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Flexible operation of combined cycle gas turbine power plants with supplementary firing

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Abstract

This article covers the use of supplementary firing in a gas-combined cycle power plant when high flexibility is required depending on the penetration of variable renewable energies and under different gas turbine loads. Process models were simulated under different operating conditions with the software EBSILON®Professional. Five main conditions were studied for the designed combined cycle: gas turbine part-load without supplementary firing, gas turbine full load with supplementary firing, the use of supplementary firing to overcome the effect of changing ambient conditions, part-load gas turbine performance with supplementary firing technology and the use of supplementary firing in case of gas turbine shutdown.

Keywords: CCGT; duct firing; off-design performance; process simulation; flexibility

1. Introduction

Over the years, research and development has enabled continual increases in plant efficiency for Combined Cycle Gas Turbine power plants (CCGTs). Developments in operational flexibility have accelerated, driven by changes in the power sector. The advantages that this technology provides are higher thermal efficiency, lower installed and maintenance costs, higher fuel flexibility, shorter installation times and high availability compared to coal-fired power plants [1].

With increased concern about reducing greenhouse gas emissions, the use and development of renewable energies have reached higher levels in recent years. Their inclusion in the electricity market results in larger supply fluctuations than before due to their variable generation of power. Because of this, the design and optimization of thermal power plants have become necessary in order to improve their flexibility and meet low and peak demands when necessary, increasing their cycling capabilities. In this respect, supplementary firing technology might gain importance [2].

This study aims at analyzing the performance of a CCGT when the need to satisfy different electricity demands arises. To this end, process models of different plant configurations are presented and a study on off-design performance results included. Several papers cover off-design performance of the power plant when a gas turbine (GT) is operated at different loads [3–5]. Others focus their research on the use of technologies such as supplementary firing in order to show its affects on emissions, including for plants with post-combustion CO_2 capture systems [6–8]. Some studies consider the use of biomass as a supplementary fuel, including analysis of the optimal process conditions [9] and energy and exergy analyses [10]. Conte et al. conducted a thermo-economic optimization of the CCGT design with supplementary firing, considering off-design performance and operating profile [11].

However, no study has been identified on how supplementary firing affects the performance of the power plant with different operational conditions - full load, peak load, or part load operation combined with different exhaust temperatures due to the higher or lower fuel consumption in the supplementary firing boiler. For this reason, five different operational strategies have been studied and are presented in this article.

Supplementary firing technology is a way of increasing plant power output by installing duct burners in the Heat Recovery Steam Generator (HRSG) [12]. Normally, in a CCGT with a single stage of combustion, there is an excess of oxygen due to the non-stoichiometric conditions in the combustor. With the use of supplementary firing, the temperature of the exhaust gases can be increased by combusting a fuel with the remaining oxygen. This allows for independent control of the electrical and thermal outputs when applied to cogeneration plants [13]. When supplementary firing is used,

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the amount of steam flowing through the steam turbine increases, which results in higher power output, but also in lower efficiency due to the extra fuel that has to be used in order to carry out the combustion process. In addition, using supplementary firing is found to be a good choice due to the flexibility it offers in variable heat loads, and the rise that can be obtained in the heat-to-power ratio of the CCGT (up to 5:1) [13].

One important role of supplementary firing occurs when the plant operates at lower GT loads. In an unfired HRSG, steam production will decrease, as less heat is available from the GT, while the supplementary firing is able to compensate this difference. During a GT shutdown, steam production can be maintained at certain levels thanks to supplementary firing [14]. Also, for changing ambient conditions, it can offset the effect of the change of the mass flow and temperature of the exhaust gases [14]. The use of this technology is well justified for off-design conditions in order to assure a higher steam production and temperature when required (fluctuations in the ambient temperature, peak demands, etc.). It enables the peak load to be increased, but the capital cost rises as a consequence [2].

Supplementary firing cannot be used without a limit, due to the temperature restrictions that the steam turbine presents in the form of the so-called metallurgical limit, of around 850 K [12], and temperature limitations in the HRSG tubing. The amount of fuel used in the supplementary boiler has to be controlled according to the requirements that need to be met, including gross power output, heat demand, and emissions while staying within allowable temperature ranges.

2. Model description including performance indicators and boundary conditions

The software that was used to carry out the modelling and simulations is EBSILON®Professional V.11.04. [15]. It is a process simulation software that simulates thermodynamic cycles based on energy and mass balances, and it is used for engineering, designing and optimization of plants. In the following section the main performance indicators and boundary conditions are presented.

2.1. Performance indicators

GT and steam cycle efficiencies are defined in Equations (1) and (2), respectively [12]:

$$\eta_{GT} = \frac{\dot{W}_{GT}}{\dot{Q}_{GT}} \tag{1}$$

$$\eta_{SC} = \frac{\dot{W}_{ST}}{\dot{Q}_{GT,Exh} + \dot{Q}_{SF}} \tag{2}$$

Where heat input in the GT, Equation (3), and exhaust heat, Equation (4), are:

$$\dot{Q}_{GT} = \dot{m}_f \cdot LHV \tag{3}$$

$$\dot{Q}_{GT,exh} \cong \dot{Q}_{GT} \cdot (1 - \eta_{GT}) \tag{4}$$

Net plant efficiency is defined in Equation (5):

$$\eta_{CC} = \frac{\dot{W}_{ST} + \dot{W}_{GT} - \dot{W}_{aux}}{\dot{Q}_{GT} + \dot{Q}_{SF}} \tag{5}$$

From Equations (2) and (4), steam cycle efficiency is defined as:

$$\eta_{SC} = \frac{\dot{W}_{ST}}{\dot{Q}_{GT} \cdot (1 - \eta_{GT}) + \dot{Q}_{SF}} \tag{6}$$

Equation (6) expresses the steam cycle efficiency of the combined cycle. For a combined cycle in which there is no supplementary firing being used, we can make an assumption in order to get an easier expression as shown in Equation (7):

$$\begin{gathered} \dot{Q}_{SF} = 0 \\ \eta_{SC} = \frac{\dot{W}_{ST}}{\dot{Q}_{GT} \cdot (1 - \eta_{GT})} \end{gathered} \tag{7}$$

If supplementary firing were added to the installation, efficiency would decrease, meaning that it is better in terms of efficiency to burn all the fuel directly in the GT combustion chamber than in the HRSG.

Combining equations (1), (5) and (7) gives the next expression (8):

$$\eta_{CC} = \eta_{GT} + \eta_{SC} \cdot (1 - \eta_{GT}) \cdot \theta_{HRSG} \tag{8}$$

Equation (8) shows a new term (θ_{HRSG}). This term expresses the amount of heat that is used from the exhaust gases to heat the water in relation to the available heat. Reference [12] does not consider it; however, it was added in this study because not all of the heat from the exhaust gases is used to heat the working fluid in the Rankine cycle. The expression for this term is:

$$\theta_{HRSG} = \frac{\dot{m}_b (h_{ST,in} - h_{eco,in})}{\dot{m}_{exh} (h_{GT,out} - h_{amb})} \tag{9}$$

Where h_{amb} is the enthalpy the exhaust gases would have if they reach the ambient conditions (15°C and 1.013 bar).

2.2. Boundary conditions and assumptions

The main boundary conditions and assumptions for the main components of the cycle can be found in Table 1. These assumptions are based on the available information from Bolland [16]. The rest of the assumptions made for the design case can also be found in this reference and in Fig. 1, where the design model is presented. In the design model in Fig. 1, SF is not activated. Saturated condensate at the condenser outlet is assumed.

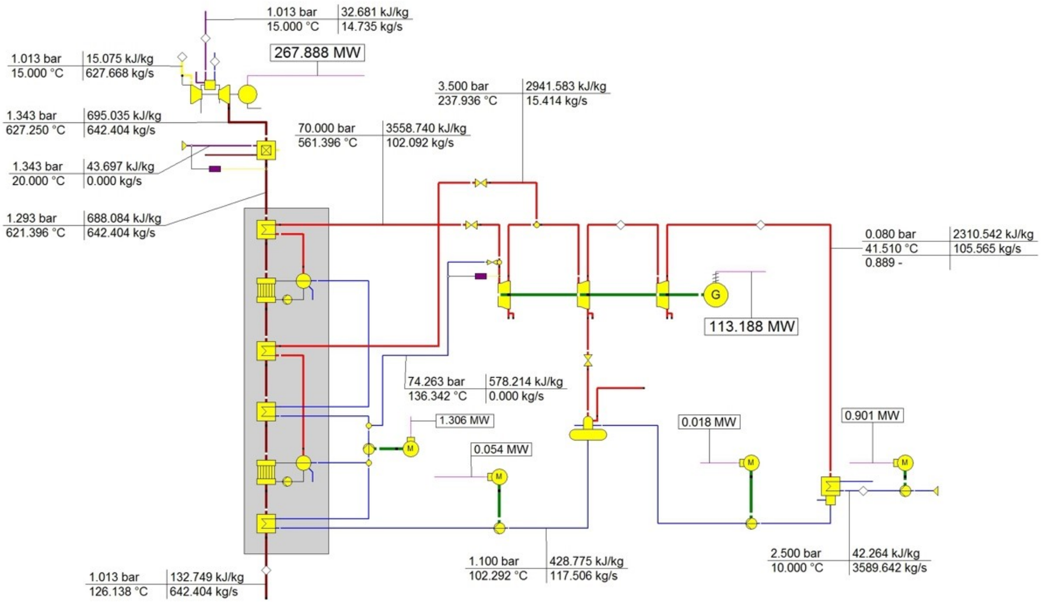

Figure 1: Flow sheet of process model without supplementary firing. This figure shows the design point of the process, with $\dot{Q}_{SF} = 0$

Table 1: Boundary conditions for the combined-cycle

Parameter	Assumption value
Ambient conditions	
- Temperature, °C	15
- Pressure, bar	1.013
Water cooling	
- Condenser pressure, bar	0.08
Gas turbine	
- Model	ALSTOM GT26 Gas
- Fuel type	Methane
H.P steam turbine	
- Pressure, bar	70
- Isentropic efficiency, %	92
L.P steam turbine	
- Pressure	3.5
- Isentropic efficiency, %	88
Superheater	
- Terminal temperature difference, °C	60
- Evaporator	
- Pinch point temperature difference, °C	25
- Approach temperature, °C	10

2.3. General description of the cycle

The cycle was designed with a dual-pressure HRSG. This choice was made based on the analysis of losses carried out in [12], in which it is found that increasing the number of pressure levels leads to a reduction of the stack losses of the total fuel energy input, but the increased Low Pressure (LP) steam mass flow means more energy is lost in the condenser. If a dual-pressure steam cycle instead of a single-pressure is used, higher efficiency could be expected because the average temperature at which heat is transferred to the steam is increased [17]. Triple pressure cycles can lead to higher efficiency compared to the single- and dual-pressure cycles, but the advantage diminishes for high flue gas temperatures, such as when using supplementary firing [12].

Depending on the boundary condititions for the plant, the design point of the steam cycle could be with or without supplementary firing. In this work, the design point for the cycle was selected with supplementary firing deactivated and the GT operating at full load. In other words, the plant was in off-design operation when using supplementary firing. This delivers high flexibility; in order to meet lower demands, the GT load will be adjusted and, when meeting peak demand, supplementary firing will be used. This configuration, as shown in Fig. 2 in which supplementary firing is utilized to get a firing temperature of 850°C, provides a higher reserve capacity which may lead to competitive advantages in the electricity market. From Fig. 1, it can be seen that when supplementary firing has no fuel input, the nominal net power is 267.9 MW for the GT and 113.2 MW for the ST, with the net efficiency of the power plant being 51.7%.

Since supplementary firing increases the temperature of the exhaust gases, more heat is available for the HRSG heat exchangers. This higher heat transfer means the inlet temperature of the steam at the high-pressure steam turbine could exceed the established limitation (it is assumed that the steam turbine can withstand a maximum live steam temperature of 570°C). In order to avoid damage in the steam turbine, desuperheating of the steam is carried out by means of spraying water from the high-pressure economizer. This is done by a controller that regulates the amount of injected mass flow as a function of the steam turbine inlet temperature. The vapor quality reaches a value of 0.889 at the outlet of the low-pressure steam turbine during design conditions.

Another controller regulates the fuel mass flow at the supplementary firing. The model was configured to control the fuel mass flow depending on the temperature of the exhaust

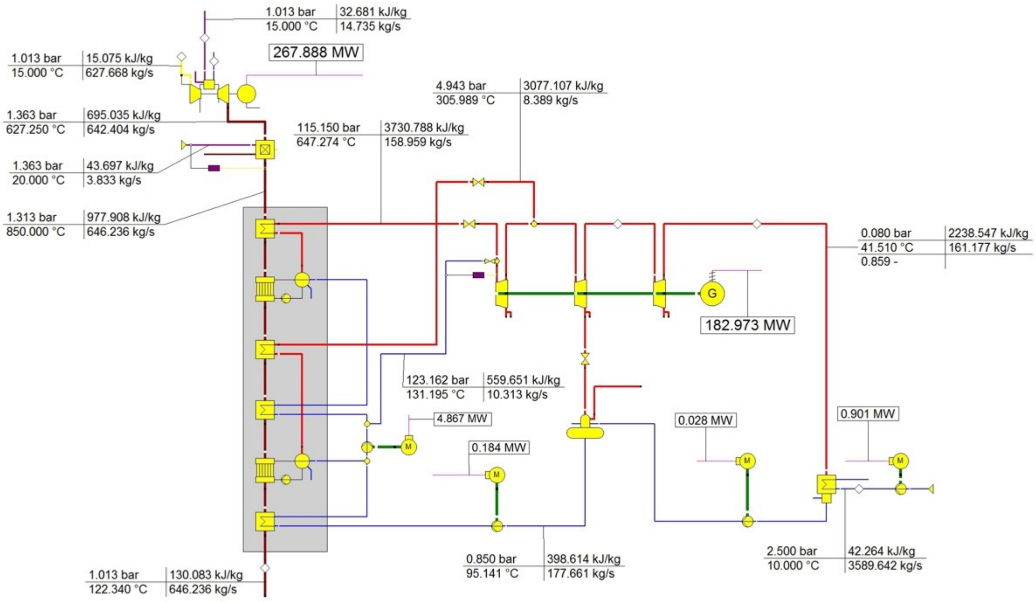

Figure 2: Dual-pressure HRSG cycle with supplementary firing, in which a target SF temperature of 850 ℃ is employed

gases at the outlet of the supplementary firing.

2.4. Off-design model

Studying the off-design conditions for a CCGT means studying how the system reacts to changes in boundary conditions or other operational parameters. Depending on the power demand, ambient conditions, operational strategies and other parameters, the plant may operate for prolonged periods at off-design conditions. This is why it is important to ensure that the system has a satisfactory performance at design and off-design conditions.

2.4.1. GT and Steam Turbine

The main off-design conditions simulated for the cycles consisted of part-load GT performance and supplementary firing functioning. For the GT model, the selected Alstom GT26 was utilized from the VTU library [18]. The GT models include correction curves that were developed by the library supplier in collaboration with the GT vendors. The correction curves for the GT model include combinations of ambient temperature, ambient pressure, inlet pressure drop, exhaust pressure drop, relative humidity and GT load; each of them paired with power output (rating), heat rate, exhaust mass flow rate, exhaust temperature and cooling duty.

The main equation that defines the steam turbine flow characteristic is defined by Stodola's cone law in Eq. 10. For GT loads higher than 50%, sliding pressure operation was implemented. For lower loads, the live steam pressure was fixed by throttle control [12].

$$\frac{\dot{m}_b}{\dot{m}_{bo}} = \frac{P_{inlet}}{P_{outlet}} \cdot \sqrt{\frac{P_{inlet,o} \cdot v_{inlet,o}}{P_{inlet} \cdot v_{inlet}}} \cdot \sqrt{\frac{1-\left(\frac{P_{outlet}}{P_{inlet}}\right)^{\frac{n+1}{n}}}{1-\left(\frac{P_{outlet,o}}{P_{inlet,o}}\right)^{\frac{n+1}{n}}}} \qquad (10)$$

Section 3.3 analyses the performance of the GT for a given scenario in which the ambient conditions changes provoke a reaction in terms of GT capacity. Therefore, it is important to understand how these parameters may affect the functioning of the power plant. The ambient conditions may change considerably throughout the year. It is important to study the sensitivity in order to predict the change in the mass flow rate that is going to be found under off-design conditions.

2.4.2. Heat Recovery Steam Generator

In off-design scenarios the overall heat transfer coefficient of the heat exchangers will vary. For off-design calculations, the overall heat transfer coefficient $U \cdot A$, i.e. heat transfer coefficient U (W/m^{2}K) multiplied by heat transfer area A (m^2), is corrected via a correction curve as a function of the exhaust gas mass flow rate $\dot{m}_{exh}$. Variations in HRSG experiments occur due to changes in properties of the exhaust gases. For example, an adequate level of superheating of the steam must be maintained. To do so, a system that regulates the feedwater valve as a function of the steam temperature is used (superheated steam temperature control by feedwater injection) [19, 20].

2.4.3. Pumps

Pumps are able to operate over a wide range of capacities. The operating point is found where the pump-head capacity

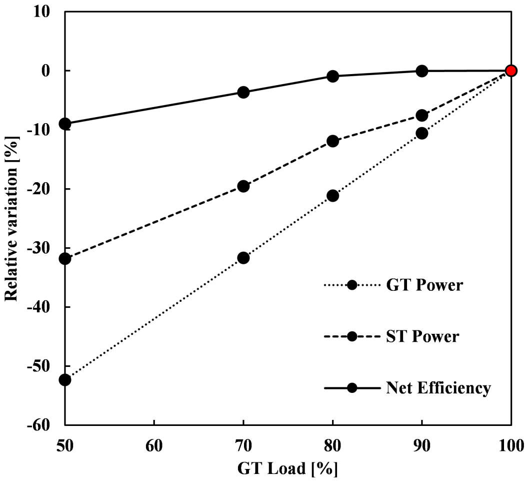

Figure 3: Effect of the GT load on the GT power output, the steam turbine power output and the net plant efficiency. Reference values at 100% GT load are: 267.9 MW GT power, 113.2 MW ST power, and 51.7% net efficiency

Table 2: Effect of the GT part load on main parameters of the cycle

Load	100 %	90 %	80 %	70 %	60 %	50 %
GT Power, MW	267.9	239.6	211.3	183.0	164.7	127.8
Fuel mass flow rate, kg/s	14.7	13.3	11.6	11	9.8	8.7
GT Exhaust gas mass flow rate, kg/s	642.4	586.3	528.3	480.4	442.3	406.3
GT Exhaust temperature, °C	627.3	629.5	650	650	650	650
H.P, bar	70	64.6	61.7	56.5	52.2	48.1
L.P, bar	3.5	3.3	3.1	2.9	2.7	2.6
Steam mass flow rate, kg/s	117.5	107.4	99.9	90.6	83.2	76.2
θ_{HRSG}	82.5	82.8	83.7	83.9	84.1	84.3
η_{sc}	31.7	31.9	32.2	32.3	32.3	32.4

curve and the system-head curve intersect. Off-design conditions for pumps are any conditions in which delivering flows in excess or below the capacity at best efficiency is required. Due to the low power demand that the pumps require compared to the power output delivered by the designed power plant, off-design analysis for the pumps loses importance.

3. Results and discussion

3.1. Part-load supplementary firing

Fig. 3 shows the performance of the GT and steam power output as well as the net power plant efficiency for different off-design GT loads. In addition, it can be seen in Table 2 that from full load to 50% load the fuel mass flow decreases by almost 40%, while, as shown in Fig. 3, the GT power output decreases by almost 55%. Note that the HRSG efficiency increases while the steam mass flow decreases. The reason for this is that from the available heat at the HRSG (although it is lower than the nominal value), more heat is used as a proportion. Because of the sliding pressure, the high and low pressure decrease, meaning that the evaporation temperature is lower. Less heat is then needed per kilogram of generated steam, resulting in better use of the heat. However, the power output that the steam turbine can provide falls due to two reasons: the generated steam mass flow is lower (because of the lower available heat from the exhaust gases), and the enthalpy drop from the turbine inlet and outlet also diminishes as a consequence of the lower pressure at the entrance. No water injection is needed in this model since the turbine inlet temperature never exceeds the temperature limitation. Also, it can be seen that from full load to 80% load, the θ_{HRSG} increases around 1% due to the higher exhaust gases temperature (it changes from 627°C to 650°C) and for loads below 80% this value keeps almost constant owing to the fixed exhaust gas temperature (650°C). Efficiency results were expressed as a relative variation, having the full-load case efficiency (51.7 %) as the reference value. Therefore, by controlling the GT performance, we can achieve combined cycle power outputs from 381.1 MW (full load) down to 205.0 MW (50% GT load).

Table 3: Main results for the combined cycle when operating at the design point and when the supplementary firing outlet temperature on the exhaust side is 850°C

Parameter	Value design	Value (850°C SF outlet temperature)
Supplementary firing		
Fuel mass flow, kg/s	0	3.8
HRSG		
Generated steam, kg/s	117.5	167.3
Steam turbine		
Power output, MW	113.2	183
Injection mass flow, kg/s	0	10.3
η_{sc}, %	31.7	33.4
θ_{HRSG}, %	82.5	88.0
H.P., bar	70	115.2
L.P., bar	3.5	4.9
Combined cycle		
Power output, MW	381.1	450.9
Net plant efficiency, %	51.7	48.6

3.2. Peak load

Similarly, as the GT load has to be decreased to meet lower demands, power production may have to be increased to satisfy peak demand. In this case, no change has to be made for the GT operational conditions, and the difference between the design power production and the peak power production is achieved by enabling supplementary firing. Different supplementary firing outlet temperatures have been analyzed (750°C, 800°C, 850°C, 900°C and 920°C). The results obtained for the design conditions and for off-design conditions (an exhaust gases temperature of 850°C out from the supplementary firing) are shown in Table 3. Energy balances for both cases are presented in Fig. 4.

From Fig. 4, it can be seen that the use of heat in the HRSG improves with the use of supplementary firing (losses can be reduced by 3%). Also, the steam turbine power output increases considerably although the proportion of this power in relation to the energy added through the fuel is lower than for the design point, hence the efficiency drops. Losses in

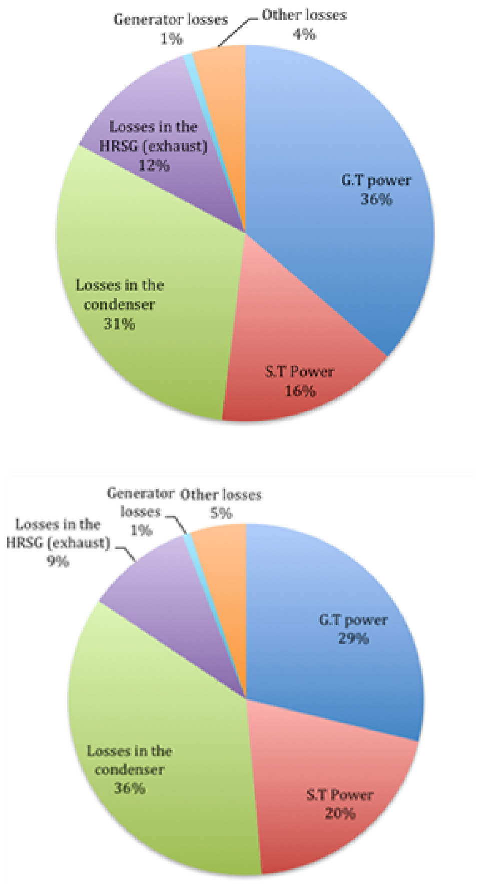

Figure 4: Energy balances for the design point (upper) and the performance of the combined cycle power plant when the supplementary firing outlet temperature on the exhaust side is 850°C (bottom)

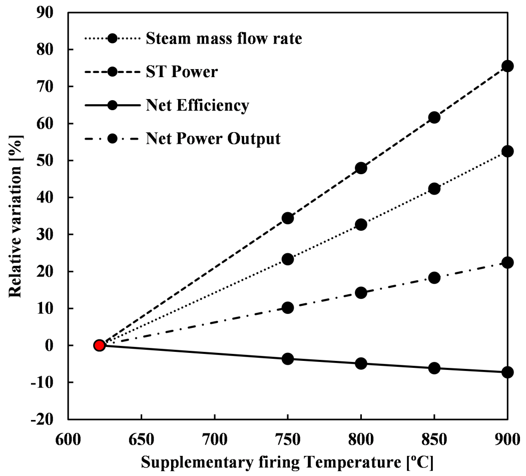

Figure 5: Effect of the supplementary firing outlet temperature on the net efficiency, the net power output, the steam mass flow and the steam turbine power output. The reference values are: 117.5 kg/s steam mass flow rate, 113.2 MW ST power, 51.7% net efficiency and 381.1 MW net power output.

the condenser increase due to the higher steam mass flow rate that is produced with the use of supplementary firing, while the generator losses proportion keeps constant. The other losses, attributed to the auxiliary power, deaerator and other heat losses, increase as a consequence of the higher water mass flow.

Fig. 5 indicates that the steam turbine power output shows the highest variation in relation to the design point, when supplementary firing is used.

Due to the higher temperatures obtained at the HRSG inlet, more heat is available for exchange at the different heat exchangers and higher steam mass flow is produced. The enthalpy drop at the steam turbine is the same, because the steam turbine inlet temperature was controlled through the injection of water. Although more power is produced, more fuel is being used for supplementary firing, resulting in lower net efficiency. Without supplementary firing, the GT produces two thirds of the overall power output. When supplementary firing is functioning with its highest allowed capacity at peak load, the bottoming cycle produces almost half of the power output of the entire power plant. Thus, the efficiency of the steam turbine becomes considerably more important with respect to determining the net efficiency of the combined cycle.

3.3. Supplementary firing to counter the effect of increasing ambient temperature

Ambient conditions have a major impact on GT efficiency and power output. This directly affects the bottoming cycle. With increasing ambient temperatures, the power output achieved in the GT can be dramatically reduced. In these cases, the use of supplementary firing can overcome this effect by raising the power output from the steam turbines. The effect of ambient temperature on net efficiency is less pronounced: GT efficiency drops almost 4% when moving from -10°C to +25°C. Ambient pressure can also affect the functioning of the power plant, as shown in Fig. 6 where a pressure drop of 0.06 bar causes a GT efficiency drop of 0.2% (due to the lower power output achieved). Since these ambient conditions cannot be controlled, it is important to have means to compensate for changing ambient conditions or to provide enough electrical power when demand increases.

3.4. GT part load with supplementary firing

It is well known that decreasing the GT load results in lower efficiency and power output, while the use of supplementary firing allows higher power output to be obtained. Therefore, why would combining these two strategies be an advantage for a power plant? The best possible scenario for these simulating conditions relates to one of the advantages that supplementary firing provides: fuel flexibility. If the duct burners are designed for another fuel, for example hydrogen, there may be an economic advantage for the power plant to reduce the GT load and burn more fuel in supplementary firing when natural gas price is high compared to other fuel sources. Although efficiency decreases, it could deliver important savings. For certain plant setups, typically for smaller

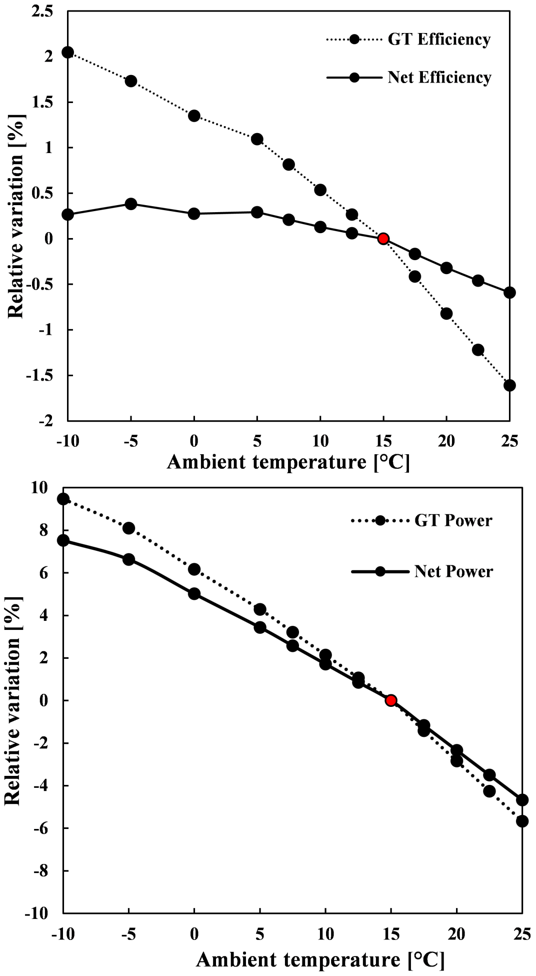

Figure 6: Effect of the changing ambient temperature (upper and middle) and pressure (bottom) on GT and net efficiency; and GT power and net power. Reference values are at ISO conditions of 15 oC and 1.013 bar: 36.4% GT efficiency, 51.7 % net efficiency, 267.9 MW GT power output and 113.2 MW ST power output

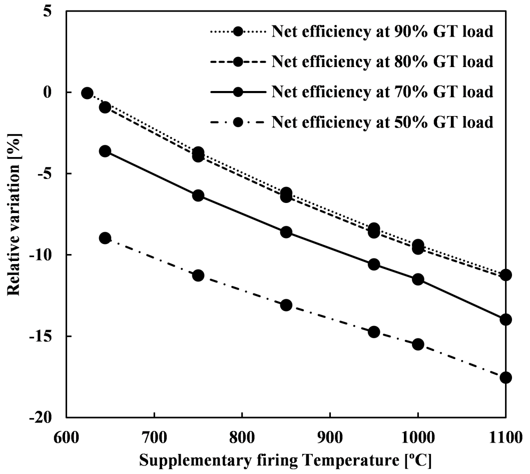

Figure 7: Effect of the supplementary firing outlet temperature on CCPP efficiency under different GT loads. All values are calculated based on nominal value at design point of 51.7% net efficiency

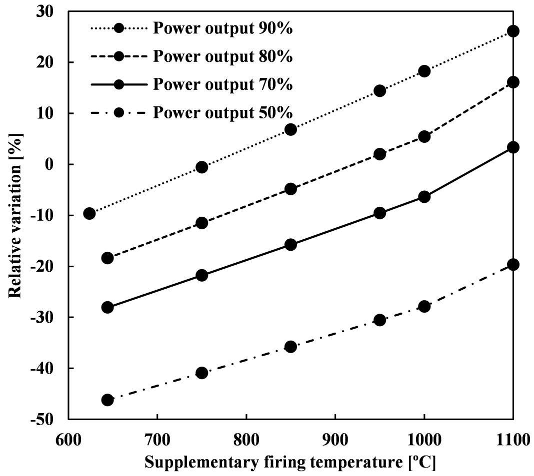

Figure 8: Effect of the supplementary firing outlet temperature on power plant power output at different GT loads. The reference value is the one at nominal conditions of 381.1 MW

gas turbines than in this study, the GT could be coupled with a direct mechanical drive which sets the demand from the GT. By adding supplementary firing as another degree of freedom, one could to a certain degree decouple the power produced in the GT and the ST.

Due to the design of the cycle, live-steam pressure decreases with part-load performance while the exhaust gases mass flow also reduces. This allows higher temperatures to be obtained at the supplementary firing outlet without experiencing simulation problems at the heat exchangers or needing to change the pinch point. Although under the listed conditions it is not likely to find the GT operating at lower than 80% loads, loads as low as 50% loads have been simulated in order to gain a better understanding of the variation.

In Fig. 7 it can be seen that all the lines seem to follow the same trend, and that the efficiency for loads of 80% is similar that for loads of 90%. Since the power output produced in both the GT and the steam turbine is higher for loads of 90%, the explanation is based on the exhaust gases temperature and mass flow. The exhaust gases mass flow falls when moving from 90% GT load to 80% GT load, while the use of the available heat at the HRSG inlet is higher for the 80% load, resulting in higher steam turbine cycle efficiency. Since the exhaust gases temperature experiences a high difference from 90% GT load (625°C) to 80% GT load (650°C), the amount of fuel needed at supplementary firing to reach the desired temperature is higher in the first case. As the GT efficiency does not vary greatly (less than 0.4%), the use of a higher fuel mass flow in supplementary firing determines similar efficiency for the 90% load when compared with the 80% load. On the other side, for loads below 80%, GT efficiency suffers a larger drop, while the exhaust gases temperature remains the same as before (650°C) and HRSG efficiency is not as high as it was for higher loads. This is the reason why net efficiency decreases significantly for GT loads below 80%.

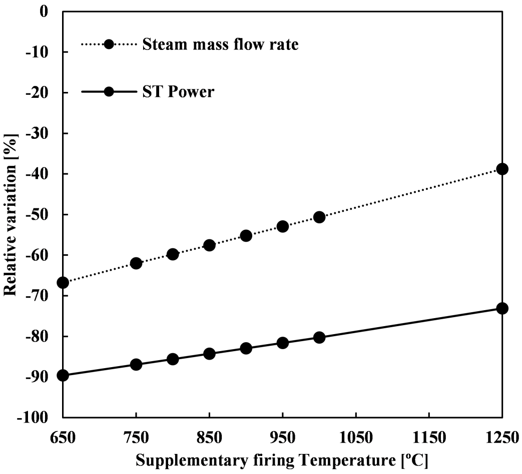

Figure 9: Effect of the supplementary firing outlet temperature on the total gross power output and steam mass flow production under GT shutdown. The reference value is the nominal value for total steam mass flow rate of 117.5 kg/s and combined cycle power output of 381.1 MW

Fig. 8 is a representation of how the power output changes in relation to the nominal one (381.1 MW). It can be observed that, even when the GT is working at part load, the combined cycle could achieve a higher power output with supplementary firing than without it at the design point for all cases but when the plant is operated at 50% GT load. For 90% load, with the lowest supplementary firing outlet temperature studied, the plant can almost produce the same power output as without it at full load. However, it seems that for loads lower than 70%, obtaining this power output was not possible. Thus, in these cases, using supplementary firing was inefficient. It has been shown in Fig. 5 that the use of supplementary firing can increase the net power output by 22.4% with respect to the net power achieved at the design point performance, which implies a maximum power output of 466.6 MW, while a net efficiency of 7.2% is lost. Supplementary firing adds importance to the steam turbine cycle, considering that this difference on the produced power output is due to the higher power that the steam turbines are able to produce (75.5% more than the one they produce at the design point). Losses in the condenser increase considerably when supplementary firing is used. Interesting results were found when the analysis of the cycle operating at GT part-load with supplementary firing was carried out. The power plant showed a similar net efficiency performance when it was functioning at 90% load than when the operating GT load was 80% with different levels of supplementary firing; for 900°C SF temperature, in the first case, a power of 421.5 MW was achieved, in the second one, the net power output was 375.7 MW. The explanation to these results was given basing them on the obtained exhaust gases results at the GT outlet.

3.5. Supplementary firing during GT shut-down

When a GT is offline, for example for maintenance, another advantage that supplementary firing provides is the ability of maintaining steam production at certain levels [2]. Fig. 9 shows how supplementary firing can maintain the production of steam while producing power. The use of supplementary firing can enable the production of 102.4 MW for really high temperatures at the supplementary firing outlet. Note that at GT shutdown, the steam turbine power output represents the total combined cycle power output. Simulations were carried out for SF temperatures up to 1250°C in order to show a larger operating window, but it must be noted that such temperatures might exceed the material temperature limit of the supplementary firing burners and tubes of the nearest superheater. This power production is 73% lower than the level achieved at the design point of the combined cycle, with 38% less steam generated. This reduction in power output, combined with the fact that net efficiency will reduce considerably since it only depends on bottoming cycle efficiency (between 26.3% and 31.9% depending on the amount of fuel used in the supplementary firing boiler), leads to two important considerations: (i) Is running the power plant to meet demand a good choice? (ii) Should supplementary firing be used merely to maintain the steam mass flow under certain levels so as to avoid shutdown of the entire power plant? Note that a fan must be installed at the HRSG inlet to overcome the HRSG pressure drop and to ensure that sufficient fresh air is provided to the supplementary firing duct burners for the firing process.

4. Conclusions

Adding supplementary firing can be of interest in terms of peak power and flexibility. Although flexibility could also be obtained when configuring the steam cycle design point for, say, 70% GT load (which also allows power production to be increased by raising the GT load), supplementary firing seems to be a good choice for achieving the highest possible operational flexibility. One reason for this is that, if the design point is established for 70% of the GT load, the efficiency at the design point would be lower than if the GT were functioning at full load, and the ST generator would be oversized, resulting in higher investment costs. Therefore, if our aim is to obtain high flexibility for power production, it might be cheaper and more efficient to add supplementary firing than to lower the GT load for the design point. Moreover, the fact of combining a ST cycle with a GT cycle allows one to maintain a certain level of power production when the gas turbine is under maintenance if supplementary firing technology is used.

The results obtained reflect that the flexibility achieved for the designed model (design point at GT full load) adding supplementary firing makes it possible to produce power with an operational window from 205 to 466.6 MW, for a plant at design point of 381.1 MW. The net efficiency of the plant decreases—compared to design point—when utilizing supplementary firing to produce peak load. When the plant is operating at design point without supplementary firing, the gas turbine produces around 2/3 of the total power output, while it produces around 1/2 of the total power output of the plant when supplementary firing is used.

Results were also obtained for the GT operating at part load with supplementary firing. In this case, the increase in power output is not as important as it is when the GT is functioning at full load. The plant showed similar net efficiency with supplementary firing when operated at 80% GT load as at 90% GT load when using supplementary firing. This is explained by the GT exhaust characteristics at part-load. The use of supplementary firing when the GT is operating at part load could be justified when it provides an economic advantage through burning fuels that are cheaper than natural gas in the supplementary firing burners.

Regarding the GT shutdown, the results showed that trying to maintain power production only by means of the steam cycle is not a good choice since overly high temperatures are required at the outlet of the supplementary firing (which may lead to material problems) and the cycle would be operating at unacceptably low efficiency. Therefore, the use of supplementary firing in the GT shutdown scenario should only be considered in order to maintain steam production and avoid shutdown of the entire power plant.

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Nomenclature

Acronyms and abbreviations

h	Specific enthalpy, J/kg
η, θ	Efficiency
A	Area, m^2
CCGT	Combined Cycle Gas Turbine Power Plant
GT	Gas Turbine
HRSG	Heat Recovery Steam Generator
HP	High Pressure
IGV	Inlet Guide Vanes
LP	Low pressure
TIT	Turbine Inlet Temperature
$\dot{Q}$	Heat duty, W
LHV	Lower Heating Value , W
$\dot{m}$	Mass flow rate , kg/s
n	Polytropic index
p	pressure, bar
T	Temperature, °C
v	Volume, m^3
W	Power, W

Subscripts

amb	ambient
p	Arrangement factor
f	Fuel
GT	Gas Turbine
i, in	Inlet

iso	Isentropic
SC	Steam Cycle
sf	Supplementary firing
ST	Steam Turbine
U	Heat transfer coefficient
aux	Auxiliary
b	Steam
cc	Combined cycle
$corr$	Corrected
e, out	Outlet
eco	Economizer
eva	Evaporator
exh	exhaust
o	Nominal conditions