, kg/s	486.1
Water temperature at fossil-boiler inlet, °C	242.4
Water temperature at deaerator inlet, °C	130.8
Specific CO2 emissions, kg/MWh	772.5
Economic assumptions and cost of electricity	
Yearly operating hours, h/yr	7446
Capital charge factor, yr^{-1}	0.105
TEC, $/kW	1600
Engineering, % of TEC	9%
Contingencies, % of TEC	13%
BOP, % of TEC	28%
Annual cost escalation rate, %	3
Fixed O&M, $/kW-yr	69.4
Variable O&M, $/MWh	8
Fuel cost, $/GJ	2.8
COE_{CAP}, $/MWh	33.8
$COE_{O\&M}$, $/MWh	24.7
COE_{FUEL}, $/MWh	17.3
COE, $/MWh	75.8

In the case of repowering based on gas turbine integration, the fossil-boiler mode of operation plays an important role. In power boosting mode, the subcritical fossil boiler operates with a fuel flow higher than or equal to design conditions. Thus, the progressive reduction of steam bleedings leads to an increase of steam flow passing through turbines stages, constrained by the maximum allowable overload at condensing cooling system: it should not exceed 20% of the nominal load, to avoid the damage or replacement of any system component [2,15]. In coal saving mode of operation, the fossil boiler generates lower superheated steam flows than the design case, thus allowing a greater reduction of steam bleedings for a fixed overload at condenser inlet. Consequently, steam power plant efficiency increases and CO_2 emissions reduces, also due to the partial fuel shift from coal to natural gas.

3. Modeling of feedwater repowering options

The coal-fired power plant selected as study case has been modeled using the commercial software GateCycle [12], that allows to simulate the thermodynamic behavior of the Rankine cycle at design conditions or with the repowering intervention. From an economic point of view, the effects of feedwater repowering are evaluated considering the unit cost of electricity, that is estimated on the basis of the NETL methodology [13]. A detailed description of cost functions used for estimating TEC of ST power plant equipment, gas-water heat exchangers and added gas turbines, as well as the methodology and main economic assumptions for evaluating the total overnight cost (TOC) and COE, were outlined by authors in [15]. In the following subparagraphs, some elements for the assessment of energy and economic system performances are highlighted for both repowering options.

3.1. Feedwater repowering by throttling steam bleedings

The efficiency of steam power plant resulting from the reduction of steam extractions is

$$\eta = \frac{P_{ST}}{q_{coal} \cdot LHV_{coal}} \tag{1}$$

where P_{ST} is the steam plant output and q_{coal} the corresponding coal mass flow rate, depending on the degree of closing of high pressure steam bleedings (γ).

As regards the additional electricity production, the marginal efficiency is defined as the ratio between the steam power plant increase and the corresponding coal mass flow variation with respect to design conditions

$$\eta_{mg} = \frac{\Delta P_{ST}}{\Delta q_{coal} \cdot LHV_{coal}} \tag{2}$$

The effects of feedwater repowering on steam power plant economics are evaluated through the unit cost of electricity production. It has three contributions related to capital charge, fuel consumption and fixed and variable O&M costs. Instead, the COE of the marginal electricity generated has only two contributions

$$COE_{mg} = O\&M_{v,ST} + \frac{c_{coal}\left(HR_{ST}E_{ST} - HR_{ST}^{o}E_{ST}^{o}\right)}{E_{TOT}} \tag{3}$$

accounting for incremental variable O&M and fuel costs due to the repowering intervention.

3.2. Feedwater repowering by gas turbine integration

Modeling of heavy-duty gas turbine is accomplished by defining specific correlations, based on manufacturer data. Technical features, including efficiency, power output, compression ratio, thermal energy exiting the turbine and exhaust gas temperature, have been evaluated using the GT standard library of GateCycle [12]. Empirical relationships have been defined to provide the efficiency, the exhaust mass flow rate and its temperature as a function of the gas turbine power, ranging from 5 to 280 MW. Considering this continuous range of power, the selection of the gas turbine for each feedwater repowering condition has been made so as to ensure an optimal heat recovery from the GT exhaust gases ($T_{HX2,\,out}$=90°C).

The efficiency of steam power cycle is still defined by Eq. (1), while that of the integrated steam-gas power plant depends on rated power (P_{GT}) and fuel mass flow (q_{CH_4}) of the added gas turbine

$$\eta_{IRP} = \frac{P_{ST} + P_{GT}}{q_{coal} \cdot LHV_{coal} + q_{CH_4} \cdot LHV_{CH_4}} \tag{4}$$

The marginal efficiency includes, beside the terms related to the steam power plant, those accounting for gas turbine integration

$$\eta_{mg} = \frac{P_{GT} + \Delta P_{ST}}{q_{CH_4} \cdot LHV_{CH_4} + \Delta q_{coal} \cdot LHV_{coal}} \tag{5}$$

The evaluation of COE and COE_{mg} for the integrated steam-gas power plant takes also into account capital charge and O&M costs of gas turbine and low/high pressure heat exchangers, as well as the additional costs of natural gas [15].

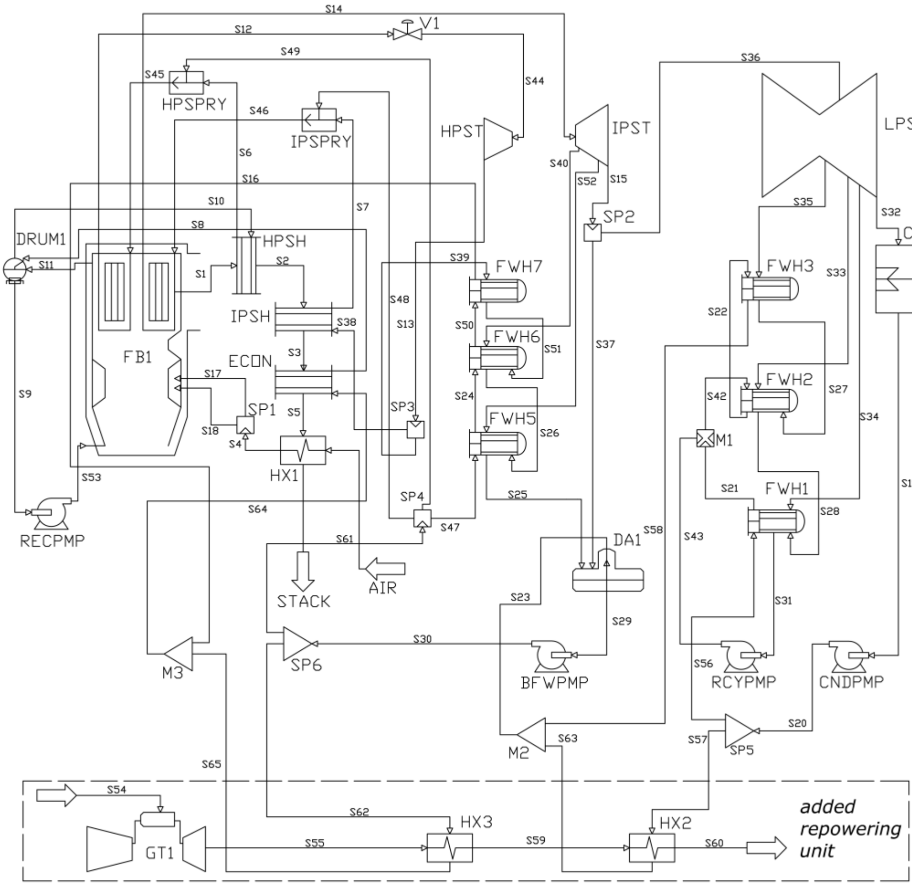

Fig. 1. Layout of a coal-fired power plant with feedwater repowering based on gas turbine integration

4. A performance plane for the feedwater repowering

The effects of two feedwater repowering options on energy performances of the steam power plant are outlined through the characteristic plane shown in Fig. 2. Effects of partial closure of steam bleedings are shown in Fig. 2a, while Fig. 2b refers to the gas turbine integration. In both cases, point O is representative of the steam power plant at design conditions (m_{SH}=100%, m_{CD}=100%, γ=1 or λ=1).

The performance plane of the feedwater repowering indicates the behavior of the ST plant efficiency and power, as a function of two operating parameters: the steam mass flow rate at the condenser inlet (m_{CD} , ranging from 100 to 120% of the value at design conditions), and the superheated steam mass flow rate (m_{SH} , from 90 to 105%). By setting the accepted condenser overload (m_{CD}) and the fossil boiler mode of operation (m_{SH}), the performance plane allows to univocally detect efficiency and power of steam cycle, as well as the degree of closing of steam bleedings (γ), corresponding to a feedwater fraction diverted from HP and LP regenerative heaters ($\lambda_{HP} = \lambda_{LP} = \lambda$) in the case of gas turbine integration.

In the case of throttling of steam bleedings (Fig. 2a), at fixed superheated steam flow production (m_{SH} = cost), condenser overload increases with γ, thus allowing a gain in steam power plant capacity, due to the higher steam flow passing across turbine blades. However, efficiency reduces because the feedwater temperature at boiler inlet decreases, requiring more fuel flow than design conditions (57.9 kg/s).

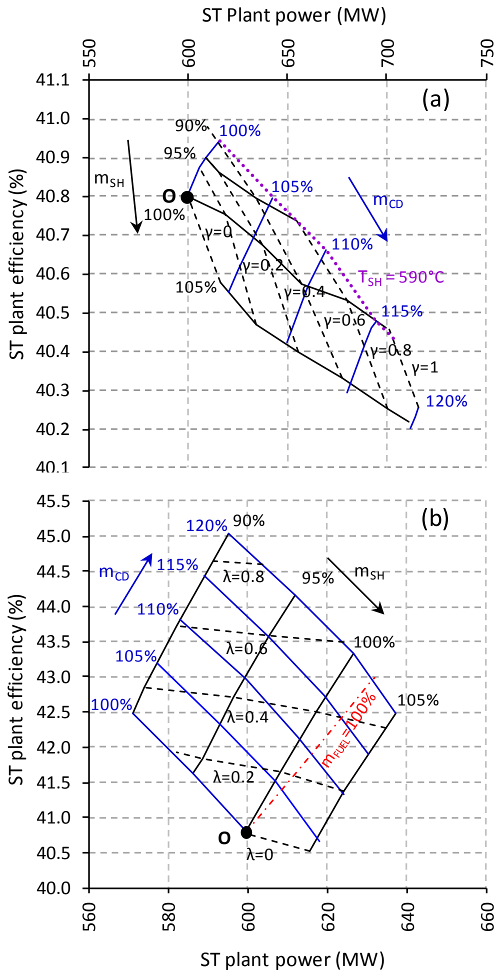

Fig. 2. Effects of feedwater repowering on steam power plant performances: (a) throttling of high pressure steam bleedings, (b) gas turbine integration

On the other hand, increasing γ at fixed condenser overload (m_{CD} = cost), the superheated steam flow production reduces in order to offset the steam flow increase at condenser inlet, due to the progressive closure of steam extractions. Thus, for a fixed γ, the gain in steam power plant capacity is much more contained, but efficiency slightly increases due to the lower fuel flow rise. It is noteworthy to observe that the maximum reduction of steam extractions is limited by the maximum allowable temperature at high-pressure steam turbine inlet, fixed at 590°C (purple dotted curve).

In the case of feedwater repowering based on gas turbine integration (Fig. 2b), the characteristic plane defines efficiency and power of the steam power plant only. The red dash-dot line represents points with coal fuel flow at design conditions (57.9 kg/s): it divides the plane into two zones, featured by different boiler operating modes. All points above this curve are representative of feedwater repowering configurations based on fuel saving mode of operation, whereas all points below this curve refer to power boosting mode of operation. At fixed superheated steam flow production (m_{SH}= cost), condenser overload increases with λ, thus allowing a moderate power increase with a correspondent efficiency gain, related to the thermal power supplied by exhaust gases of the additional gas turbine. Moreover, at fixed condenser overload, increasing λ reduces the superheated steam flow production to offset the effect of progressive reduction of steam turbines extractions.

Consequently, the steam power cycle reduces, whereas the efficiency gain is much more significant with the same increase of λ, due to the greater reduction of fuel flow.

5. Energy, environmental and economic performances of feedwater repowering options

Energy, environmental and economic performances of both feedwater repowering options (based on throttling of steam extractions or gas turbine integration) have been evaluated, considering operating ranges defined by the characteristic plane discussed above. This investigation has led to the construction of color maps that identify the range of variability of different performance parameters, allowing to compare directly and effectively feedwater repowering options based on different condenser overloads and fossil boiler modes of operation.

5.1. Throttling of high pressure steam bleedings

Figures 3 and 4 highlight the effects of throttling of HP steam extractions on performance parameters of the steam power cycle. Maps in Fig. 3 refer to COE and specific emission of carbon dioxide, while those in Fig. 4 to marginal indices, that define the extent, the efficiency and the unit cost of electricity of the additional power generated.

Increasing γ at m_{SH}=100%, the electrical energy gain (Fig. 4a) increases, at the expense of an increase of fuel flow that adversely affects the marginal efficiency and the specific CO_2 emissions.

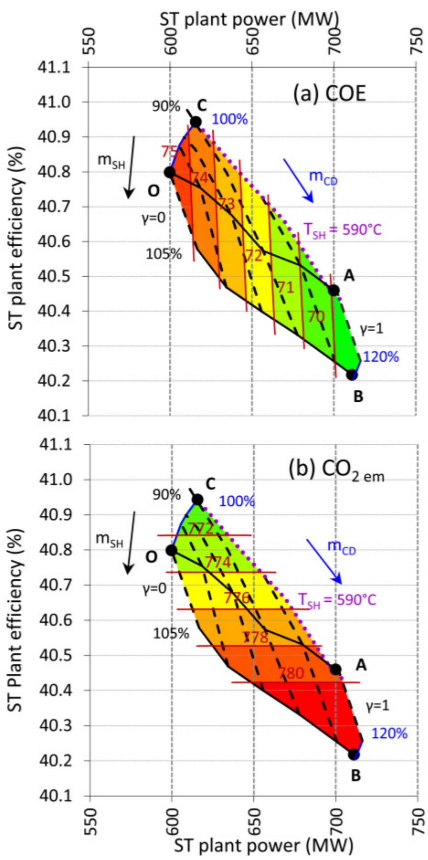

Fig. 3. Economic and environmental effects of feedwater repowering based on throttling of HP steam bleedings

Thus, at point A (m_{CD}=116%, γ=98.5%) the electrical energy gain reaches about 17%; being the marginal efficiency of 38.4% (Fig. 4b), steam power cycle efficiency slightly decreases with respect to design conditions, while CO_2 emissions increase of less than 1% (Fig. 3b). From the economic point of view, it is noted that the cost of additional electricity is rather low (34.2 \$/MWh, Fig. 4.c), as it primarily accounts for the fuel cost contribution. Thus, the cost of electricity significantly reduces, falling below 70 \$/MWh, being the increase of fuel costs more than compensated by the reduction of capital charge and O&M contributions.

Increasing the superheated steam flow production (m_{SH}=105%), the maximum reduction of steam extractions reduces to 0.9, being constrained by the maximum condenser overload (m_{CD}=120%). The slight boiler overload increases the electricity gain, that reaches 18.7% at point B, at the expense of a further reduction of the marginal efficiency (37.3%). Thus, the steam cycle efficiency decreases, always remaining above 40%. In spite of the lower value of γ, the fuel flow rate increases to meet the fossil boiler overload, thus leading to a further increase of specific CO_2 emissions (784.1 \$/MWh). Although the cost of the additional electricity slight increases with respect to point A, COE reaches the minimum value (69.4 \$/MWh) due to the reduction of capital charge and O&M contributions.

Finally, increasing γ at m_{CD}=100%, the superheated steam flow production reduces in order to offset the increase of steam flow rate at condenser inlet. The marginal efficiency increases, exceeding 46% at point C. However, due to a slight electricity gain (almost 3%), the effects on the steam power plant are mitigated. Specifically, the steam cycle efficiency reaches about 41%, while specific CO_2 emissions remain almost unchanged (769.9 kg/MWh) with respect to design conditions, since the effect of reducing the steam extractions is counteracted by the decrease of superheated steam flow. Thus, the additional cost of electricity drops below 30 \$/MWh, due to the slight increase of fuel consumption, while COE states at 74.5 \$/MWh.

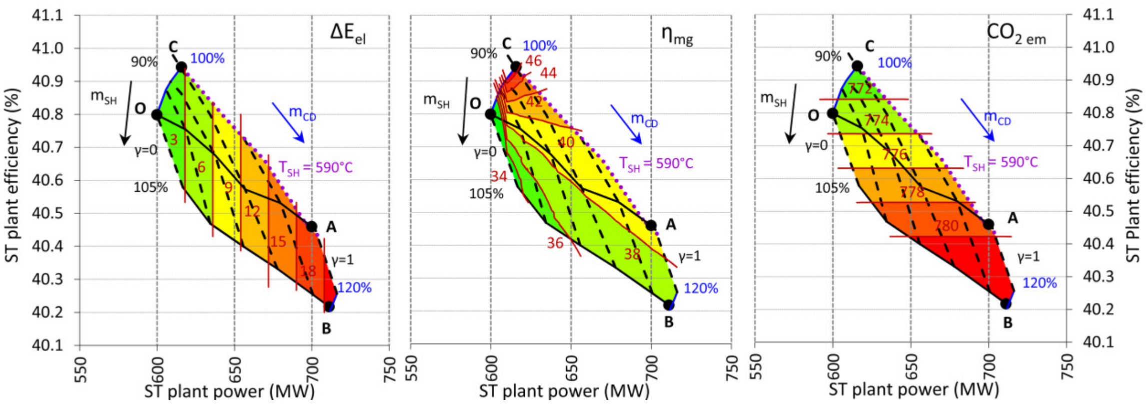

Fig. 4. Feedwater repowering based on based on throttling of HP steam bleedings: effects on energy and economic marginal indices

5.2. Gas turbine power plant integration

Maps in Figures 5 and 6 show the effects of feedwater repowering based on gas turbine integration on performance parameters (η_{IRP}, P_{th}, P_{GT}, C_{FR}, COE, $CO_{2,em}$) of the integrated steam-gas power plant and on marginal indices (ΔE_{el}, η_{marg}, COE_{marg}) respectively.

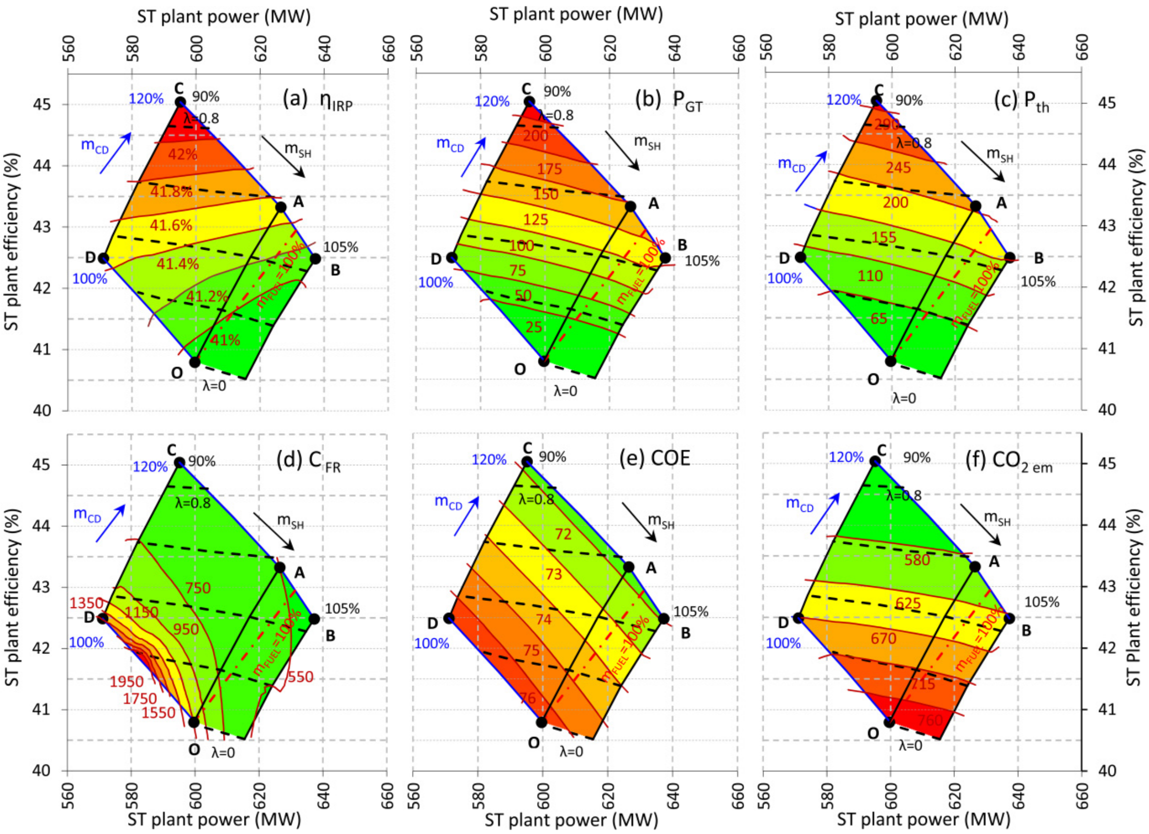

Fig. 5. Feedwater repowering based on gas turbine integration: effect on performance parameters of the integrated steam-gas power plant

Increasing λ at m_{SH}=100% (curve OA), the rated capacity (Fig. 5b) and the thermal power (Fig. 5c) provided by the additional gas turbine increase, due to the progressive reduction of extractions from low and high pressure steam turbines. As a result, the capacity of the integrated steam-gas power plant increases, due to the higher steam cycle power and to the contribution of the added gas turbine, that reaches a rated power of 149 MW at point A (m_{CD}=120%, λ=57.3%). Under these operating conditions, the steam-gas power cycle states at 775 MW, thus enabling an electricity gain of about 30% (Fig. 6a), attributable to the steam cycle for the 15% and to the additional gas turbine for the remaining 85%. Despite the marginal efficiency of about 44% (Fig. 6b), the integrated steam-gas cycle efficiency increases of less than 1 percentage point (41.5%) with respect to design conditions. Due to the efficiency gain and to the partial fuel shift from coal to natural gas, specific CO_2 emission markedly reduces, from 760 to 589 kg/MWh (Fig. 5f). From the economic point of view, due to the progressive increase of gas turbine rated power, the specific cost of repowering intervention reduces, reaching about 558 $/kW (Fig. 5d) at point A. Having a cost of marginal electricity of about 57.6 $/MWh, the COE reduces from 76 $/MWh (at design conditions) to 71.7 $/MWh (Fig. 5e).

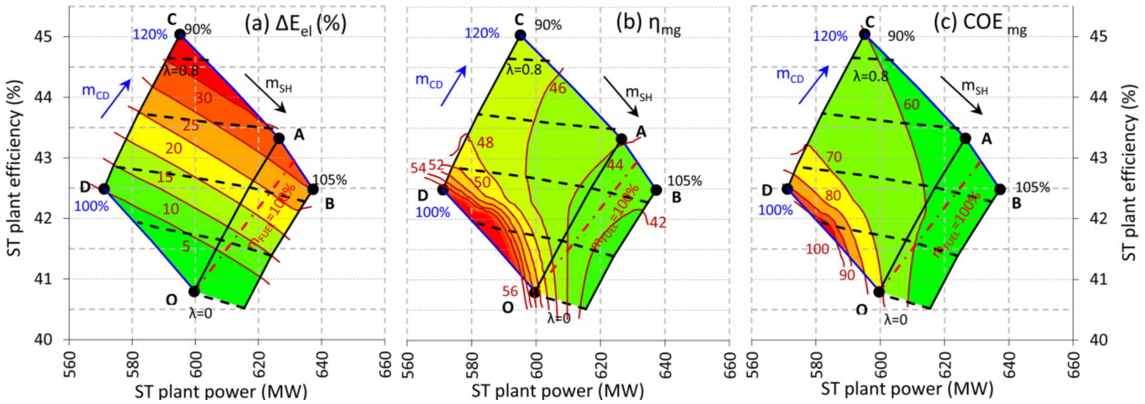

Fig. 6. Feedwater repowering based on gas turbine integration: effects on energy and economic marginal indices

Starting from point A and increasing the superheated steam flow production at maximum condenser overload, λ reduces, reaching 43.7% at point B (m_{SH}=105%). Consequently, thermal power from exhaust gases reduces to 160.7 MW, while the rated capacity of the added gas turbine to 115 MW. Hence, in spite of the increase of steam power cycle capacity, the electricity gain of the integrated steam-gas power cycle reduces to 25%, the additional gas turbine accounting for about 75%. Compared to the point A, the marginal efficiency decreases (42.3%), due to the lower efficiency of the gas turbine (34.8%) and to the increase of the coal flow rate (59.1 kg/s), that adversely affects the specific CO_2 emissions (630 kg/MWh). In spite of the reduction of the gas turbine size, the specific cost of the repowering intervention decreases to 530 \$/kW, due to the decrease of the water-gas heat exchangers surfaces. Hence, the unit cost of marginal efficiency reduces (56.5 \$/MWh), whereas COE slightly increases, due to the greater incidence of capital charge and O&M contributions.

On the other hand, starting from point A and decreasing the superheated steam flow production at maximum condenser overload, the feedwater deviation λ increases up to a maximum value of 88% at point C (m_{SH}=90%). Due to the coal saving, the steam plant capacity reduces, while the electricity gain of the integrated steam-gas cycle exceeds 35% , fully ascribed to the additional gas turbine (215.8 MW). Due to the higher gas turbine efficiency and to the reduction of coal flow rate, marginal efficiency increases up to 47%. This positively affects the global efficiency (42.2%), as well as the specific CO_2 emission, that reaches a minimum value of about 515 kg/MWh, also due to the substantial fuel shift from coal to natural gas. Moreover, this issue accounts for an increase of fuel costs incidence, allowing to a higher unit cost of marginal electricity (60.3 \$/MWh). Conversely, the unit cost of electricity remains almost unchanged (71.8 \$/MWh), as the effect of fuel costs increase is offset by the reduction of the capital charge contribution.

Reducing condenser overload at constant superheated steam flow production (m_{SH}=90%), the deviation from feedwater heaters reduces, reaching 30.6% at point D, featured by the minimum value of the steam power cycle (571 MW). Due to the integration of a gas turbine with a rated power of 62 MW, the steam-gas power plant capacity states at about 633 MW, leading to an electricity gain of 5%. The marginal efficiency increases significantly compared to the previous cases, as the effects of coal saving are accentuated by the low gas turbine size. However, due to the slight electricity gain, global efficiency reduces with respect to maximum condenser overload conditions (41.4%), while specific CO_2 emissions (670 kg/MWh) exceed those at point B, despite to the lower fuel flow (52.9 kg/s). The small gas turbine size adversely affects the specific cost of repowering intervention and the unit cost of marginal electricity, that reach about 1540 \$/kW and 92.4 \$/MWh. Consequently, COE increases, almost equating the design value.

6. Conclusions

The present study aimed to evaluate the benefits of a feedwater repowering intervention of an existing steam power plant, varying condenser overloads and boiler operating conditions. The analysis enabled the definition of a characteristic plane with color maps that identify the range of variability of energy, economic and environmental system performances, thus allowing the comparison of different feedwater repowering options.

When feedwater repowering is operated by throttling of high pressure steam bleedings, the study shows that the power plant capacity gain ranges from 3 to 18%, at the expense of a fuel flow increase for feedwater preheating. If boiler operates with m_{SH} lower than 100% and the condenser overload is relatively low, the marginal efficiency exceeds 40%. However, due to the slight electricity gain (lower than 5%), the benefits on global efficiency and specific CO_2 emissions are quite contained and COE is comparable to the design value. On the other hand, if m_{SH} is higher than 100%, the electricity gain reaches about 20% at maximum condenser overload, whereas marginal efficiency falls below 40%, due to the greater fuel flow consumption. As a result, the steam cycle efficiency reduces of less than 1 percentage point, with an increase of CO_2 emission of about 2%. Moreover, having a marginal cost of electricity in the range 30-40 \$/MWh, COE significantly reduces, falling below 70 \$/MWh for γ=1.

When feedwater repowering is operated by integrating a gas turbine, the analysis highlights that the capacity gain increases with feedwater deviation from regenerative heaters, up to a maximum value of about 35%. If the condenser overload is relatively low and m_{SH} lower than 100%, the marginal efficiency takes values higher than 50%, with an electricity gain lower than 10%. As a result, the global efficiency increases of less than 1 percentage point, whereas the specific CO_2 emission drops below 700 kg/MWh. Due to the small size of the additional gas turbine, the specific cost of repowering intervention ranges from 1100 to 1900 \$/kW, whereas the unit cost of electricity slight decreases with respect to design conditions. On the other hand, increasing λ at maximum condenser overload, the size of the additional gas turbine increases from 125 to 200 MW, the electricity gain from 25 to 35%, while the marginal efficiency from 42 to about 47%. The efficiency gain of the whole integrated steam-gas power plant is about 1 percentage points, while the specific CO_2 emissions reduce from 630 to 515 kg/MWh, due to the higher fuel saving and to the greater fuel shift from coal to natural gas. The specific cost of the repowering intervention increases from 530 to about 600 \$/kW, due to a higher incidence of the heat exchangers capital costs, while the unit cost of electricity is always below 72 \$/kWh.

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