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COMBINED CYCLE INLET AIR COOLING BY COLD THERMAL STORAGE: AERODERIVATIVE VS. HEAVY DUTY GT COMPARISON

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ABSTRACT

An assessment of energetic performance achievable by GT inlet air cooling through cold thermal storage is presented. Results have been obtained by a numerical code specifically developed to model the whole system behavior all over a year. Some cases with hot climatic condition have been compared and discussed in order to enlighten performance differences due to GT characteristics and possible enhancement strategies for different configurations. An existing 127 MWe combined cycle power plant with a twin GT configuration was assumed as a reference case. Two heavy-duty units with different technology levels have been compared with an advanced aero-derivative model, in the range of 40 MW power output. Aero-derivative unit provided a much better performance than the more advanced heavy-duty model; this was strictly related to the higher sensitivity to inlet air temperature of the aero derivative unit. The comparison between the two heavy-duty GTs has clearly shown that a high specific power is needed to obtain cost-effective solutions for inlet air cooling systems. The analysis for the considered GT units was then extended also to a plant configuration including an inlet air supercharging system. The boost fan head has been selected in order to only compensate all inlet pressure losses, i.e. inlet duct, filters and air coils pressure drops.

NOMENCLATURE

CC	combined cycle
GT	gas turbine
IC	inlet cooling
IRR_{15}	Internal Rate of Return, %
NPV_{15}	Net Present Value, k€
PBT	payback time, year
S	supercharging
ΔE	electric energy overproduced, GWh
ΔP	power overproduction, MW_e
ΔQ	extra fuel consumption, MW_{th}
$\Delta\eta$	efficiency variation, %
η	net efficiency, %
η_{incr}	incremental cycle efficiency, %

Subscripts

0	in reference condition (without IC)

INTRODUCTION

It is well known that Gas Turbine (GT) performances highly depend on inlet air conditions: in particular, power output strongly decreases as inlet air temperature increases. An ambient temperature increase of 10°C gives rise to a simple cycle Gas Turbine (GT) power output decrease of about 5% to 13% and to a cycle efficiency reduction of about 1.5% to 4%, depending on the GT model. When considering a Combined Cycle (CC) power plant, a similar power output decrease of about 5 to 8% takes place [1].

Among the different strategies available to compensate for power reduction at high ambient temperatures, the adoption of inlet air cooling systems (IC) appears a very interesting choice in almost all CC configurations and specifically for aero-derivative machines, as reported by Bianchi et al. [2]. Heat transfer IC systems, like those based on direct mechanical chilling, direct adsorption chilling or indirect mechanical chilling through cold thermal storage, allow better performances when compared to water evaporation systems (evaporative cooling and inlet fogging); this because IC systems can ensure lower inlet GT air temperatures and hence a higher power augmentation. In fact, lower air temperatures can be obtained by using appropriate heat exchange surfaces and coolant temperatures (for water they are typically about 4 to 6 °C), while for evaporative systems the limit is the ambient wet bulb temperature. Moreover, the use of a cold thermal storage produces a further economical benefit by allowing to increase the electric power production when ambient temperature and electricity price are higher, while shifting chillers electrical consumption during night time, when energy is cheaper. Another advantage is the improved possibility to control the power output independently on the ambient conditions so that the difference between the energy that has been programmed to be sold and the one that is effectively sold to the market is reduced and the profits optimized [1].

To evaluate cost-effectiveness of an Inlet Cooling system, a detailed investigation of CC operation integrated with IC system is necessary because of the deep influence on the thermodynamic as well as on the economic final result of each site's climate and plant configuration: for example, Gareta et al. [3] have shown, for the Spanish climate and power market scenario, that small direct cooling systems perform better than indirect ones with large thermal storage. Chacartegui et al. [4], compared different IC systems applied to a combined cogeneration power plant. They showed that the introduction of a thermal storage coupled with an electrically driven chiller does not give relevant advantages with respect to the direct cooling solution; however, the thermal storage system allowed for a larger Net Present Value.

Cold thermal storage type and size selection may also lead to very different economical results. In fact, the choice of the technology highly influences the investment costs: an ice storage with ice harvester machines is much more expensive than a system based on stratified chilled water requiring a much greater storage volume but a traditional and cheaper chiller. A power output increment over 25% has been reported by Al Bassam and Al Said [5] for an ice harvester system applied to a simple cycle power plant operating in Saudi Arabia, while Ameri et al. [6] for a plant in Iran has shown that the high investment cost made the choice unprofitable.

Yokoyama and Ito [7] developed a numerical code to study inlet cooling with ice storage applied to GT cogeneration plants: the most relevant effect was the reduction of peak electricity demand obtained through an increase of capital cost and natural gas consumption. Palestra et al. [8] explored both chilled water and ice storage technologies for a 127 MWe combined cycle power plant in two different climatic scenarios (northern and southern Italy) and showed that an optimized chilled water storage system gives better results. Another interesting application in the field of cold storage systems is the use of phase-changing materials PCM, although this technology requires further development and investigations for a GT inlet air cooling implementation (Bedecarrats [9]).

Finally, Wang and Braquet [10] and Bhargava and Meher-Homji [11] have pointed out that inlet cooling system performance (and thus the achievable profits) is strongly correlated with the key gas turbine design parameters. They have shown that aero-derivative gas turbines, compared to heavy-duty machines, achieve higher performance by direct inlet air cooling system (e.g. fogging with and without overspray).

When considering indirect cooling systems, the introduction of heat exchangers in the inlet duct gives rise to a slight performance degradation due to pressure losses. Such an effect sums with inlet duct and air filters losses. A possible solution which is helpful in mitigating power output reduction due to pressure losses, site location altitude and ambient pressure variation is given by pressurizing the inlet duct with a fan [1].

In the present study, an in-house code developed for modeling GT inlet air cooling and supercharging [1,8] was used to evaluate the thermodynamic performances and the economics of a CC plant with different GT types. Three types of GT of similar size were considered: an industrial GT, an aero-derivative one of similar specific output and a second heavy duty engine but characterized by a reduced mass flow rate. The behavior of the whole system (combined cycled power plant with inlet air cooling and cold thermal storage) is examined for a hot climatic scenario in southern Italy, with and without an inlet air supercharging system. The economical performance achievable for the three cases in the actual Italian market is also presented.

Reference Power Plant and Inlet Air Cooling System Layout

The reference power plant of the present study is a 120 MW combined cycle, based on two 40 MW GTs in a twin configuration. The following three GT models have been selected to analyze the IC system performances:

1. Siemens SGT-800, a modern heavy-duty machine with a relatively high cycle efficiency;
2. GE LM6000PC, a high performance aero-derivative model presenting similar mass flow rate and specific work but a higher sensitivity to inlet air temperature variation;
3. GE 6581B, a less advanced heavy duty unit with a lower specific work (i.e. a larger mass flow rate) and a reduced sensitivity to inlet air temperature with respect to the aero-derivative one.

The main features of the three GTs are reported in Table 1. Note that the three considered engines present quite different pressure ratios or specific work (see Table 1), giving rise to a different behavior versus ambient temperature variation.

Figure 1 shows the power output and efficiency variations vs. air temperature for some widespread reference GT models; the reported data have been obtained . Besides the GT models here considered, Fig.1 shows data corresponding to others GT models all obtained by using a commercial software (ThermoFlex©). These data will allow to some extent the reader to transfer the results obtained in this investigation also to other engines of different size, but with similar behavior vs. ambient temperature variation. Figure 1 clearly shows that the performance reduction significantly varies depending on the GT model: in particular aero-derivative engines and specifically those with higher pressure ratio, appear to be mostly affected by inlet air temperature variation. The reason is that at high air temperatures the compressor work undergoes a large increase, while turbine work remains almost the same. For the aero derivative engines, a temperature variation of 35°C is responsible for a huge variation of power output and efficiency, i.e. up to 40% and 8% respectively.

GT Type	Siemens SGT-800	GE LM6000PC	GE 6581B
Specific work [kJ/kg]	344.0	336.4	295.3
Pressure ratio	19.0	28.9	12.3
GT Power Output [MW]	43	43	43
GT Efficiency [%]	36	41	32
GT exhaust gas T [°C]	540	441	545
HP - LP pressures [bar]	80-7.7	50-12	80-7.7
ST Power [MW]	41	25	41
CC Power Output [MW]	127	111	127
Fuel Consumption [MWth]	235	206	250
CC efficiency [%]	54	54	50

Table 1. GTs and CCs parameters at ISO condition.

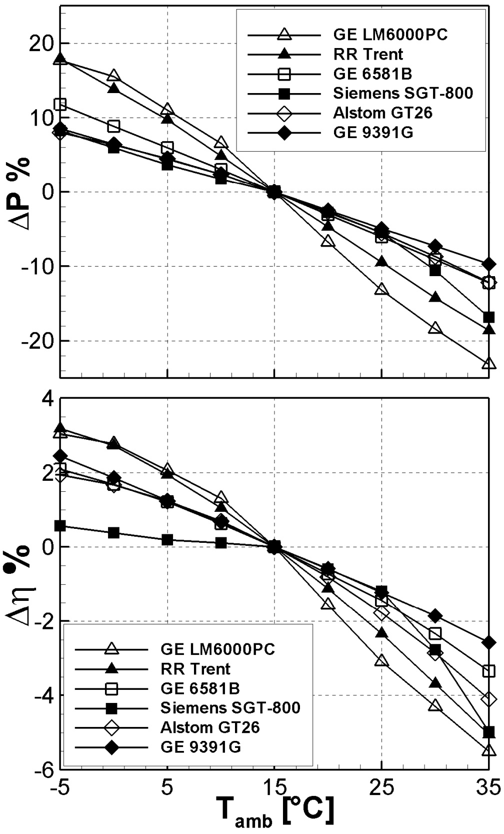

Fig. 1. GT power and efficiency variation vs. ambient temperature.

As a reference plant, an existing 127 MWe combined cycle based on two Siemens SGT-800 gas turbines and a two-level pressure bottoming steam cycle has been assumed (Fig. 2). The cycle is rated with an efficiency of 54% and is built in a 2x1 configuration with every gas turbine equipped with its own HRSG. A 540°C exhaust gas temperature allows the production (for each gas turbine) of about 15.6 kg/s of 520 °C / 80 bar high pressure steam, and 7.4 kg/s of 220 °C / 7.7 bar low pressure steam. Condenser pressure is 0.06 bar and the steam turbine produces 41 MW of gross power.

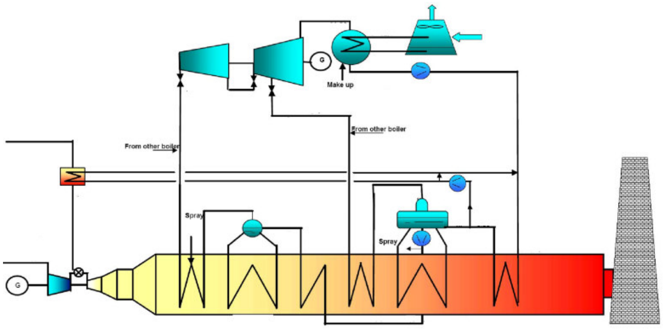

Fig. 2. Layout of the 127 MWe reference CC power plant.

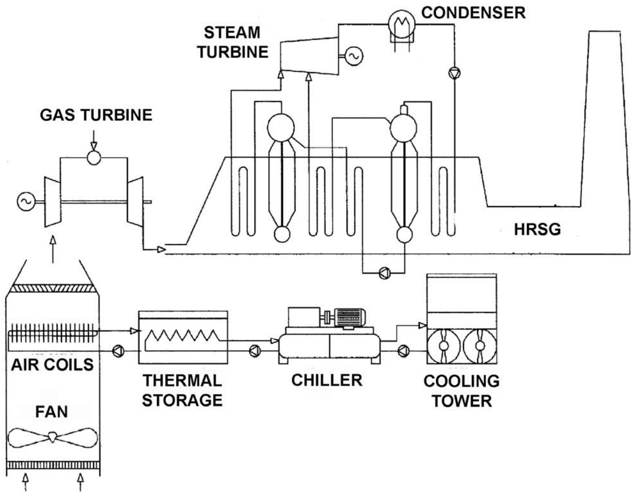

Fig. 3. Cool thermal storage and inlet air cooling system layout.

The same layout, originally optimized for SGT-800, has been also used for the two other GT models, in order to correctly set the comparison between the different types of gas turbines. Some changes have been applied to the steam parameters in order to assure, for the two other selected GTs, the best design steam cycle performance. Main cycle parameters are shown in Table 1. In case of GE6581 model, the less advanced heavy duty machine, minor and straightforward steam cycle parameters changes were applied. In particular, the sub cooling temperature difference was slightly increased while the super-heating temperature was slightly reduced in order to improve the cycle performance during the coldest decades of the year. When considering the GE LM6000PC aero-derivative model, HRSG temperature and pressure levels were instead almost everywhere modified because of the lower GT exhaust gas temperature.

The GT inlet air conditioning system has been already analyzed by the authors in previous studies comparing different storage systems [1] and also considering inlet air supercharging [8]. In the present analysis, according to the plant layout of Fig. 3, chilled water is produced using centrifugal compressor chillers driven by AC motors, operating during the off-peak hours to accumulate coolant capacity into the storage system. The storage system is based on stratified chilled water tank. Chillers Coefficient of Performance COP (defined as the ratio of the useful cooling energy to the electric energy input to the compressor) is rated at 5.5. When the inlet cooling system is turned on, the chilled water is pumped into cross flow heat exchangers installed in the inlet casing just upstream the compressor inlet. Water design inlet temperature is 4 °C, as required by thermal stratification. The water to cooled air stream pinch-point has been set to 2 °C. Chillers have been supposed to be cooled by evaporative towers, so their performance will be partially affected by ambient conditions.

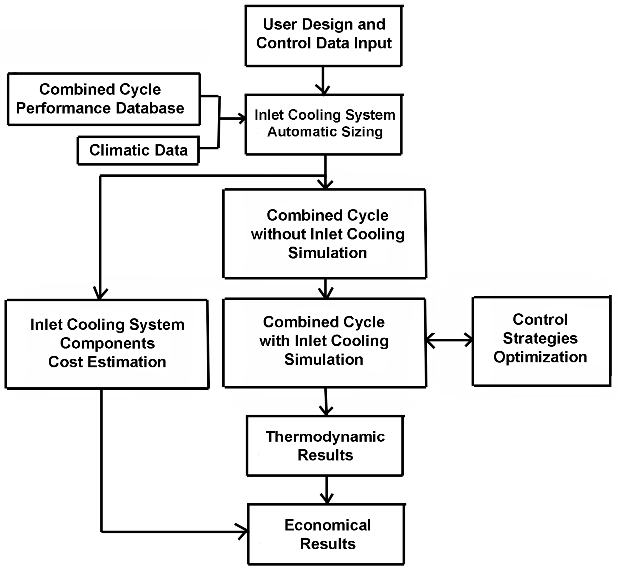

Fig. 4. Simulation program structure.

Besides the GT inlet air cooling system, inlet air supercharging is also adopted to compensate for the pressure drop introduced by air coils or even for inlet pressure differences with respect to ISO condition. Supercharging is accomplished by using axial machines installed in front of the cooling air coils. This in order to provide a pressure increase in the range of 2-4 kPa for an air flow rate of 125 kg/s that is requested by the SGT-800 engine. With a fan overall efficiency of 80%, the electric motor for a single fan pressurizing inlet air up to 3.5 kPa resulted to be rated at 500 kWe. Lateral air dampers located between supercharging fan and air coils give the possibility to both the systems to work independently without affecting combined cycle operations and availability.

Simulation method and assumptions

An in house developed Matlab© computer code was used to model and analyze the performance of the whole plant (i.e the combined cycle, the inlet air cooling and the inlet air supercharging systems) for any possible operating condition. A detailed description of the code has been already presented in [2,8]. The structure of the simulation code is presented in Figure 4. Once the GT model and the site location are defined, the first step of the integrated inlet cooling system simulation consists in providing all the input required for the automatic design of cooling and inlet air supercharging system components. These input data can be organized in three main subcategories:

1. climatic data;
2. reference CC power plant performance database;
3. user defined input data and control strategy, including the economic assumptions.

Climatic data for the selected site location (data collected hourly during 2008 for Gela city, southern Italy) were extrapolated from NOAA database [12]. The CC power plant performance database has been developed over the year on hourly basis for all possible operating conditions by means of Thermoflex© commercial software. Climatic data occurring in the site all over a year and inlet air conditions provided by inlet air cooling and supercharging systems (air temperature, humidity and inlet pressure losses due to air coils) have been considered. Plant simulations by Thermoflex© were previously tuned with performance data available by the manufacturer. This in particular for GE LM6000PC model, for which a particular calibration was carried out in order to adequate the off-design results obtained with Thermoflex© to those found on manufacturer's site. The calibration procedure mainly consisted in modifying the IGV control, resulting in a change in the GT load variation versus ambient temperature. The improvement achievable by this procedure was about 10% at 35°C. The use of the standard non-calibrated results would lead to an underestimation of the achievable power overproduction and, as a consequence, to a conservative evaluation of inlet air cooling benefits.

Heat exchanger design is automatically performed on the basis of the assumed temperature values for air cooling in the most severe ambient conditions occurring on site. A limit value of 10°C for the coils air exit temperature has been assumed in the heat exchangers design. According to the electric price trend and in order to limit the storage volume required, daily system's operation was limited to nine hours. Indeed storage tank volume is selected by considering the cooling demand during on-peak hours, while chiller is sized in order to restore completely, during off-peak hours, the stored cold energy. Optimization routines have been used whenever different design options were possible, to satisfy imposed design conditions. During the design procedure, the user may decide to undersize the cooling storage in order to limit installation costs. If this happens, inlet air temperature values higher than the set point can take place in the hottest summer days, depending on the selected storage tank volume.

Location	Southern Italy
Ambient pressure [bar]	1.015
GT inlet air temperature set point [°C]	10
Chilled water temp. [°C]	4
Water return temp. [°C]	8
Inlet air cooling and supercharging daily operational hours	9
Inlet Cooling system sizing	50%
Storage Tank Sizing	50%
Booster Fan Head [kPa]	3.5

Table 2. Design data.

Simul. Case	***All GTs***
AIR COILS	
Nr of Batteries	24
Nr of Ranks	6
Battery L [m]	2.5
Battery H [m]	1.44
Front Area [m²]	86.4
Head Losses [Pa]	80
STORAGE TANK	
Volume [m³]	13000
Capacity [kWh]	52600
Chiller Capac. [kWf]	3500
CHILLING SYSTEM	
Chiller Size [kWe]	824
Chiller Av. COP	4.25
Ev. Tower Size[kWf]	4350
BOOSTER	
Nr of Fan	2
Diameter [m]	2.80
Overall Eff. [%]	78.5
Fan Size [kWe]	530

Table 3. Inlet cooling system data.

Fan geometry and fan efficiency are selected using Balje diagram for compressor stages [1]. Fan efficiency was considered to be constant.

Finally, the following assumptions have been adopted in the economic analysis:

- an hourly energy price based on the electric Italian market results for the year 2010 [13];
- a natural gas cost of 0.19 €/Sm³;
- O&M expenses of 1.5% of total installation cost;
- investment was evaluated over 15 years; this assumption ensures a 5 years margin for the return of the investment with respect to the life of the plant (typically assumed to be 20 years);
- a 6% discount rate;
- a power plant availability of 8000 h/year, the yearly average operational hours for CC power plants in the Italian scenario.

All the input data defined, the code performs a simulation of the plant all over the year, determining for each hour the operating conditions of combined cycle and inlet air cooling and supercharging systems. An optimization is also carried out concerning the control strategy: the number of operational hours or the inlet air temperature may be varied, in order to maximize the income of the single day operation. However, for the present study, design cooling capacity and storage sizing have been fixed for all the three configurations to the values previously optimized for the SGT-800 case. This assumption is favorable to the aero-derivative machine because of its slightly lower mass flow; it is instead expected to penalize the heavy duty engine because, due to the lowest specific work, it will require a greater chilled water provision in order to cool its higher mass flow. Tables 2 and 3 respectively present the input values shared by all the three simulations and the design results for each component of the inlet air cooling system. Finally, the supercharging system is turned on only when IC system is in operation.

At the end of the simulation, all relevant parameters are available for every hour of every day in the year. So, day by day the code computes the larger amount of electric energy produced by the combined cycle with the inlet air supercharging and cooling system, the related natural gas consumption increase, the fan power request and the chillers energy consumption during night time. Finally, from these data, indicators of profitability like pay-back time, net present value NPV_{15} of the investment and internal rate of return are determined.

Thermodynamic results

The year simulation has been carried out for the three GT models, both with and without supercharging. Figure 5 and 6 show the actual values of stored chilled water consumption and gas turbine inlet air temperature during plant operation on two typical days. Because of the similar mass flow rate characterizing GE LM6000PC and SGT-800 engines (parameter primarily influencing the cool water consumption), the comparison is only limited to the two heavy-duty machines.

As shown in the Fig. 5, the inlet air cooling temperature is different for each day, depending on ambient temperature and cooling system capacity. An optimization routine provides indeed the hourly inlet air temperature control that maximizes the daily revenue. Typically, during the hottest days, a slight increment of inlet air temperature may grant the inlet air cooling system to remain operational all along the peak period. Conversely, if a lower inlet air temperature would have been chosen, thermal storage would have been ended earlier and inlet cooling should have been turned off. This happens for GE6581B model: this is due to the fact that the storage system has been undersized for this engine, as mentioned before. Figure 6 shows the chilled water storage level during the same typical days. One can note that during summer days cold energy is completely consumed, even before the due time. This is due to the design assumption that thermal storage could only ensure 50% of maximum cooling demand: value that is generally lower than cooling energy required during summer.

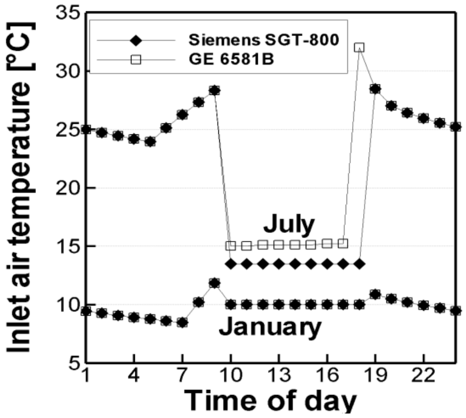

Fig. 5. Inlet air temperature vs. time of day for heavy-duty GT cases.

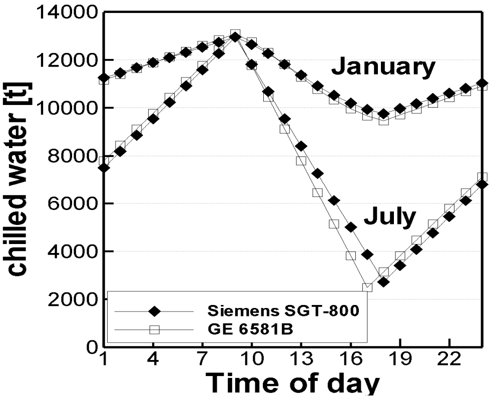

Fig. 6. Chilled water stored for heavy-duty GT cases.

Figure 7 reports power overproduction for each configuration without supercharging during a typical day for a cold and a hot decade. Net power overproduction ratio is defined as :

$$\Delta P_{net} = \frac{P_{net} - P_0}{P_0} \tag{1}$$

where $P_{net} = P_{CC} - P_{aux}$ is the net power output calculated as the difference between the CC gross power output and all auxiliaries power consumptions, also including the inlet cooling and supercharging ones. P_0 is the CC net power output without GT inlet air cooling and supercharging. Please note that negative values of net power overproduction ratio take place night time during the hot season, when chillers are in operation.

As can be noted, GE LM6000PC engine performs much better than the two heavy-duty GTs, both in hot and cold seasons, giving a power gain of about 30% and 5% respectively. Siemens SGT-800 shows a power increase that is only about one third of the aero-derivative one. The power increase for the GE6581B based plant (i.e. the less advanced heavy-duty) is even lower during the summer time, due to its larger air flow that leads to a premature stored cold water depletion. An automatic procedure that increases the air temperature set point to optimize the cold water usage is adopted to limit this effect.

CC efficiency variation is presented in Fig.8. It is defined as the difference between the net CC plant efficiency with and without IC (with supercharging, when considered):

$$\Delta \eta = \eta_{CC,IC} - \eta_{CC} \tag{2}$$

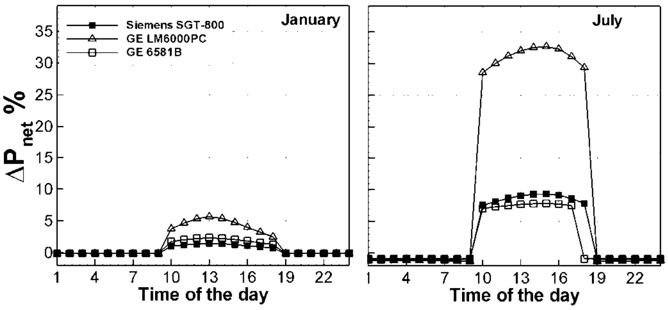

Fig. 7. Net Power overproduction ratio without supercharging.

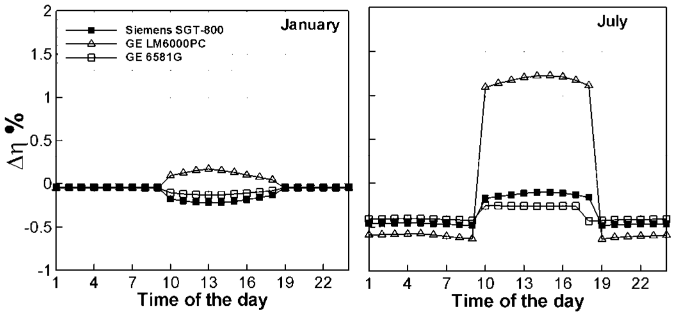

Fig. 8. CC efficiency variation without supercharging.

Efficiency variation takes into account also for IC and supercharging systems consumptions, when in operation. During daytime the CC plant is expected to improve its net efficiency, especially in summer time, when the power overproduction is higher. Conversely, during the night, when IC system is off and chillers are in operation to restore the storage system, auxiliaries consumption will increase, resulting in a decreased efficiency. Again this is expected to take place mostly in the summer period, while in winter time the efficiency reduction during the night will be reduced, due to the lower consumed cold thermal energy.

It can be noted (Fig. 8) that GE LM6000 makes the CC efficiency to increase of about 1.2% in July when the IC system is in operation, while it remains almost unchanged in January. Conversely, heavy duty GTs CC efficiency undergoes a small decrease, even in the hottest hours of July.

Figures 9 and 10 present the results obtained with supercharging fan application. Note that an additional increase of about 2-3% power augmentation (up to 35%) takes place in case of LM6000PC. CC efficiency on the opposite is slightly reduced, both in winter and summer decades: this stands for all the three GTs, and particularly for GE LM6000PC showing the highest penalty during summer nights.

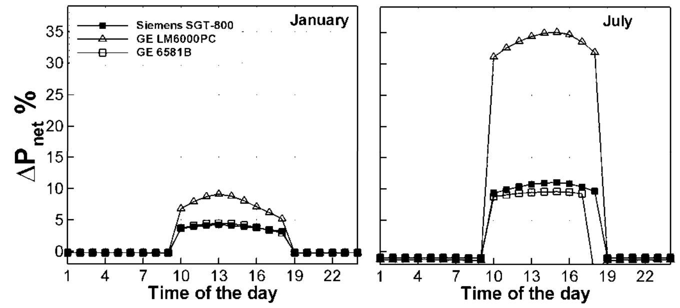

Fig. 9. Net Power overproduction ratio with supercharging.

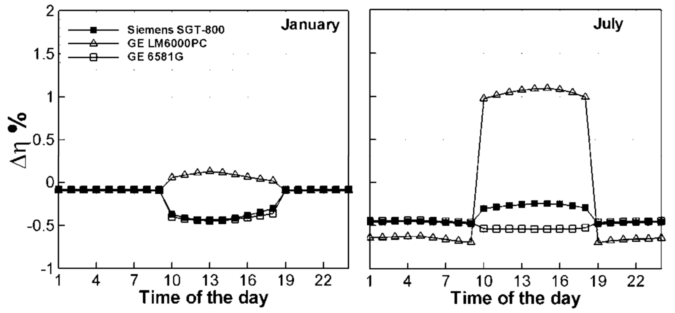

Fig. 10. CC efficiency variation with supercharging.

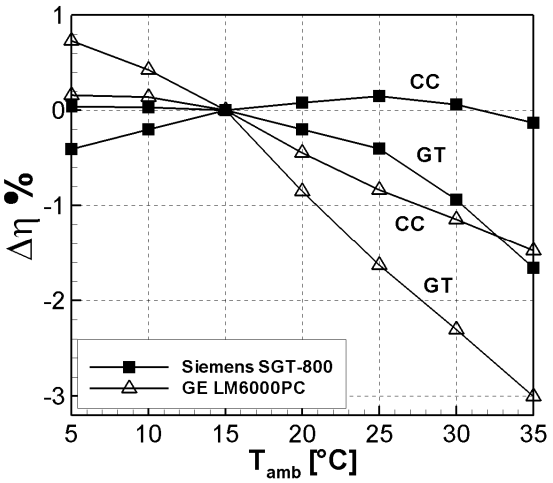

Fig. 11. CC e GT efficiency variations vs. ambient temperature.

CC and GT efficiency variations vs. inlet air temperature are presented in Fig. 11. These data allow to explain CC efficiency variations taking place for the different GT models. When IC is operated, GT air mass flow undergoes a significant growth and this larger mass flow through the HRSG results in a higher stack energy loss. This is the reason why heavy-duty CC efficiency does not take advantage from GT efficiency increase when IC is switched on. Nevertheless, the sensitivity of aero-derivative GT efficiency to air temperature is so great to produce a relevant positive effect also on CC efficiency.

Figure 12 summarizes the results obtained for the three cases in terms of net annual energy overproduction, evaluated integrating the net power output all over the year. The net energy overproduction achievable with the aero-derivative model appears to be significantly higher than those of heavy duty machines (see the plot on the left of Fig.12). In the hottest months GE LM6000PC ΔE_{net} is three times higher than the heavy duty ones and about 6.5 GWh, while in winter this gain is strongly reduced (down to about 1 GWh as a minimum). The two heavy duty GTs present a quite similar behavior. The plant with the less efficient heavy-duty GT shows the worst improvement during summer time (about 1.5 GWh against 2 GWh of Siemens SGT-800), when its auxiliaries consumption is higher and power overproduction is low, but performs slightly better during winter time.

The aero-derivative model shows the highest gain, particularly in summer time with both IC and S systems in operation (see Fig. 12 on the right): in July energy overproduction grows up to about 7 GWh/y. The positive effect for the heavy-duty machines is lower than for the aero one; SGT-800 in particular shows an appreciable positive effect only during the hottest months of the year, when ΔE_{net} is about 2.8 GWh. Moving to the GE6581B machine, the peak overproduction is lower, but ΔE_{net} is quite uniformly distributed all over the year, only varying between 1 GWh in winter time and 2 GWh in summer time. This depends on the achievable temperature levels and system sizing; while the peak overproduction increment is small the implementation tends to spread its advantage all over the year.

The CC efficiency variations (Fig. 13 left) of the two heavy-duty machines are very similar: the cycle undergoes a maximum efficiency reduction of about 0.4% in summer time that reduces down to 0.1% in winter time. The aero-derivative GT instead does not show any penalty during the year, but presents a slight increase of $\Delta\eta$ of about 0.15% Supercharging gives rise to a further decrease in the cycle efficiency for all GT models (Fig. 13 right). This is due to fans consumption that has to be included in the net efficiency and power output evaluation during the IC+S operational hours. GE 6581B is the one mostly affected by supercharging: the CC efficiency penalty now reaches 0.5% in the hottest months and 0.2% in winter time. When supercharging is introduced in the aero derivative case, the small gain IC gave is completely lost, resulting in an almost constant efficiency variation about 0.0% all over the year.

A useful parameter for the estimation of how efficiently peak energy is produced by this system is the incremental cycle efficiency defined as:

$$\eta_{incr,CC} = \frac{\Delta P_{cc,net}}{\Delta Q_{cc}} \qquad (3)$$

being $\Delta P_{CC,net}$ the net increment of power output and ΔQ_{CC} the extra heat provided by the fuel for the combined cycle with the inlet air cooling system (and supercharging when applicable) application. $\eta_{incr,CC}$ is an important parameter as it gives, for every peak hour, the reference marginal cost of generated peak energy by means of inlet air cooling. Thus it is possible to compare $\eta_{incr,CC}$ with the average efficiency of other typical peaking solutions (inlet fogging, supplementary firing, simple-cycle gas turbines etc).

Figure 14 shows the annual trend of the monthly average of $\eta_{incr,CC}$ for the three considered GTs, with and without the implementation of the supercharging fan. Please note that averaging has been performed only considering the IC operational hours. It can be seen that GE LM6000PC engine provides a very good result, as η_{incr} is about 57% for most of the year when only the IC system is considered; it means that IC system produces extra-power with an efficiency gain of 3% with respect to the design CC efficiency value at ISO condition (54%). Conversely, heavy duty machines show much lower incremental cycle efficiencies with respect not only to the aero-engine GT, but also to ISO conditions (see Table 1). Moreover, Siemens SGT-800 GT shows a highly varying distribution over the year: the 52% peak value of august quickly decreases down to 41% in January, while GE 6581B machine maintains an almost constant value of about 45-46% all over the year.

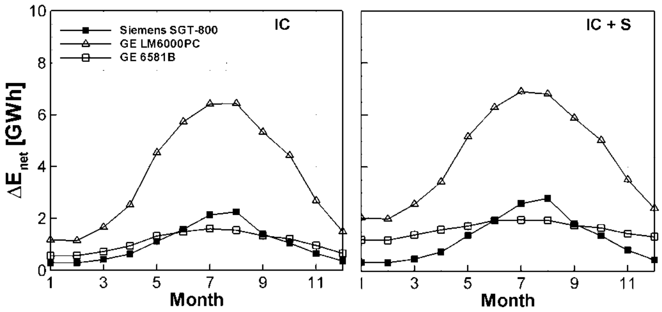

Fig. 12. Annual cycle energy overproduction with and without supercharging.

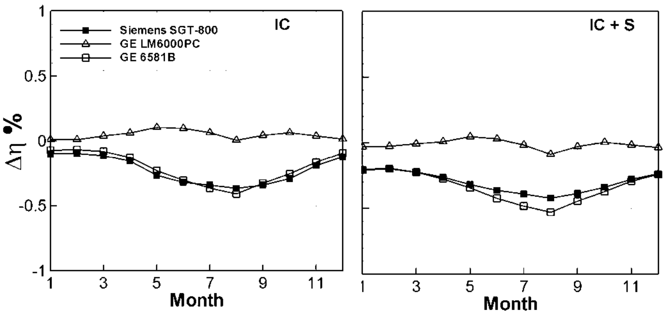

Fig. 13. Annual cycle efficiency variations with and without inlet air supercharging.

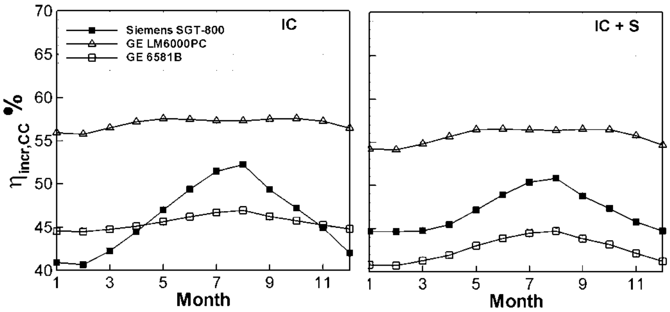

Fig. 14. Annual incremental cycle efficiency (during the hours of operation) with and without inlet air supercharging.

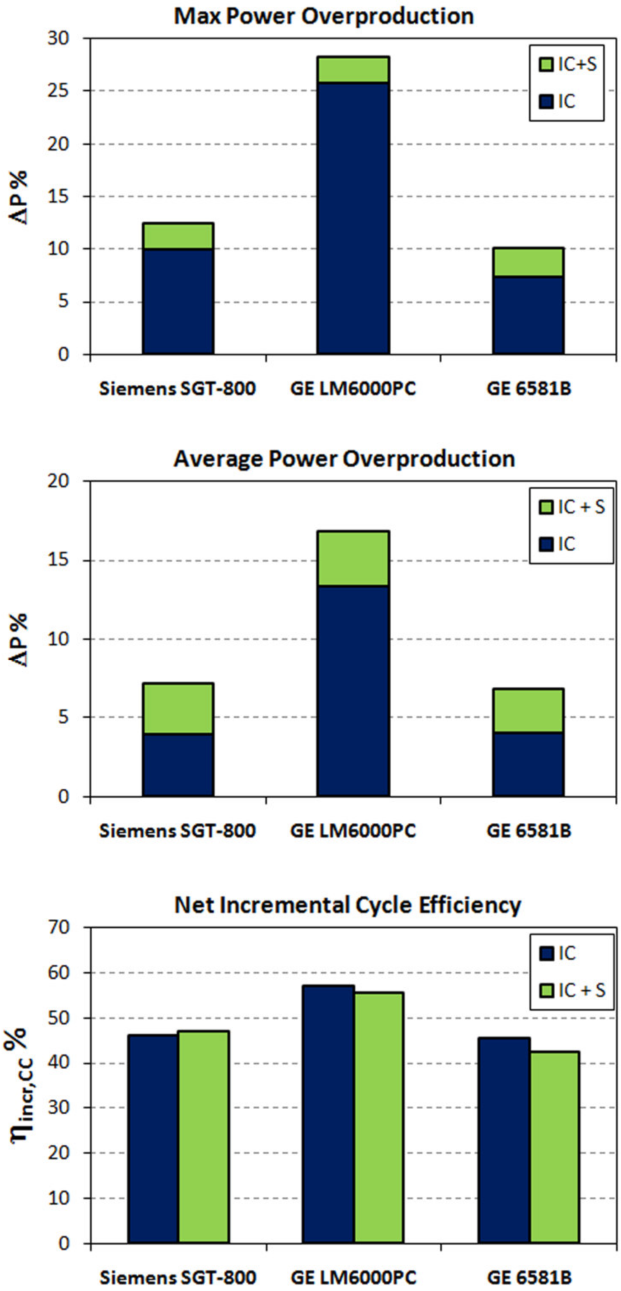

Fig. 15. Maximum and average power overproduction and incremental cycle efficiency for the three configurations.

The introduction of supercharging (IC+S – right of Fig. 14) gives rise to positive effects only for Siemens SGT-800 GT during the coldest months of the year (+ 4.0%). In the other two configurations, for most of the year the net incremental cycle efficiency is reduced: about -1.5% and -4.0% for GE LM6000PC and GE 6581B GT respectively.

Finally, Fig. 15 summarizes global thermodynamic performances related to a whole year operation for all the investigated configurations. For both IC and IC+S configurations, peak power overproduction occurring in the hottest decade results to be much higher for the case of the aero-derivative GT than for those with heavy-duty machines (see top of Fig. 15). A maximum ΔP of 26% takes place for GE LM6000PC in the IC case, rising up to 28% if supercharging is implemented. Such a relevant result is strictly related to the high sensitivity of GT power output to temperature variations of the aero-derivative engine. Much worst results have been found both for Siemens SGT-800 and GE 6581B, being the peak overproduction ΔP = 10% and 7% respectively, for the IC case. Only a 2-3% further increase can be achieved with supercharging.

Yearly average overproduction for GE LM6000PC is 13.5% and 17% respectively for IC and IC+S configurations (middle of Fig. 15). Once again it has to be underlined the good result of this GT, showing the relevant effectiveness of IC by thermal storage in case of the aero-derivative unit. On the opposite, for both the heavy duty engines ΔP is only 4%, rising to 7% with supercharging implementation.

The introduction of a supercharging system results to be effective, in terms of power overproduction, for all the considered solutions; however only limited improvements take place for peak overproduction, while more significant increases are achieved if the yearly average ΔP value is considered. In fact, the absolute power increase is almost the same for all the engines, but the relative increase is much larger for heavy-duty units (ΔP almost doubles) than for GE LM6000PC.

Looking at the net incremental efficiency (bottom of Fig. 15), it can be seen that for the GE LM6000PC the yearly average value is about 57%. It means that during day hours extra power is produced with an average efficiency significantly higher than the CC design one. This does not stand for the heavy duty units as $\eta_{incr,CC}$ are 46% and 45.5% respectively, both lower than the design values. Supercharging does not improve $\eta_{incr,CC}$: both for aero-derivative and less advanced heavy-duty machines a small but noticeable reduction takes place.

Economic results

The simulation code also provides an economic analysis, adaptable to the user's energy market scenario, in order to evaluate the profitability of each proposed solution. The cost of every component of the inlet air cooling system has been related to some of its operational and design parameters by means of correlations suggested in the literature [14] or provided by manufacturers [15]: the computed values for every configuration (inlet cooling and inlet cooling with supercharging) are shown in Table 4. As the cold water thermal storage represents about 50% of the total capital cost by itself, an optimization of the size of this component, also accounting for the best capacity selection and local soil cost is straightforward.

Table 5 summarizes the economic results obtained by the investment for all the cases They have been evaluated calculating the Net Present Value (at 15 years) NPV_{15}, the Internal Rate of Return IRR_{15} and the Pay Back Time PBT of the investment. The economic analysis clearly indicates that the implementation of an inlet cooling system with cold water thermal storage always appears a profitable strategy, as NPV_{15} values are always positive. Economical parameters for Siemens SGT-800 configuration are in-line with the ones obtained in former works [1,8] even if the economical scenario has been updated to 2010. In particular, profitability indexes indicate that to install an IC system in southern Italy gives a NPV_{15} of 0.8 M€ with an IRR_{15} of 12.4% and a pay-back time of about 9 years. Including a GT inlet air supercharging system (IC+S) allows to increase the NPV_{15} and the IRR_{15} up to about 2.6 M€ and 20.3% respectively, in the meanwhile reducing the PBT to less than 6 years.

Worst economic results characterize the GE 6581B configuration: an NPV_{15} of about 0.65 M€, an IRR_{15} of 11.1% and a pay-back time of about 10 years make this solution unattractive. Moreover profitability indexes are only marginally affected by the introduction of an inlet air supercharging system, with the PBT always about 10 years.

	Siemens SGT-800 **GE LM6000PC**		**GE 6581B**	
	IC	**IC+S**	**IC**	**IC+S**
Booster	-	540	-	618
Air Coils	212		250	
Storage	1030		1030	
Chillers	332		332	
Cooling Tower	104		104	
Piping	34		36	
Pumps	62		64	
El. Aux.	52	55	66	70
Total	**1826**	**2369**	**2113**	**2504**

Table 4. Costs in kilo € of the GT inlet air cooling system.

	Siemens SGT-800		***GE LM6000PC***		***GE 6581B***	
	IC	**IC+S**	**IC**	**IC+S**	**IC**	**IC+S**
NPV_{15} [k€]	831	2661	12940	14817	649	784
IRR_{15} [%]	12.4	20.3	82.1	73.1	11.1	10.5
PBT[years]	8.82	5.58	1.30	1.47	9.75	10.10

Table 5. Investment's profitability.

Much better economic results are obtained by the configuration equipped with the LM6000PC: it gives place to: (i) the highest NPV_{15} of about 13 M€ with IC, growing up to about 15 M€ in the case with supercharging, (ii) the highest IRR_{15} equal to 82.1 % for IC and 73.1% for IC+S, (iii) the shortest PBT i.e. 1.3 years, and 1.5 years with supercharging. All these parameters indicate that the implementation of an IC system with cold thermal storage in a CC power plant equipped with a GE LM6000PC GT provides quite good economic results.

CONCLUSIONS

A detailed simulation of three different CC power plants coupled with a power augmentation system has been carried out. The configuration considered (indirect inlet air cooling systems with chilled water storage and supercharging fans) proved to be a profitable choice at least for southern Italy climate and Italian energy market.

The comparison between the three different combined cycles of the same size, based on different gas turbines, has shown that the aero-derivative model may get the largest benefits from inlet air cooling due to its important sensitivity both in terms of power output and efficiency to ambient temperature variations. On the other hand, the results for heavy-duty machines demonstrated how power augmentation systems can be less effective as power plant configuration is already optimized (or less affected) in terms of off-design behavior.

A peak power overproduction of 26% can be achieved in the IC case with GE LM6000PC GT, rising up to 28% if supercharging is implemented. Yearly average overproduction gets 13.5% and 17% respectively for IC and IC+S configurations. Also economic indicators result to be quite good: for IC case payback time is only 1.3 years and IRR_{15} gets 82.1 %.

The results for heavy-duty units are much less attractive, particularly for the less advanced unit. However modern heavy duty units with high efficiencies like Siemens STG-800 can provide good enough results, especially if supercharging is implemented.

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