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COMBINED CYCLE PERFORMANCE GAIN THROUGH INTAKE CONDITIONING

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ABSTRACT

The increasing share of electricity produced from renewable energy sources (RES), with the consequent strong penetration in the current energy network, is causing a growing need of balancing power to compensate power supply from such fluctuating sources. For these reasons, nowadays the power plants are running more often at part-load providing ancillary services and sustaining the grid operability. Therefore, an increase in efficiency during part-load operation impacts positively the year-round efficiency. A possible solution, studied in the framework of PUMP-HEAT H2020 Project[1] for flexibility enhancement, is characterized by the intake conditioning. Such concept, after a general introduction, is here applied to increase the temperature of the intake of power oriented combined cycle (PO-CCGT), mitigating the Gas Turbine off-design and resulting in an enhanced efficiency. In this work, a statistical analysis of actual PO-CCGT production profiles and climatic data is performed considering the Italian context, to assess the potential of this practice under the economic and environmental point of view.

INTRODUCTION

The need for flexibility experienced by the programmable power plants, is crucial for the future of the natural gas fired Combined Cycle Gas Turbine, CCGT, power plants, which are currently the backbone of EU electrical grid and are foreseen by the EU as the bridging technology (till the horizon of the 2050) to a decarbonized scenario, thanks to their reduced carbon footprint and fast response in terms of grid stabilization.

Within the PUMP-HEAT H2020 Project, a solution focusing on the conditioning of the gas turbine intake was presented for the Power oriented CCGT, exploiting the invariancy of the CCGT efficiency with the intake temperature, but the high impact over the power produced. The complete layout integrates the CCGT with an Heat Pump, HP, and a cold Thermal Energy Storage, TES, in an approach that is OEM independent. The selection of the heat pump as cooling equipment is due to the chance to charge the TES during the low electrical price periods to reduce the minimum environmental load, or even acting, in a demand response scheme as a smart load when the CCGT is off. The use of an air-cooled Heat Pump was made for sake of generality, because does not requires specific sites condition for the installation.

In particular, the Integrated Inlet Conditioning system, Figure 1, allows increasing the operation flexibility of CCGT in term of: 1) Power Augmentation: useful during high electricity price periods (Peak Periods), to increase CCGT power output; 2) Minimum Environmental Load reduction; 3) Off-design efficiency enhancement.

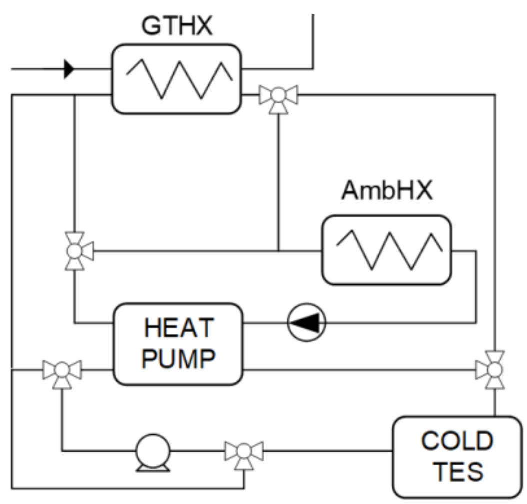

Figure 1 – Integrated Inlet Conditioning Layout

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The thermodynamic performances of the system were assessed by Sorce et al. (2019): 1) Discharging the TES has the potential, starting from the summer condition (35°C), to increase power output up to 50 MW (+14%) while efficiency slightly increases by 0.1 percentage point (+0.17%); while using the HP for continuous cooling, once the TES is empty, results always in an efficiency reduction.

2) The Minimum Environmental Load reduction, particularly useful during low electricity price periods, brings to a decrease in fuel consumption, increasing turn down period sustainability with respect to an intraday shutdown/start-up cycle. Increasing inlet temperature up to 45°C, a load reduction of 30 MW (-16%) against an efficiency reduction of just 0.75 pt% (-1.5%) can be achieved with respect to MEL at ISO condition. This results into a fuel consumption reduction which enables to prolong turn down periods (up to 15%), increasing the running hours and thus the chance of revenues in the ancillary service market. Concerning the analysis of pollutant emissions: despite the longer turn down period, CO2 emissions are lower via inlet heating, even without taking into account the avoided SU/SD emissions.

3) The off-design efficiency enhancement, during intermediate load operation by the means of inlet heating was assessed, as well as the increase in part-load efficiency and in annual average efficiency. The adoption of the HP in the Power Oriented configuration, as continuous heating, can bring about 1.2% increase of the average efficiency yearly; while using a Cold TES, decreasing the HP evaporator temperature, the global efficiency enhancement is reduced to 0.5%.

Mantilla et al. (2020) assessed the economical performance of such system basing on a MILP optimization strategy that it fully accounts for the complexity of the energy system, considering the trade-off between component performance and the revenue obtained under various scenarios. The CCGT integrated with the inlet conditioning unit on an Italian case (Nord Zone) increases its annual operational profit by 1.05% and presents a positive difference of 0.5% in NPV than a conventional power plant, with an HP size between 2.0 to 3.5 MW of electrical capacity and a thermal energy storage between 5 to 10 MW. This indicates that, even focusing on a specific case located in Turin (average market conditions and unfavourable climatic condition) the integration of the unit becomes a viable solution for current and new projects, even if considering energy-only revenues.

Giugno et al. (2021), demonstrated as the optimal sizing of the HP even for the simpler continuous cooling integration (without the TES) is highly dependent by both market and meteorological conditions. Beside the rule of thumb that an air-cooled heat pump, with an electrical consumption of the 1% of the electrical combined cycle capacity, 4MWe over 400 MWe F-Class CCGT, is enough to maximize the power production in the temperate climate (i.e. Humid subtropical climate and Mediterranean hot summer climates zones), the actual sizing and the economical results are highly dependent by the market conditions. As matter of example, Sicily, which market electricity prices is 6.8 €/MWh higher than the Italian national average price, the system is able to repay the 4 MWe HP 3.1 times, with a PBP of ca 6.5 years, still just considering the energy-only revenues.

A step forward was done considering revenues from ancillary services and balancing market where the CCGT flexibility has greater technical and economic relevance, Vannoni et al. (2021), assessed how analysing the economic results of the 2018 and 2019, the Ancillary Services Market has overtaken the Day Ahead Market, DAM, providing, on average, the 46% of the total profits against the 42% of DAM and the 15% of Balance Market. However, the relevance of this market is strongly affected by the offer strategy that the operator can adopt based on the local market conditions, presenting a daily and seasonal variability, so the statistical results cannot be generalized without a specific study.

Figure 2 shows a simplified infographic of the results of the pump heat project: under high and stable electricity price (i.e Clean Spark Spread), the system can be used as an inlet cooling device, just to take full advantage of the full capacity. Under these, nowadays unrealistic conditions, the selection of the technology can be different from the proposed one.

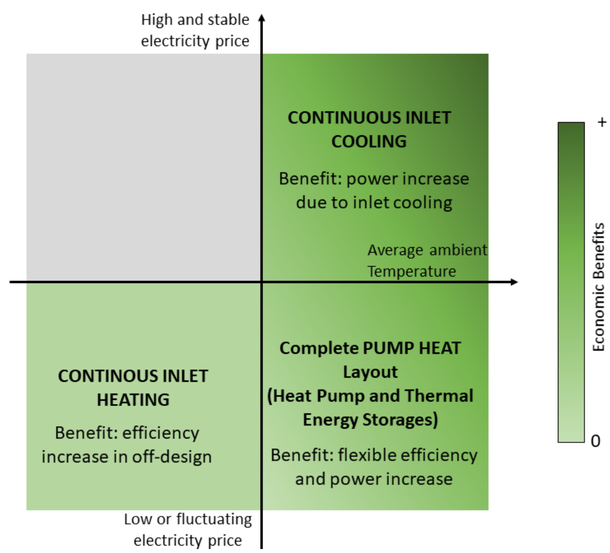


Figure 2 – Quantitative Intake Conditioning Economic benefit

When the electrical prices and the change of revenues are variable on a daily basis, the complete PUMP-HEAT layout, equipped with the TES can be adopted, with higher benefit under higher average ambient temperature.

Lastly, when the average temperature are usually low the 15°C, the impact of the cooling is reduced and the benefit is reduced to just the increase of the efficiency in off-design via inlet heating. This solution can be easily adopted, with a reduced installation cost, and in general can be seen as an extended anti-ice system. The solution apply to off-design operative condition

In this paper we assess the impact of such intake heating solution in term of yearly efficiency increase. As test case all the 43 Italian CCGT power plant are taken into account, to underline the effect of the different ambient temperature or operational profiles.

CCGT MODEL

The CCGT was modelled within Gate Cycle as a state of the art 3 pressure level reheat Combined Cycle, with a water-cooled condenser, as reported in Figure 2. Gas Turbine and Steam turbine plus the fourteen heat exchangers that make the Heat Recovery Steam Generator (HRSG). Water sprays were used to not exceed pipe related constraints, maintaining appropriate live steam temperatures, and a circulation pump in the ECO LP is used to keep the minimum inlet temperature (55 °C) to avoid condensation and then corrosion.

The results of the 24 complete GTCC calculations were performed in Gate Cycle under different ambient temperatures (from -10°C to 45°C) and GT Load (from 40% to 100%). The maximum intake temperature, 45 °C, was suggested by OEM on the base of their experience in hot climate and allow neglecting any effect over the life-time of the machine. The main risks in running the machine at high inlet temperature is related to the higher temperature of the cooling air drained by the compressor. No changes were made with respect to the condenser pressure, in order to simulate just the effect on the GT intake. More information about the model can be found in Sorce (2019).

INTAKE HEATING PERFORMANCE IMPACT

The dependence of GT performance on compressor intake temperature well known and documented in literature, while information about CCGT can be found in Kelhofer (2009) and in Sorce (2019)

In this paper the analysis will focus on the effect of air temperature only, since this is the main contributor to performance variation (gross power produced and efficiency), while all the other external conditions as well as condenser pressure remain unchanged.

An increase of the GT inlet temperature affects the power output and the efficiency of the gas turbine for three reasons: 1) The changes of intake air density, in such a constant volume engine, influence the mass flow and thus the gas turbine power output; 2) The specific power consumed by the compressor increases proportionally to the air intake temperature; 3) The increase of the intake temperature leads to pressure ratio reduction which, in a machine operated at constant Turbine Inlet Temperature (TIT), results in Turbine Outlet Temperature (TOT) increase, and thus GT efficiency reduction.

On the Combined Cycle perspective, the increase of TOT improves steam-cycle performance (efficiency and relative power output). Therefore, an increase in the air temperature performed in the inlet heating condition, has a slightly more positive effect on the efficiency of the CC than by compensating the reduced efficiency of the GT unit (Kelhofer, 2009). It was assessed that Combined Cycle efficiency has low sensitivity to the ambient temperature, losing the 2% at 45°C, when increasing temperatures and losing just the 0.25% at 5°C (Sorce, 2019). On the other hand, increasing the temperature reduces the off-design degree of the CCGT since the GT operates with a more open Inlet Guide Vane angle, of IGV resulting in an overall higher efficiency.

This can be visualized in Figure 3 were, as matter of example, the 85% of the CCGT load can be reached at 100% of GT load by increasing the intake temperature to 40°C. The efficiency benefit for this specific case is highlighted in green

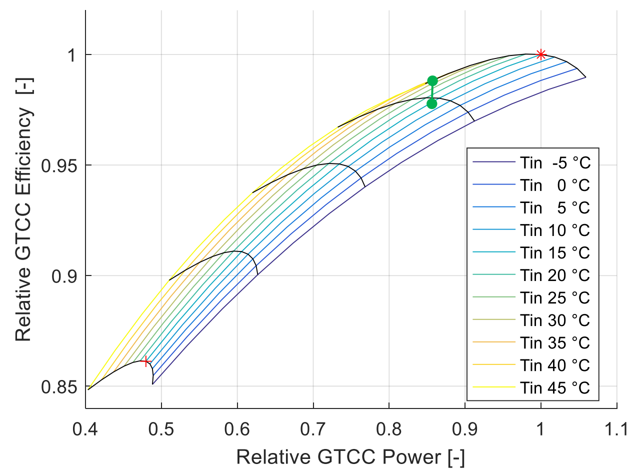


Figure 3: Off-design average F-Class based CCGT Performance with GT intake Temperature as parameter (in colour); Black line (40%, 55%, 70%, 85%,100% of the GT percentage load) – red +: MEL ISO – red *: Pmax ISO. Sorce (2019)

Even if, in theory, a change in temperature could be used to control the CCGT also close to full load, this cannot be performed in reality, so the intake heating is performed just in off-design conditions, defined as CCGT load lower than the 90%. On the other side, the minimum environmental percentage load was set equal to the 38% to exclude start-up and shut down from the analysis.

Different methods can be adopted to perform the intake heating: the heat can be recovered from the bottoming cycle exploiting the flue gas thermal content or by extracting low-pressure steam.

In our calculation the increase in temperature is limited to 20K, a quantity that can be covered by the flue gas maintaining the temperature at the chimney above the 80°C for all the ambient and GT load condition, so no reduction of the power or of efficiency in necessary to feat up the system. Finally, the impact of the pressure drops of the heat exchanger located at the intake and at the CCGT discharge was neglected.

To estimate the efficiency gain potential, an optimization of this parameter is performed on hourly basis for each power plants, imposing the production the same absolute power, a limit of the intake temperature to 45°C or a limit of the temperature increase of 20K.

ITALIAN COMBINED CYCLE POWER PLANTS

The analysis is carried out considering only the Power Oriented, PO, power plants (i.e. exclusively generating electricity), since those that are devoted to the combined generation of heat and power, CHP, have to fulfill the local thermal demand, so are less affected by the flexibilization imposed by the power market. Today in Italy are currently active 45 CCGT units in 31 power plants sites, of these 28 are 1 GT +1 ST unit, 17 are 2+1, thus the overall number of gas turbines operating in CCGT power plants is 61, Table 1 shows how those machines are distributed among the market zones. All the turbines considered are F-class with 645-715 MW thermal power input.

Table 1. Italian Power Oriented CCGTs[2]

	n. sites	n. CCGT units	n. GT	**Overall zonal capacity**
NORD	13	22	30	10,394 MW
CNORD	2	2	2	756MW
CSUD	7	10	13	4,077MW
SUD	4	4	6	2,713MW
ROSN	4	6	8	3,275MW
SICI	1	1	2	780MW
SARD	0	0	0	0MW
Total	**31**	**45**	**61**	**122 GW**

As shown by Table 1, the different power plants are spread along the different market zones.

The input data to the model are the actual power generation of each power plant, the cost paid by the plant for the gas and the local ambient temperature, the calculation has been performed over three years (2018, 2019 and 2020), covering also the pandemic period, where the reduced load experienced by the grid can be seen as a hint of a future period of higher RES/load ratio that are envisaged due to RES capacity growth.

Temperature and power generation historical time series were needed on hourly basis as input to the assessment presented in this paper. Concerning the power generation of the Italian CCGT fleet it has been computed from the market results data published by the GME. *Gestore dei Mercati Energetici* (GME) is a public company vested with the economic management of the Italian electricity market, on its website are published the quantity offered and awarded by each generation unit of the Italian electricity grid. Summing, for each time interval (1 hour) the energy sold and bought by each CCGT on all the market sections (Day Ahead Market, Intra-day Market, Ancillary Service Market, Balance Market) we get a close estimation of the actual power plant power generation. Small errors may occur since the result of this data processing is a scheduling from which the actual generation could have moved away because of grid or plant unbalances, moreover it is a mean on one hour during which real data could have been non-constant. The gas price was retrieved adding to the Day Ahead market price, continuous negotiation, available on the GME's website, the average taxes and levies reported by the Italian authority ARERA. Finally, it has been reported on the LHV basis considering a ratio equal to 1.1 between the LHV and HHV of natural gas, as reported in Figure 4. The CO_2 price was set constant equal to 21 €/ton, the three years average.

Figure 4: Gas price trend (with taxes and levies)

Each power plant location was tracked, and the ambient temperature time series, is estimated by means of hourly geospatial data of the temperature at 2 m of height from the soil available on the ERA5 dataset with a resolution of 9 km. The results obtained were tested for 4 specific power plant and found in good agreement.

CCGTs generally operate according to four different profiles, as depicted in Figure 5. This chart allows to cluster the power plants on the basis of annual number of Start-Ups, SUs, and Fired Hours, FH, so on how much flexibly they operate. It is possible to identify four cluster:

- Continuous: less than 60 SU and more than 4000 FH annually
- Mid-Continuous: approximately 60 FH for each SU on average
- Mid-Range: approximately 30 FH for each SU on average
- Peaker: more than 200 SUs annually

[2] The reported grid division in zones was in force until December 31st 2020, the last day included by the collected data

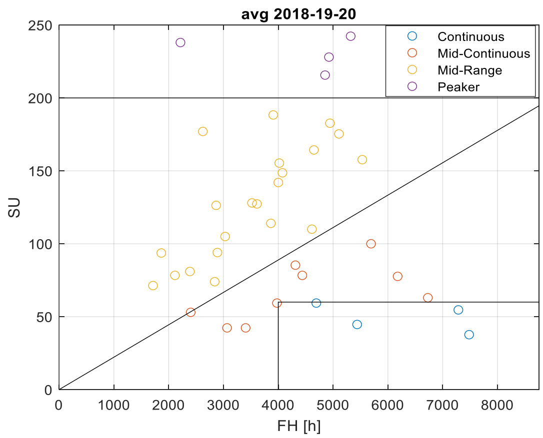


Figure 5: Italian CCGT Operating profiles

So far, it was found any particular correlation between the main parameter of operating profile clusters (i.e. Load Factor; Fired Hours; Number of Start Up and the Off-Design Fired Hours, ODFH, defined with the respect to the 0.38-0.9 range of the capacity evaluated at the real ambient temperature as

$$ODFH = FH(0.38 \leq CCGT\% \leq 0.9)/FH \quad (1)$$

However, all the operating profile clusters have on average more than the 50% of ODFH.

Table 2. Average parameter of the different

Operating Profile	Load Factor [%]	FH [h]	Annual SU	ODFH [%]
Continuous	54.3	6226	49	52.0
Mid-Continuous	34.3	4467	67	66.5
Mid-Range	28.5	3524	128	63.8
Peaker	29.7	4329	231	60.7

On the other side, Figure 6 shows clearly how the production evolved in the last two years with the CCGTs that spend nowadays more percentage of their time at partial load (about the 70% of the time against the 60% of two 2018). The hypothesis of those author is that such

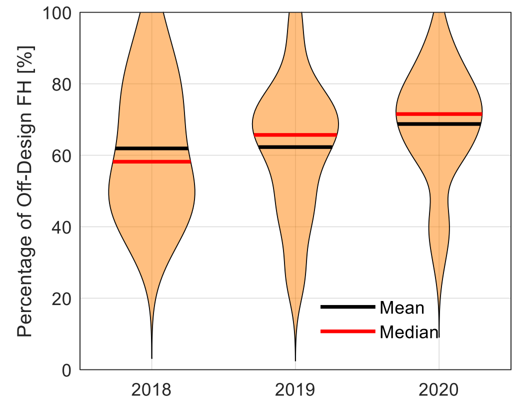


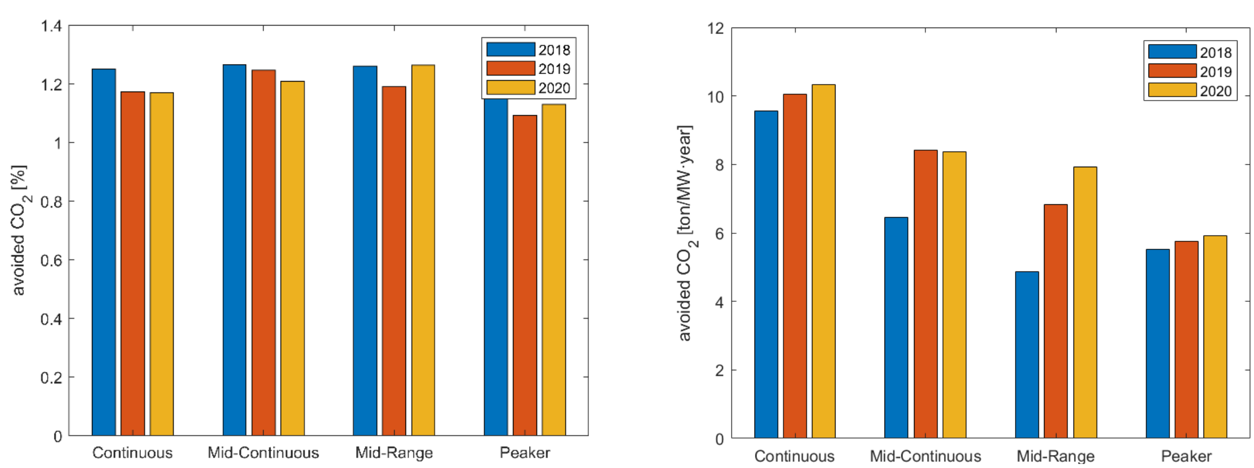
Figure 6: Italian CCGT: Percentage of Operating Hours in Off-Design

intermediate load is mainly due to the more extensive production as grid supporter as Ancillary Services providers, that intensified in 2020 because of the high RES/load ratio.

Nevertheless, this is expected to increase the impact of the intake heating system over the overall yearly efficiency.

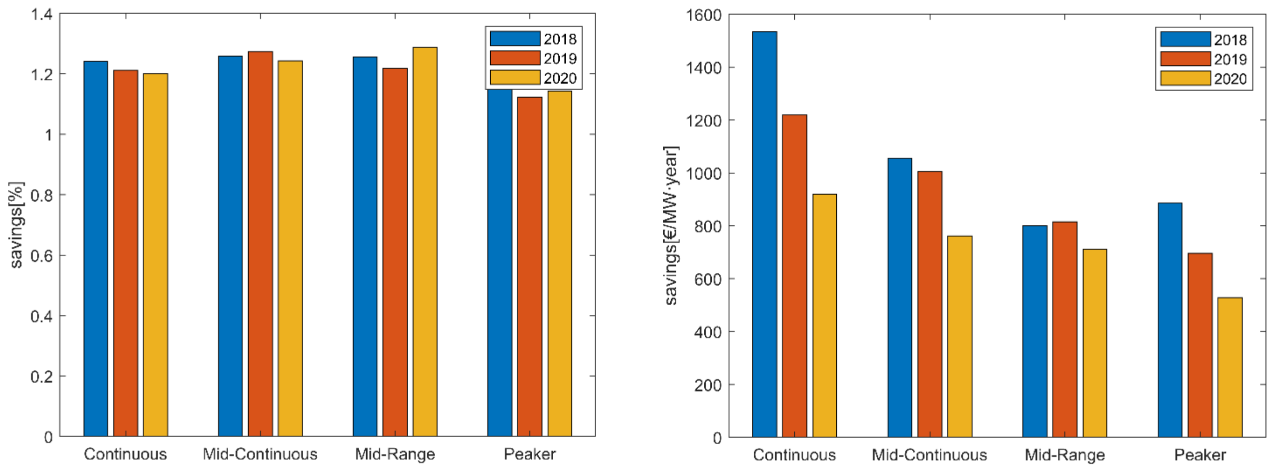
RESULTS

The results of the use of an intake heating system during off-design hours were ordered in function of the different years and divided by operating profiles. The percentage of reduction of carbon dioxide emissions, Figure 7(a) is pretty constant along the year and the use and it is equal to the enhancement of the average efficiency, that in all the condition is increasing of a minimum of 1%. This slight increase is having a larger impact for the CCGTs operated for longer time that can avoid up to 10 tons of CO_2/(MW·year) equal to 4000 tons/year of CO_2 for an average 400 MWe CCGT. Finally, it can be noticed that absolute amount of the avoided CO_2 is directly related to the number of Fired Hours, of the different operating profiles, while variation along the years are related to the increase of the percentage Off-Design Fired Hours.



(a) (b)

Figure 7: Intake Heating environmental impact: Percentage (a) and absolute (b) avoided Carbon Dioxide as function of the different years and operating profiles



(a) (b)

Figure 8: Intake Heating economic impact: Percentage (a) and absolute (b) fuel savings as function of the different years and operating profiles

Figure 8(a) straightforwardly confirm that the amount of saving achievable with the intake heating reflects the percentage of unburnt fuel, and so the overall increase of efficiency.

More important, in Figure 8(b) the absolute savings follows a trend similar to the one driven by the amount of fired hours of the different operating profiles, but the weight of the gas cost brings to a reduction of benefit in the last two years, with the continuous CCGTs that goes from 1534 €/(MW·year) equal to 613,600 €/year for a 400 MWe CCGT in 2018 to 920 €/(MW·year) equal to 368,000 €/year with the gas cost that went below 10 €/MWh with the minimum due to the pandemic crisis.

For the other operating profiles, a good estimation of the yearly savings was found around 800 €/(MW·year) equal to 320,000 €/year for 400 MWe CCGT. The Peaker units have a lower economic performance, so the solution may be adopted just if an anti-icing is already in place.

Even if the percentage impact of the intake heading results in a mere 1.1%, an investment on this technology must be evaluated against the last figure. For 2021, the rising cost of CO_2 ETS allowances that characterized the 2021 reaching the value of more than 60 €/tons, the triple of what was considered here and the price of gas that already reached an average of 35 €/MWh (up to September), bringing up the savings to around 1 million euro per year for a 400 MWe Continuous CCGTs and around 500,000 euros per year for the others operating profiles, making this solution interesting and possibly self-sustaining.

FLEET ANALISYS FOR REPLICATION

Beside the operational profiles, the second parameter that influences the increase in efficiency is the ambient temperature, synthetized in Figure 9 as the average temperature registered. The slight negative correlation can be exploited and is related to two main effects:

1) The constraint of 45°C limit the use of the intake heating technique on the hot side, reducing then the positive effect of intake heating.
2) The effect of the efficiency behaviour with the temperature, is beneficial to low temperature, since to the increase of temperature is associate and increase of efficiency when operating in the 20°C-30°C range.

Basing on that, it is expected to have a marginal increase (0.02 percentage points/°C of ambient temperature) in the benefit of the proposed solution when applying the solution further to the northern region. Moreover, since the installation of anti-icing system is a practice that become most common with the lower temperature, it would be easier to extend their use with an efficiency enhancement logic as a first zero-cost application, even if the potential of the solution could not be completely exploited.

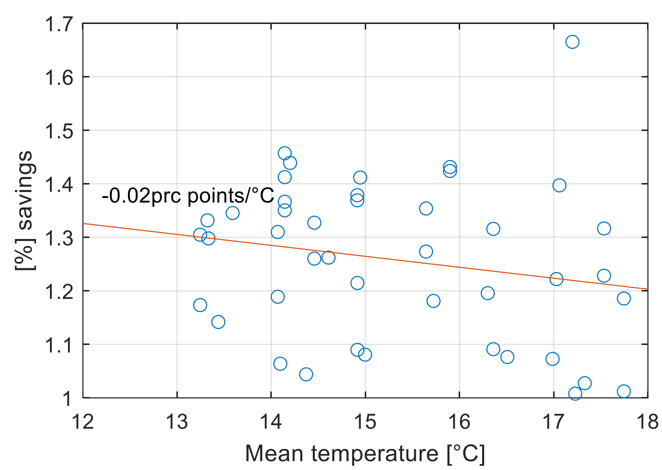


Figure 9: Effect of the average ambient temperature over the percentage of savings for the single CCGT, average 2018-2020

CONCLUSION

The PUMP-HEAT H2020 Project developed a solution focusing on the conditioning of the gas turbine intake to for the Power oriented CCGT, to increase operative range and operating efficiency. The complete layout integrates the CCGT with a Heat Pump and a cold Thermal Energy Storage, in an approach that is OEM independent.

Beside the economic benefit of the complete solution that was investigated in other publications, this paper focuses on the efficiency enhancement generated by heating the CCGT intake when operating a part load, a solution that can be applied with a simplified layout, similarly to the already exiting anti-icing systems.

This operative condition in fact is becoming more common in the entire Italian CCGT fleet and it is foreseen to increase with time.

A statistical analysis of the Italian CCGTs Power Oriented fleet, composed by 45 Units for a total of 122 GW of installed capacity, confirmed this hypothesis. Data shows clearly how the production evolved between 2018 and 2020 years with the CCGTs that spend nowadays more percentage of their time at partial load (about the 70% of the time against the 60% of two 2018).

The optimization of the off-design performance via intake heating leads to an average increase of efficiency larger than the 1.1% with a proportional impact on the CO_2 emissions and fuel cost savings.

Looking to the absolute economic results, the savings are largely influenced by the gas cost brings to a reduction of benefit in the last two years. For the continuous CCGTs (the one performing less than 60 start-ups per year and operating for more than 4000 fired hours) the benefit reduced from 1534 €/(MW·year) equal to 613,600 €/year for a 400 MWe CCGT in 2018 to 920 €/(MW·year) equal to 368,000 €/year with the gas cost that went below 10 €/MWh due to the pandemic crisis in 2020.

For the other operating profiles, the reduction in gas cost was balanced by the higher persistency at intermediate load, making the result more stable over the years. A good estimation of the yearly savings was found around 800 €/(MW·year) equal to 320,000 €/year for the 400 MWe example. Peaker units, have a lower economic performance.

For 2021, the rising cost of CO_2 ETS and Natural Gas cost brings up the savings to around 1 million euro per year for Continuous CCGTs and around 500,000 euros per year for the others, making the intake heating an interesting and possibly self-sustaining solution.

Of particular interest are the installations in the northern regions, due to the slight increase in the expected efficiency increase and to the presence of already installed anti-icing devices that can be exploited directly or upgraded to fully take advantage of this untapped potential.

NOMENCLATURE

AmbHX	Ambient Heat Exchanger
PBP	Pay Back Period
CCGT	Combined Cycle Gas Turbine
FH	Fired Hours
GT	Gas Turbine
GTHX	Gas Turbine Heat Exchanger
HP	Heat Pump
HHV	Higher Heating Value
IIC	Integrate Intake Conditioning
LHV	Lower Heating Value
MEL	Minimum Environmental Load
MILP	Mixed Integer Linear Programming
ODFH	Off-Design Fired Hours
RES	Renewable Energy Sources
SU	Start-Up
TES	Thermal Energy Storage

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