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Hybrid systems for distributed power generation based on pressurisation and heat recovering of an existing 100 kW molten carbonate fuel cell

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Abstract

In this paper, different pressurisation and heat recovering techniques for an existing 100 kW molten carbonate fuel cell developed by Ansaldo fuel cells (formerly Ansaldo Ricerche) such as electrically driven compressors for anode (fuel) and cathode side (air), turbocharger, simple cycle gas turbine and regenerated gas turbine are analysed and discussed.

The analysis has been carried out using for the FCS–MCFC stack simulation a model developed by the Thermochemical Power Group of the University of Genoa carefully tested with available experimental design point data. The design point hybrid system configurations have been analysed in detail using the code HS-MCFC based on the cited MCFC stack model and developed using Simulink language [Master Thesis, University of Genoa, 2001].

The different hybrid systems design point performance are presented and discussed in great detail, taking into account efficiency, specific power, costs, feasibility, and the need of modification of the existing FC–MCFC systems.

Due to the size of the hybrid systems investigated (100–150 kW) they are very interesting for distributed power generation applications.

Keywords: Molten carbonate fuel cell; Hybrid systems; Distributed power generation

1. Introduction

Fuel cells are electrochemical reactors that allow an efficient and ecological conversion of energy. High efficiency close to 50% also at part load conditions, and low pollution, make fuel cells a very interesting system for distributed power generation.

In particular molten carbonate fuel cells (MCFCs) and related hybrid systems have been analysed in this paper. Their name comes from the electrolyte employed, a mixture of alkaline carbonate (K, Na), inserted into a ceramic matrix ($LiAlO_2$); the anode and cathode are made of Ni powder, via a proper tape-casting process. MCFCs belong to the "high temperature" fuel cell class: the operating range is about 600–700 °C, in which the electrolyte has a good ionic conductivity.

The main goal of this paper is the evaluation of the possibility:

- to recover energy from MCFC exhaust gases, since they are at very high temperature (700 °C) and (for pressurised stack) at high pressure (0.35 MPa);
- to pressurise the stack itself;
- to generate extra electrical power to increase the system performance from the point of view of the efficiency, the specific power, the costs; etc.

In particular, in this work the MCFC stack has been considered with reference to an existing plant, named here fuel cell system (FCS) developed by Ansaldo fuel cells, (formerly Ansaldo Ricerche), based on a molten carbonate fuel cell stack [2]. The performance of the FCS–MCFC

Abbreviations: MCFC, molten carbonate fuel cell; FCS, fuel cell system; HS, hybrid system; SHR, sensible heat reformer; CCB, cathodic catalytic burner; ECB, exhaust catalytic burner; TIT, turbine inlet temperature; TOT, turbine outlet temperature; MGT, micro gas turbine; GT, gas turbine; compr., compressor; turb., turbine; comb., combustion; d.p., design point

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Nomenclature

e/q	electricity to heat ratio
P	power
T	temperature
U_f	fuel utilisation rate
Greek letter	
η	efficiency
Subscripts	
ex	exhaust
eq	equilibrium
Superscript	
$*$	refers to the 0.35 MPa standard case

stack are presented in the paper and have been used to assess the performance of MCFC analysis codes developed by Thermochemical Power Group (TPG) at the University of Genoa [1–4].

Several hybrid system configurations to pressurize the FCS–MCFC stack and recover its exhaust heat are presented. In particular the following systems have been investigated:

(i) electrically driven compressors for anode (fuel) and cathode side (air);
(ii) turbocharger;
(iii) simple cycle gas turbine;
(iv) regenerated gas turbine (micro gas turbine).

The analysis of the hybrid systems performance has been carried out using the code HS-MCFC developed by TPG [1]. Since the main goal of this work was the comparison among different pressurisation techniques at fixed MCFC stack working conditions, the above-cited systems have been considered at design point. The HS performance are compared to the one of the existing FCS stack from the point of view of efficiency, specific work, electricity to heat ratio and cost.

Finally, the influence of post-combustion and the possibility to increase the pressurisation of the stack have been analysed to verify their influence not only from the hybrid system point of view but also for the stack performance and constraints (particularly for the operative pressure).

2. Fuel cell system–MCFC stack

Fuel cell–MCFC systems (100 kW size) is based on a molten carbonate fuel cell stack shown in Fig. 1. The stack is made up of two 75 cells-modules, for a total active area of 100.32 m^2. The FCS cell works at fixed temperature and pressure conditions. In particular, the constraints for the minimum temperature of the molten carbonate is 580 °C, while the operating stack pressure is fixed at 0.35 MPa, in order to keep stack standing alone efficiency upper to 50% and electrical power close to 100 kW.

The complete plant lay out is shown in Fig. 2. A sensible heat reformer (SHR), two catalytic burners (exhaust catalytic burner (ECB); cathode catalytic burner (CCB)) and two recirculation blowers (anodic and cathodic) are added to the stack shown in Fig. 1 to complete the system. The sensible heat reformer is a catalytic reactor whose function is to convert methane into a hydrogen richer mixture. Reactant sensible heat, thanks to the anodic exhaust recycle, provides the necessary energy so that the reforming reaction occur (endothermic reaction). The stack is fed with a mixture of H_2, CO, CO_2, CH_4, H_2O (anodic side) and with air and CO_2 (cathodic side). The products of the overall reaction are

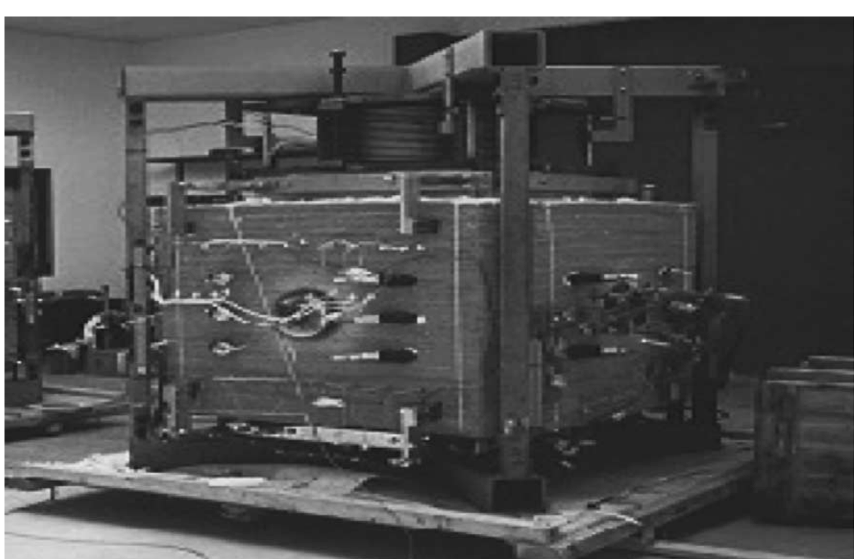

Fig. 1. MCFC stack.

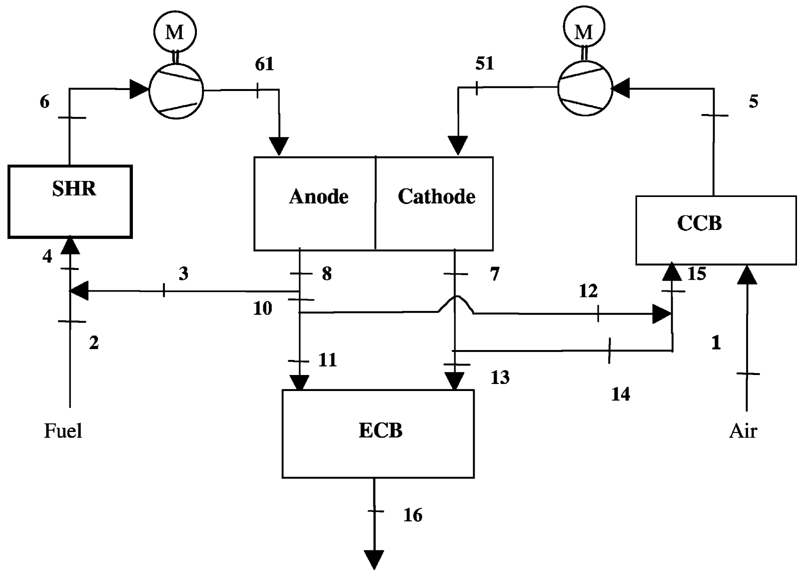

Fig. 2. Fuel cell system plant lay out.

electrical power, heat, steam, and the transfer of CO_2 (in the form of CO_3^{2-}) from the cathode to the anode through the electrolyte. The blowers are necessary for the anodic and cathodic flow recirculation and to recover the pressure losses inside the stack. Several internal recycles characterise the stack plant. At the anodic side, a significant fraction of the exhausts (89%) is recycled for fuel (H_2 and CH_4) and heat recovering. This plant configuration, thanks to the anode-to-anode recycle, allows exploiting about the 90% of fuel inlet, even if—for a single pass—reformer efficiency is not high, as well as the stack fuel utilisation rate (U_f). A part of anode exhausts is recycled to cathode inlet in order to ensure a minimum percentage of CO_2 to be verified [4]; cathode exhausts are recycled to the electrode inlet for heat recovering. The design point performance of the stack are reported in Table 1, while Table 2 shows the thermodynamic data of the MCFC state point reported in Fig. 2.

It is important to point out that the stack system performance shown in Table 1 does not take into account the power necessary for the stack pressurisation.

The option employed in the fuel cell system to pressurize the stack is the use of two compressors electrically driven one for the anodic side (fuel compressor) and one for the cathodic side (air compressor) as shown in Fig. 3.

This solution named here ‘‘standard lay out’’ does not exploit any heat recovering of the exhaust gas energy at the stack exit. Fuel flow rate feeds the anodic side (point 29 in Fig. 3) and it is available at atmospheric condition and

Table 1
FCS design point performance (these values do not take into account the power necessary for the stack pressurisation)

Efficiency (%)	Power (kW)	Cell voltage (V)	Stack temperature (K)	Electricity to heat ratio	Fuel utilisation rate	
50.13	100.4	0.6528	922	0.9933	0.4068 (Single pass)	0.9377 (Total)

Table 2
Temperature and composition at design point

System point[a]	T (K)	Molar fraction rate (%)						
		H_2	CH_4	CO	CO_2	H_2O	O_2	N_2
4 (reformer inlet)	948	4.136	2.584	4.254	61.85	27.17	0	0
61 (anode inlet)	856	8.37	0.743	6.729	58.81	25.34	0	0
8 (anode outlet)	967	4.092	0.7001	4.346	63.19	27.67	0	0
51 (cathode inlet)	904	0	0	0	8.175	9.087	11.1	71.6
7 (cathode outlet)	962	0	0	0	3.855	9.758	9.461	76.89
15 (CCB inlet)	959	0.464	0.110	0.493	10.58	11.79	8.388	68.17
16 (exhaust)	976	0	0	0	4.806	10.16	9.184	75.85

[a] See Fig. 2 for explanation of numerals in this column.

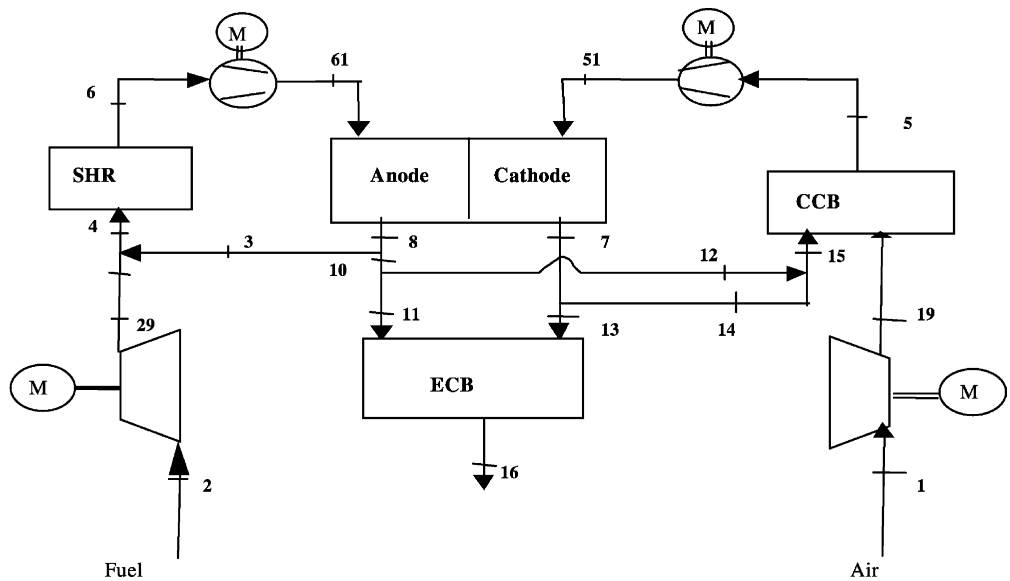

Fig. 3. FCS plant lay out (pressurisation realised by auxiliary compressors).

pressurised at 0.35 MPa by the auxiliary compressor and the power necessary for this compressor is about 1.5% of the whole plant power, owing to the small fuel flow rate (4.97 g/s). The air compressor (point 19 in Fig. 3), indeed, needs about 22% of the total stack power, due to the large air flow rate (139.3 g/s).

Taking into account the power for the two auxiliary compressors the stack system efficiency is reduced to 40.08%, since power for pressurisation (air/fuel compressors plus blowers) is almost 30% of the stack net contribution.

It is worthy to note that in this standard case the exhaust gas pressure is about 0.35 MPa and the temperature is about 700 °C. In this way the exhaust enthalpy recovery may be very useful to pressurise the stack and for co-generation (electricity and heat) purposes. In particular the heat that can be recovered between the stack exhaust temperature and 90 °C is about 100 kW. Therefore, the electricity to heat ratio of the standard MCFC stack is about 0.76.

3. Fuel cell system–MCFC stack pressurisation and heat recovering

The exploitation of the exhaust gas enthalpy to pressurise the stack and to increase its efficiency may be carried out using different solutions; in the following some possible configurations are investigated in detail.

3.1. MCFC hybrid system using a turbocharger

This solution is characterised by a partial heat recovering from the cell exhausts ($T_{ex} > 690$ °C; point 16 in Fig. 4), employs an auxiliary compressor at the anodic side (point 29 in Fig. 4) such as for the standard case, while the air pressurisation (cathodic side) is realised by a turbocharger system (point 19 in Fig. 4). In this case, the power necessary for air pressurisation is supplied by the turbine expander. Total net power increases since only the recirculation blowers and the fuel compressor use power from the stack. As a consequence, efficiency increases, thanks to the increase of the power supplied with the same fuel flow rate.

It is very interesting to note that the gas temperature at the stack exit matches very well with the temperature used for turbocharger applications in the field of internal combustion engine (600–700 °C), and also the expansion ratio is compatible with the ratio of existing turbochargers, in fact the pressure at the turbine exit section is about 1.71 bar and the expansion ratio is 1.98. The TOT value (594 °C) allows again the possibility of heat recovering for district heating to be carefully exploited. In particular the heat that can be recovered from TOT and 90 °C is about 82 kW and the electricity to heat ratio of this solution is 1.23.

3.2. MCFC hybrid system using simple cycle gas turbine

The solution is based on the coupling between the stack and a simple cycle gas turbine as shown in Fig. 5. The stack is the "topping" element while the gas cycle is the "bottoming" one. In this solution, the expander generates both the mechanical power for the air compressor and extra electrical power. Due to the stack size and the gas flow rate, the gas turbine size is in the range 15–30 kW.

Cell exhaust gas enters the gas turbine expander at about 0.35 MPa and 700 °C. This value is lower than the value normally used with uncooled micro gas turbines (900–950 °C). However, if the possibility of post-combustion in the ECB of fuel coming directly from the fuel compressor is considered the gas turbine can be fed with gas at about 900 °C increasing the expander power in a significant manner.

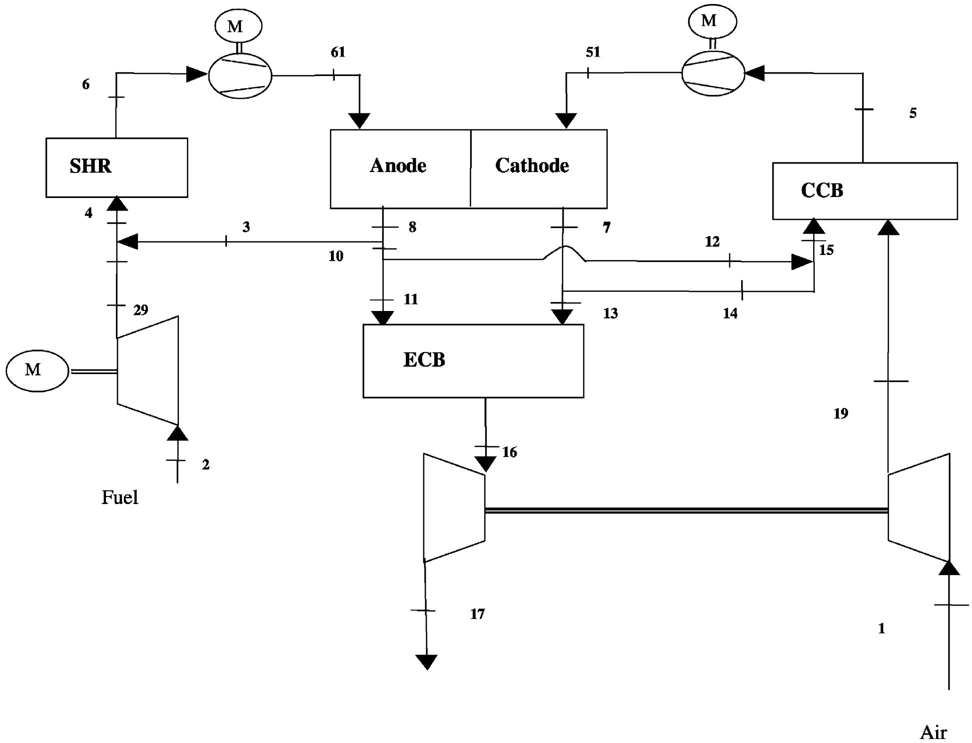

Fig. 4. FCS plant lay out (pressurisation realised by turbocharger).

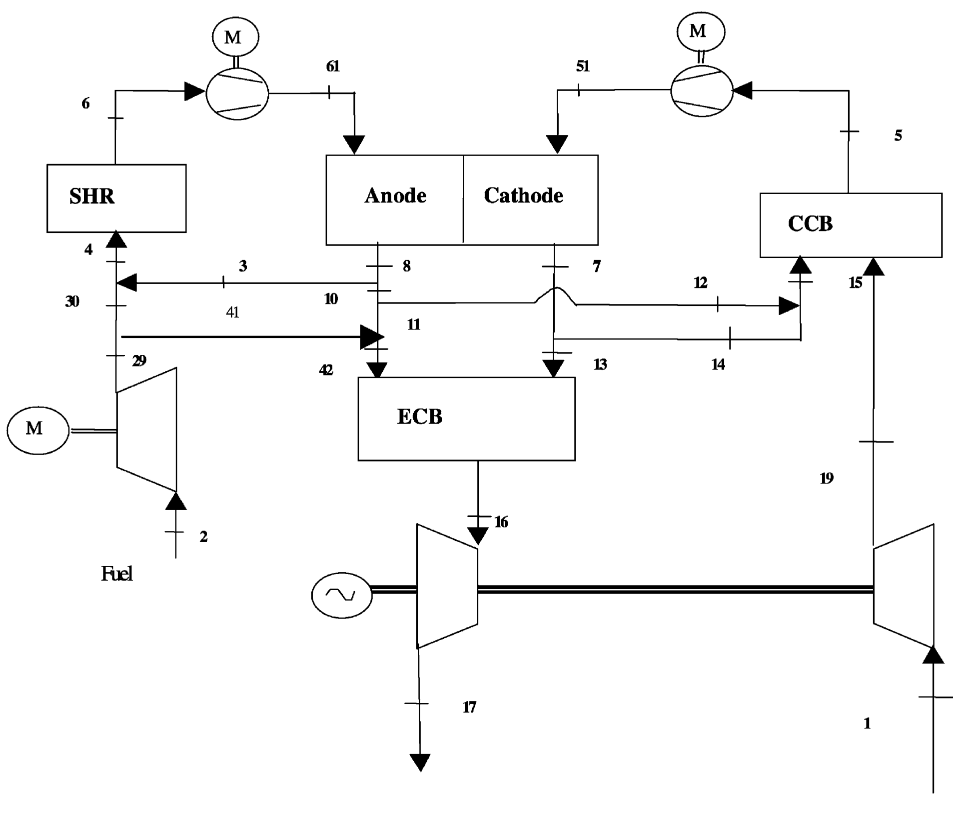

Fig. 5. FCS–GT hybrid system plant lay out.

Therefore, hybrid system electrical power increases, if compared to standard stack power, and efficiency increases too since the fuel flow rate is the same (if post-combustion is not utilised). If this option is considered the expander increases its electrical power but also fuel flow rate increases and therefore the benefit from the efficiency point of view is not still the same and will be discussed in detail in the following paragraph. This solution has been carefully analysed by the authors, with particular reference to its performance at part load condition [4].

3.3. MCFC hybrid system using a regenerated cycle gas turbine

The coupling of the existing FCS stack with a regenerated microgasturbine is very simple for the microturbine since it operates for size under 50 kW at pressure ratio in the range 3–4 and no evident MGT modifications are necessary. The coupling involves some modification of the stack plant configuration: the most significant is the cathodic recycle elimination since its regenerative function may be played by the turbine recuperator with a simplification of the plant lay out and without compromising the system performance. On the contrary, anodic recycles (both anode to anode and anode to cathode) are deeply connected with the system working. Anode to anode recycle elimination, in fact, would involve a re-design of reformer section, since the exhausts enthalpy provides the necessary energy so that the reforming reaction occur (endothermic reaction); this system is known as "sensible heat reformer". Moreover, anodic recycle allows a fuel recovering at the stack outlet, avoiding a direct combustion into the exhausts burner and, thus increasing the global reformer efficiency.

Anode to cathode recycle is necessary since it guarantees a minimum percentage of CO_2 at the cathode inlet (about 9% of inlet mass flow rate). Thus, the existing plant modifications concern with the cathodic recycle only: it has been substituted with a pre-heating process of the air inlet, realised by a counterflow heat exchanger (regenerator) which exploits the turbine exhaust enthalpy. Nevertheless, pre-heated air temperature is still not sufficient since an additional air flow rate is required to compensate the recycle elimination. Owing to an elevated air to fuel ratio, the cathodic burner needs an additional fuel contribution to keep the proper temperature level at the electrode inlet.

Two different plant configurations have been considered: the first solution (Fig. 6) is characterised by an additional fuel contribution to cathodic burner (about 18% of the total

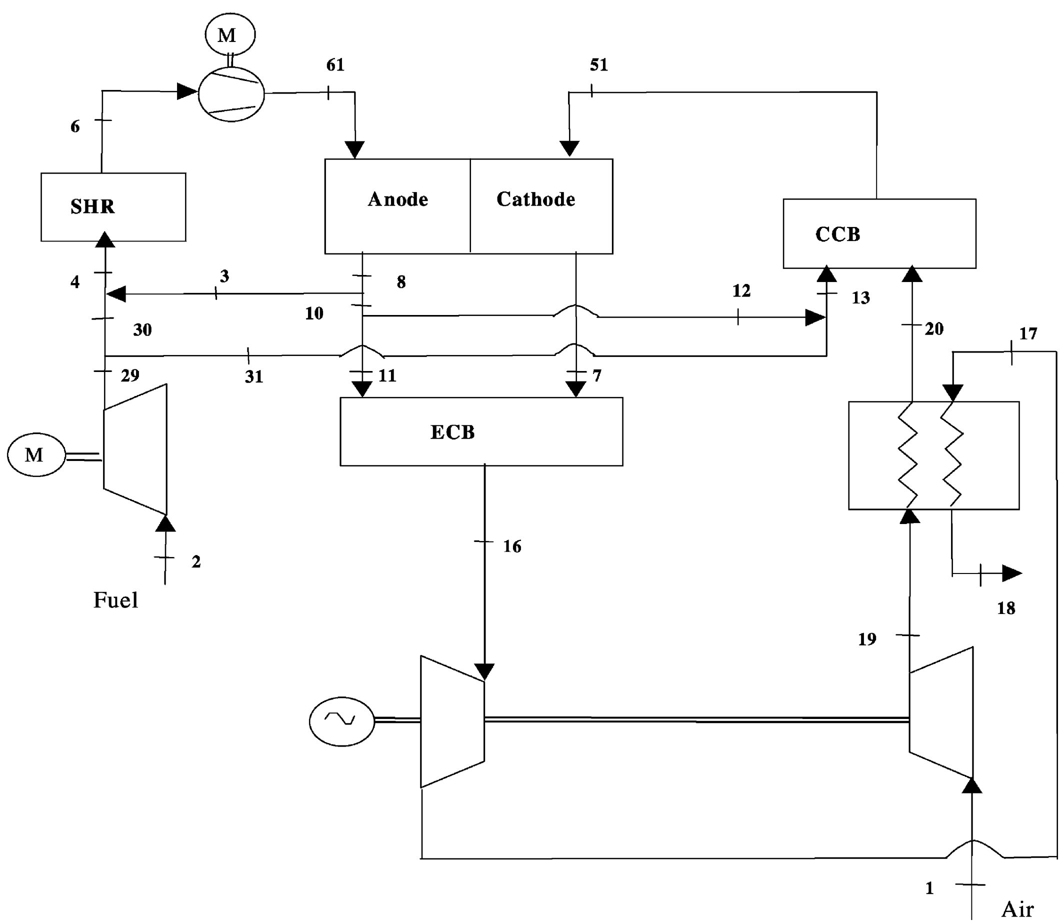

Fig. 6. FCS–MGT hybrid system plant lay out (first solution).

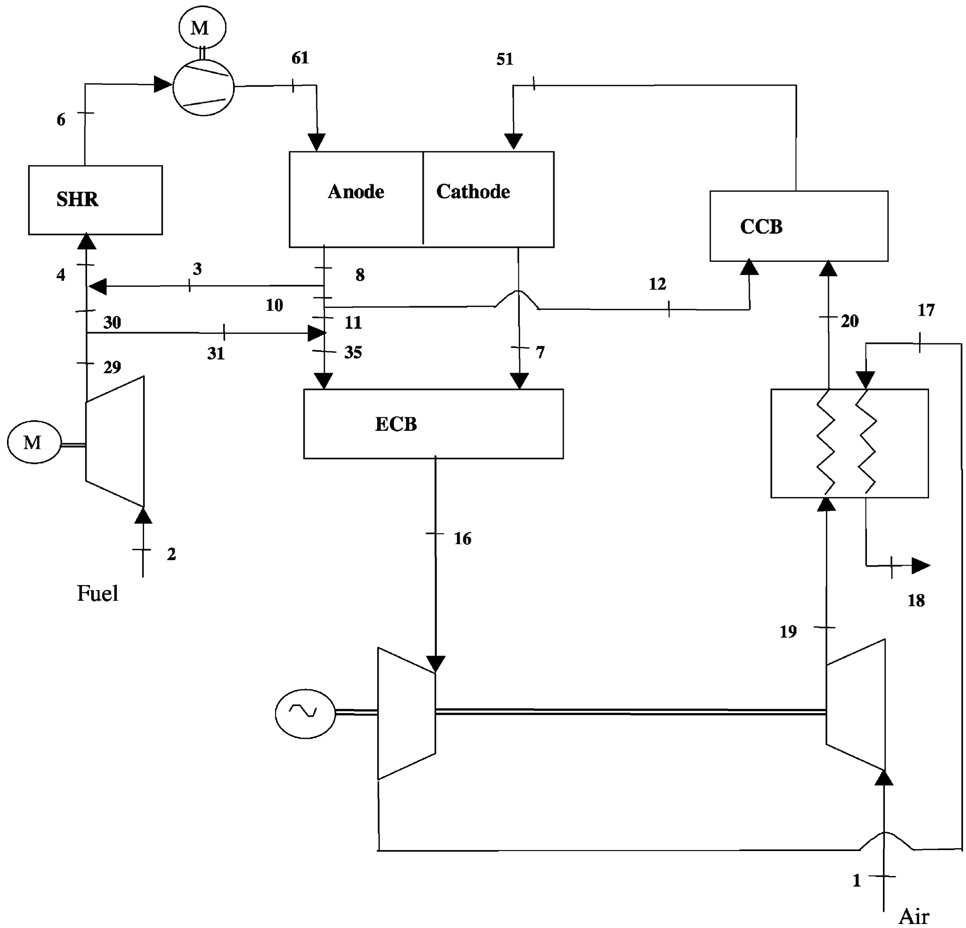

Fig. 7. FCS–GT hybrid system plant lay out (second solution).

fuel flow rate): this allows the stack inlet temperature to be just over the operating limits (>580 °C).

In the second solution (Fig. 7), the additional fuel (21% of the total fuel flow rate) is sent to the exhausts burner (point 31 in Fig. 7). In this way, as already discussed for the previous solution with post-combustion, turbine inlet and outlet temperatures increase and this fact has positive effects on the regeneration section.

4. FCS–MCFC stack and hybrid system model

To carefully investigate the performance of the previous hybrid system lay out and compare them to the FCS standard solution a simulation model of the stack and of the whole plant, including sensible heat reformer, catalytic burners, etc. has been developed.

A stack simulation model, using a variable cell geometry approach, was previously developed by TPG, University of Genoa in Fortran language and positively tested with available experimental data [3]. This model has been included in the thermoeconomic modular program (TEMP) [5] to carry out detailed design point investigation of large size (10 MW_e) hybrid systems as already discussed by the authors [3]. Moreover, as already carried out at TPG concerning hybrid systems based on SOFC technology [6], in order to study MCFC stack and hybrid systems off-design performance, a new model, named HS-MCFC has been developed using Simulink language [1]. Such model is a zero-dimensional one. It is based upon the energy balance equation of each component; the different terms are evaluated according to the actual temperature value but no temperature profile is considered inside the stack. This approach allows considering the MCFC-stack design point behaviour from the plant point of view and to compare several solutions to determine the most efficient one.

On the other hands, it does not require the knowledge of detailed stack geometrical data and may be easily applied to different system typology with reduced calculation time.

In the sessions above, the Ansaldo fuel cells model and the hybrid system one are described in detail.

4.1. FCS model

In this case, the stack area is considered fixed at the beginning of the calculation and main input data of the model are: chemical and thermodynamic characteristics of inlet flow rates such as temperature, pressure and composition. Also current density is considered an input data. The main assumptions in the model are: shift reaction at equilibrium; operating temperature considered as the average value between inlet and outlet gas temperatures; an apt sharing of electrochemical heat between anode and cathode [1]; heat losses considered as a percentage of electrical power. Since current value is known (input data) the unknown term is the equilibrium temperature T_{eq}. The calculation is based on the stack energy balance equation; starting with a T_{eq} value of first attempt, it is possible to evaluate:

- outlet mass composition and specific heat rate;
- electrochemical and shifting heat rate;
- Nernst potential and voltage losses.

The balance equation applied for each electrode, supplies outlet mass temperatures and a new value of operating temperature (calculated as the average between inlet and outlet values) until data convergence.

Also the sensible heat reformer model structure is based upon the energy balance equation. Input data are the chemical and thermodynamic characteristics of the inlet flow rates while the unknown term is again operating temperature. The model considers both reforming and shifting reactions at equilibrium [1]. As for the cathalitic burners, operation at fixed percentage of fuel consumed has been considered.

The FCS model results have been verified by comparison with the data reported in Table 2 and the results of the above mentioned Fortran model (TEMP-code). Fig. 8 shows the comparison among the data and the calculation results (temperature in the system points and percentage error). The calculation error for temperature in each point of the plant, is always less than 1.5%. Fig. 9 shows the percentage error on chemical compositions and also in this case the agreement between the data and the calculation is very good, in particular the error on the chemical composition is always less than 1%.

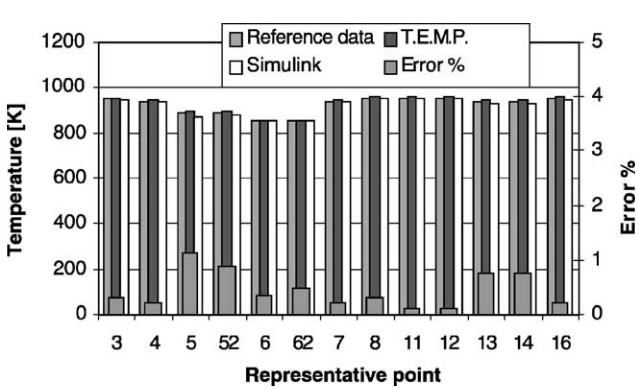

Fig. 8. Temperature in the representative system points: comparison among results (Simulink and T.E.M.P.) and reference data.

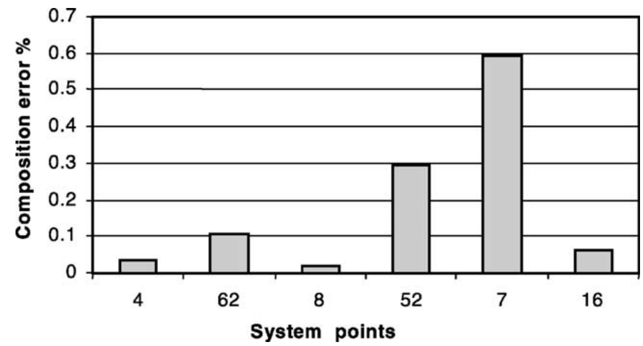

Fig. 9. Percentage error on chemical composition (Simulink results and reference data).

4.2. HS model

Hybrid system model has been realised by coupling the fuel cell model with gas expander, air and fuel compressor, according to the particular plant configuration. As for MCFC–GT case study, in order to determine the matching between the air compressor and gas turbine, the unknown terms are:

- compressor flow rate;
- pressure ratio;
- compressor and turbine isoentropic efficiencies, depending on operating conditions.

Simulation requires an external loop for pressure ratio calculation and an internal one for flow rate and efficiency evaluation (for both turbine and compressor models). The input data for the compressor module are air inlet pressure and temperature, rotational speed and first-guess pressure ratio. The model is based on apt compressor and expander maps (efficiency and pressure ratio versus non-dimensional flow rate) [6].

5. Hybrid systems performance

Design point performance of the above-cited plants have been compared. It is important to point out that the analysis has been made at fixed conditions (in terms of flow rates and chemical composition) at the stack inlet (points 51 and 61 in Fig. 2). Inlet temperature is almost constant for the first three solutions while undergoes a small decrease (about 4%) for the regenerated ones (stack plus regenerated microgasturbine), due the elimination of cathode to cathode recycle.

Fig. 10 shows the plant efficiency versus the stack percentage contribution to the total net power. In the standard lay-out (FCS plus two auxiliary compressors) about 30% of the net power supplied by the stack is used for the plant. In the turbocharger solution the exhaust enthalpy is exploited for the air compression; plant efficiency rises up to 50% since only the 2% of the stack power is necessary for auxiliaries (blowers and fuel compressor).

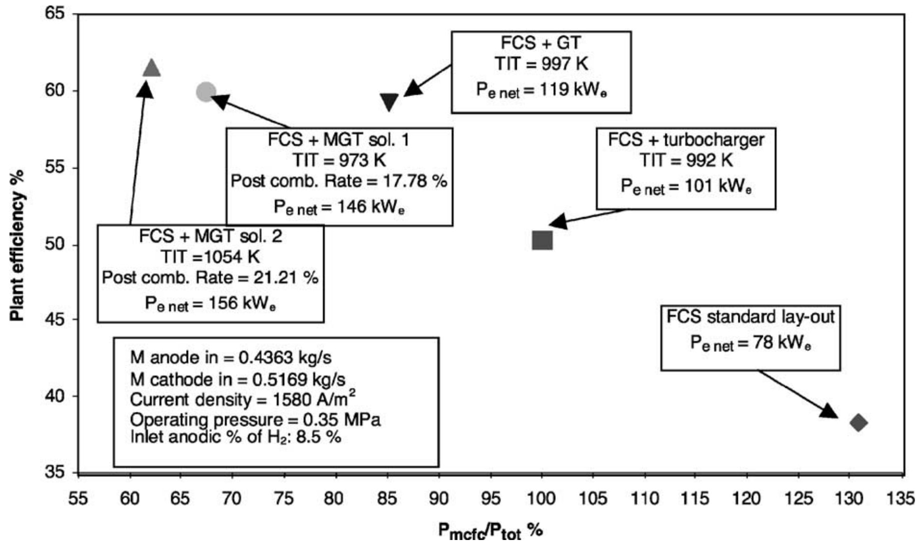

Fig. 10. Comparison between the different plant solutions.

The coupling between FCS and a gas turbine allows higher efficiency: the turbine expander (whose pressure ratio is 3.5) supplies the necessary power for pressurisation (23 kW) and a further contribution to the plant net power (17 kW). The overall plant supplies about 120 kW, shared between the stack (84%) and the turbine expander (16%). Efficiency value is 59% also considering the power for the blowers and the fuel compressor (about 5 kW).

Hybrid systems based on FCS and a regenerated micro-gasturbine have been considered too. This configuration makes post-combustion necessary in order to verify the feasibility of temperature operating limit. The last two systems, despite the post-combustion presence (at cathodic burner for first solution and at the exhaust burner for the second one) show an increase of overall efficiency (up to 60%) with a lower stack contribution to the total net power (about 60%).

The heat exchanger makes air temperature rise up to 500 °C. This involves feeding the cathode at 615 °C against 650 °C of the MCFC–GT solution (where the cathode exhaust enthalpy is recovered by internal recycle). This cooling has a negative effect on the FCS performance: the cell voltage decreases due to the greater ohmic losses as shown in Table 3. Power supplied by the plant is 146 kW for the first and 156 kW for the second one. The second solution (ECB post-combustion) allows rising TIT value up to 780 °C, against 700 °C of the first solution (where post-combustion is considered at the CCB inlet). Power supplied by the turbine expander is 137 kW against 126 kW of the first solution while the one necessary for cathode pressurisation is 79 kW. It is necessary to point out that the greater value of power consumed for pressurisation (79 against 23 kW of the FCS–GT plant) is due to the cathodic recycle elimination; a greater air flow rate (0.45 against 0.139 kg/s), in fact, feeds the FCS–MGT plants in order to keep constant the stack inlet conditions (reported in Fig. 10). As a consequence, the turbine supplies more power (136 against 41 kW).

In the comparison among the different hybrid systems typologies, the possibility of co-generative applications has been considered through the evaluation of the electricity to heat ratio; it has been calculated as the ratio between the total net power and the recoverable heat from the exhaust (until 90 °C). It is necessary to point out this heat flow rate is available at different sections for the system considered:

- at the exhaust burner (ECB) outlet for the standard lay out;
- at the expander outlet for the FCS coupled with turbo-charger or gas turbine;
- at the recuperator outlet for the regenerated solutions.

Table 3
Comparison among the hybrid systems (design point)

Plant configuration	Cell voltage (V)	Stack efficiency (%)	Electricity to heat ratio (kW/kW)	T_{ex} (K)	Q, recoverable (kW)
Standard lay out	0.6617	38.98	0.761	985	102.5
FCS + turbocharger	0.6643	50.3	1.233	866	81.8
FCS + gas turbine	0.6669	50.49	1.861	760	63.8
FCS + microgasturbine (1st solution)	0.6488	49.16	2.170	450	67.2
FCS + microgasturbine (2nd solution)	0.6410	48.57	2.186	508	71.5

Last configurations (FCS + MGT) are characterised by the higher value of electricity to heat ratio since the exhaust sensible heat is exploited to increase the turbine enthalpy rate; these results are as shown in Table 3.

6. Post-combustion effect

Influence of post-combustion has been considered only with reference to the FCS–GT and FCS–MGT case study since TIT greater than 700 °C does not match well existing turbocharger operating limit. The parametric analysis has been performed at fixed stack flow rates and current density; as for regenerated system, inlet temperature (in particular at cathodic side) is not constant due to its dependence on post-combustion. The additional fuel flow rate has been increased in accordance with the stack-temperature operating limit. The stack efficiency has been evaluated under the following hypothesis:

- net power is calculated as the electrical power without the one necessary for blowers and fuel pressurisation (including the post-combustion rate);
- inlet thermal power is only the one supplied to the anode (the one exploited for post-combustion is considered for the plant efficiency).

6.1. FCS–GT system

The design point does not involve any post-combustion. In order to study the influence of such parameter, the plant performance has been evaluated by increasing the value of fuel flow rate. The one supplied to the stack (4.16 g/s) (point 30 in Fig. 5) does not vary, while an additional fuel feeds the

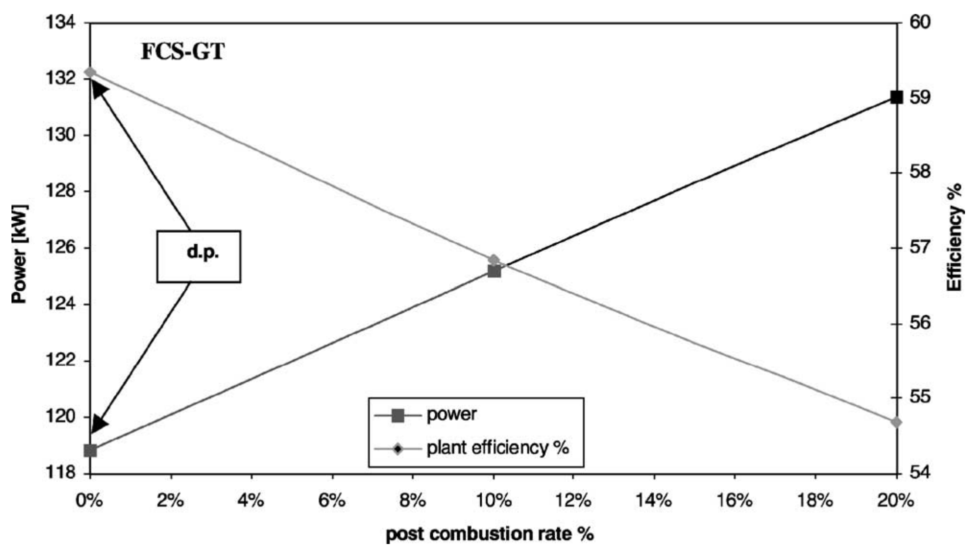

Fig. 11. FCS–GT: plant efficiency and power vs. post-combustion rate.

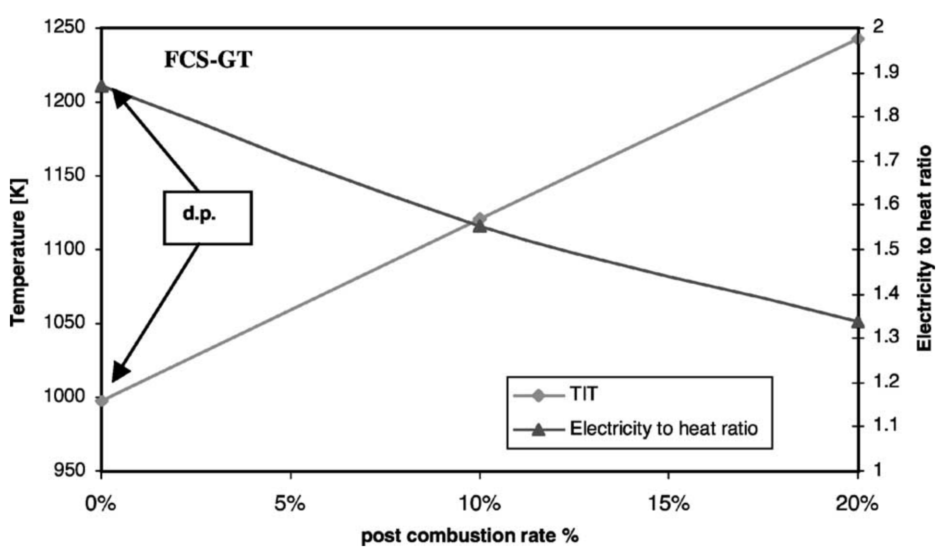

Fig. 12. FCS–GT: turbine inlet temperature and electricity to heat ratio vs. post-combustion rate.

ECB, in order to increase TIT up 900 °C. Since no regeneration of the turbine exhaust is considered, the FCS section is not influenced at all by the post-combustion increase: it supplies the same power with the same efficiency than the design point case study.

At 20% of post-combustion rate, while power supplied by the overall plant rises up to 10% of its design point value thanks to the increase of turbine contribution, the total efficiency decreases, as shown in Fig. 11. Fig. 12 shows the electricity to heat ratio trend; it decreases with post-combustion since greater TIT values make the exhausts available at higher temperature and thus more suitable for co-generative applications (since they are not exploited inside the plant).

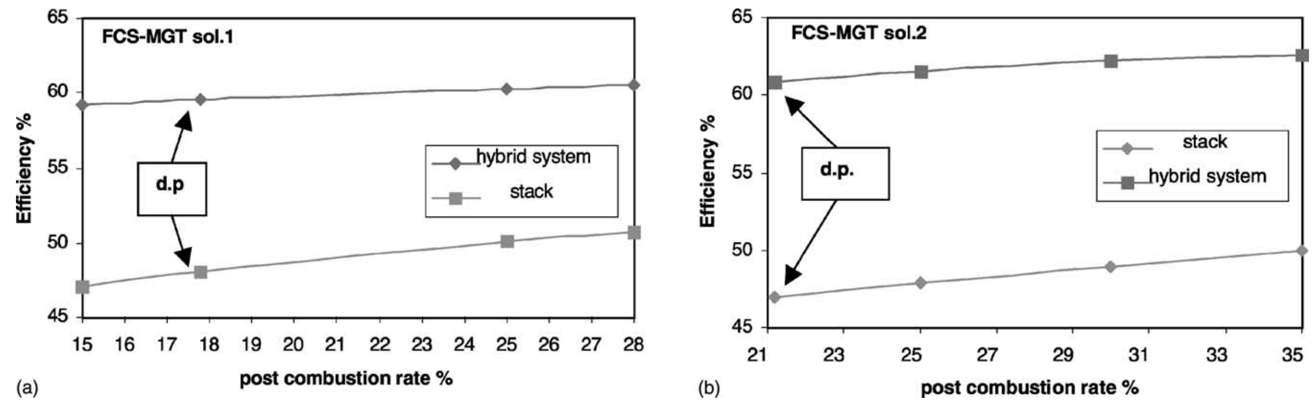

Fig. 13. (a) FCS–MGT (first solution): efficiency vs. post-combustion rate. (b) FCS–MGT (second solution): efficiency vs. post-combustion rate.

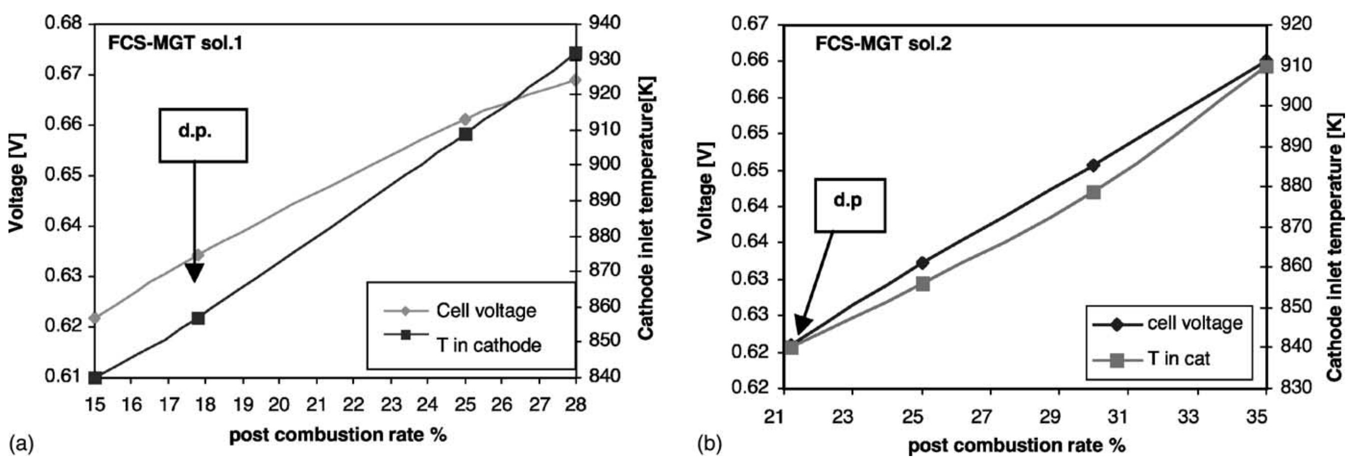

Fig. 14. (a) FCS–MGT (first solution): cell voltage and cathode inlet temperature vs. post-combustion rate. (b) FCS–MGT (second solution): cell voltage and cathode inlet temperature vs. post-combustion rate.

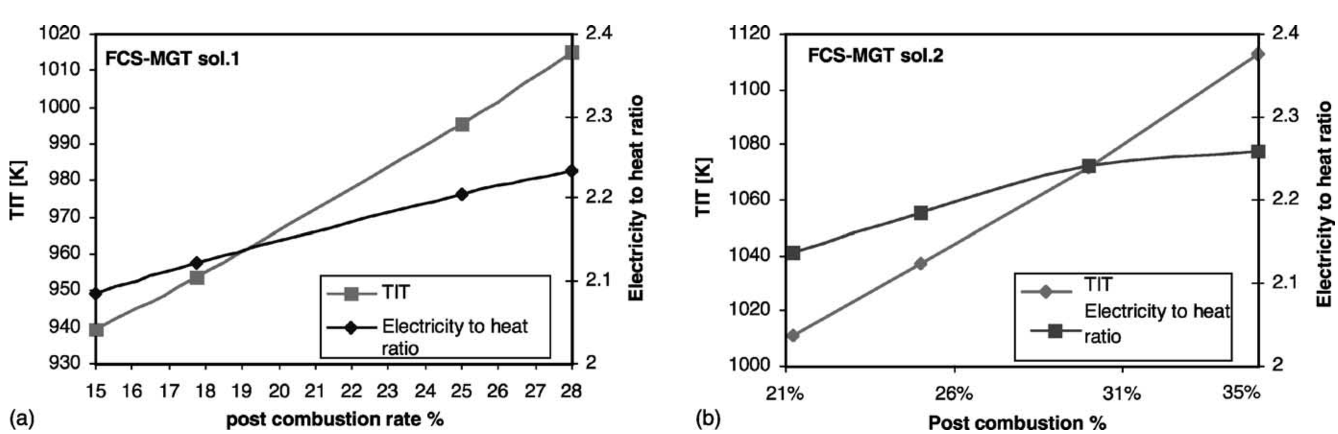

Fig. 15. (a) FCS–MGT (first solution): turbine inlet temperature and electricity to heat ratio vs. post-combustion rate. (b) FCS–MGT (second solution): turbine inlet temperature and electricity to heat ratio vs. post-combustion rate.

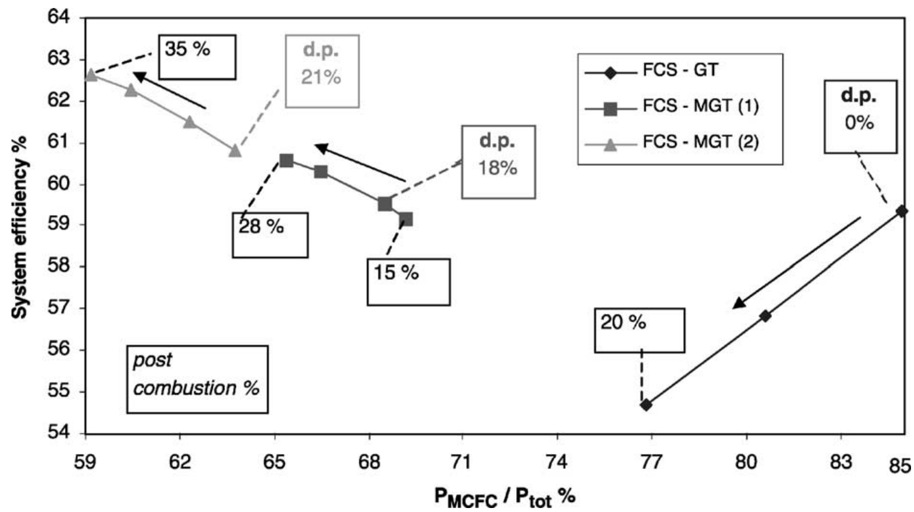

Fig. 16. Post-combustion effects on hybrid systems performance.

6.2. FCS–MGT (solutions 1 and 2)

As already stated, these hybrid systems require post-combustion at design point too, in order to manage the stack temperature and keep it inside the operating limit and the stack working conditions depend on the bottoming section. This fact explains the different behaviour of the FCS–MGT systems to a post-combustion increase. An efficiency improvement has been obtained thanks to the greater contribution of both turbine and stack section, as shown in Fig. 13(a) and (b). Cathode inlet temperature rises with post-combustion involving an increase in the cell voltage, thanks to the lower ohmic losses (Fig. 14(a) and (b)).

Possibility of co-generative applications has been evaluated: electricity to heat ratio rises with post-combustion rate, as shown in Fig. 15(a) and (b), according to the improved plant efficiency and the higher power supplied. The post-combustion increase influences the stack section: TIT greater values make the cell temperature rise and the voltage losses fall down.

Results are summarised in Fig. 16; an increase in post-combustion involves a greater turbine contribution on the overall power for all system considered, but efficiency shows opposite trends for regenerated and not regenerated systems.

7. Influence of the stack operative pressure

The FCS stack system is normally pressurised at 3.5 bar; nevertheless, it is interesting to analyse the pressure influence on stack and hybrid systems performance through a parametric study.

In order to evaluate the effect of a pressure increase on the hybrid systems, several aspects must be considered since such parameter has contrasting effects on the different plant sections.

As for the stack, its potential rises with pressure for several reasons:

- both reactant partial pressures and gas solubility increase;
- the electrolyte losses for evaporation decreases by working at elevated pressure.

On the other hand, high pressure promotes some detrimental reactions, such as the coke and methane synthesis, whose equations are:

$$2CO \rightarrow C + CO_2 \quad \text{(coke synthesis)} \tag{1}$$

$$CO + 3H_2 \rightarrow CH_4 + H_2O \quad \text{(methane synthesis)} \tag{2}$$

Coke synthesis, that may take place at the anodic side, causes the electrode pores occlusion. As for the methane synthesis, being the opposite process of the reforming reaction, involves a hydrogen consumption (for each mole of CH_4 produced, 3 mole of H_2 are consumed, with a great loss of reactant and efficiency). Thus, by increasing pressure ratio the stack is fed with a lower percentage of hydrogen. Moreover, it is necessary to point out that a pressure increase involves greater plant and structure expenses and an additional power for pressurisation.

7.1. FCS–GT (without post-combustion)

In order to evaluate pressure influence only and to keep air and fuel temperature inside the stack operating limit an intercooled compression has been considered for the cathodic side. At first, this solution has been adopted for the 0.35 MPa—standard case; the advantage due to the reduction of compression work (about 3 kW) is limited by a stack efficiency decreases due to the greater ohmic losses (connected with the lower operating temperature).

Then, the same plant solution has been analysed at increasing operating pressure (until 0.65 MPa). Results are shown in Table 4: power values are referred to the standard case (3.5 bar without intercooling). The power

Table 4
Pressurisation effect on FCS–GT system

FCS–GT pressure ratio	U_f	P/P^*, stack (%)	P/P^*, HS (%)	Cell voltage (V)	TIT (K)	P/P^*, compr. (%)	P/P^*, turb. (%)	η_{stack} (%)	η_{HS} (%)	P_{MCFC}/P_{plant} (%)	TOT (K)	e/q
3.5[a]	0.39	100	100	0.6669	996	100	100	50.5	59.2	85.2	760	1.86
3.5	0.38	98.5	100.5	0.6569	982	88.3	98.5	49.7	59.6	83.5	746	1.95
4.5	0.39	100.3	103.6	0.6709	992	109.5	115.4	50.6	61.4	82.4	716	2.19
5.5	0.41	100.6	105.2	0.6743	990	124.5	128.2	50.8	62.4	81.4	682	2.47
6.5	0.44	100.6	106.1	0.6764	989	136.7	137.5	50.8	62.9	80.7	658	2.71

[a] This case study is the one at 0.35 MPa without intercooling.

supplied by the overall power increases; this is due, above all, to the turbine contribution increase connected with the inlet pressure rising. As for the FCS–MCFC stack, a pressure increase has no noteworthy effects: pressurisation up to 0.65 MPa involves a voltage increase of about 1.5% but net power is almost constant, due to the greater power for fuel pressurisation (from 1.4 kW at 0.35 MPa to 2.6 kW at 0.65 MPa).

It is worthy to note the reformer efficiency decrease at higher pressure (equilibrium constant, in fact, increases with temperature and decreases with pressure); thus a reduced percentage of H_2 feeds the anode inlet. Power for the air compressor increases of about 8.7 kW, while the turbine work is increased of 15.5 kW; thus the turbogas contribution to the total net power increases of 7 kW (about 7% of the stack power). While turbine inlet temperature almost does not vary by increasing pressurisation, the outlet one decreases of about 100 K: thus the turbine power increases.

As for the plant efficiency versus pressure ratio, the improved performance is due above all to the turbine section. By increasing operating pressure from 0.35 to 0.65 MPa, plant efficiency rises from 59.2 to 62.9% while the stack performance is rather constant; thus the fuel cell contribution to total net power decreases at higher pressure. Intercooling at 0.35 MPa is not profitable for the stack section since it makes the operating temperature decrease of about 15 °C with the consequent TIT reduction. Nevertheless, plant net power is almost constant thanks to the lower power necessary for pressurisation.

Outlet turbine temperature (TOT) trend has been analysed, in order to evaluate co-generative applications. By increasing operating pressure from 0.35 up to 0.65 MPa, TOT decreases (of almost 100 °C); as a consequence, the electricity to heat ratio (e/q) increases.

7.2. FCS–MGT

The same analysis has been carried out also for FCS–MGT systems (first and second solutions). Starting from design point condition, pressure has been increased up to 0.65 MPa. Since an intercooled compression has been considered, only pressure effects have been evaluated. Results are shown in Tables 5 and 6. Under these operating conditions, TOT decreases with pressure, causing a cooling of the overall plant. Thus, a pressure increase from the design point value involves greater post-combustion rates, in order to keep the stack temperature inside the operating limit. This necessity is due above all to the cathodic side where only the recuperator plays the regenerative function owing to the absence of cathodic recycle. Post-combustion rate has been increased from the design point value (17% for the first solution and 21% for the second one) up to 28% for the first solution and 35% for the second one. The tables also show the performance comparison at different pressurisation levels.

At first, intercooling has been considered for 0.35 MPa case; it appears profitable thanks to the lower power necessary for pressurisation, even if it involves a small temperature decrease.

For both solution, plant performance decreases with pressure. Higher pressure involves a temperature decrease at the stack section (of about 25 °C); thus the stack voltage

Table 5
Pressurisation effect on FCS–MGT (first solution)

FCS–MGT (1) pressure ratio	Post-combustion rate (%)	P/P^*, stack (%)	P/P^*, HS (%)	Cell voltage (V)	TIT (K)	P/P^*, compr. (%)	P/P^*, turb. (%)	η_{stack} (%)	η_{HS} (%)	P_{MCFC}/P_{plant}	T_{ex} (K)	e/q
3.5[a]	17.8	100	100	0.6523	977	100	100	49.3	60.1	67.2	719	2.204
3.5	17.8	99.5	102.1	0.0.6489	973	94.8	99.7	49.0	61.4	65.6	712	2.923
4.5	22.1	98.5	102.9	0.6462	966	118.5	116	48.5	58.7	64.5	674	2.305
5.5	25.9	98.0	105.6	0.6464	965	134.8	129.5	48.3	57.2	62.5	643	2.425
6.5	28.6	97.7	106.8	0.6471	966	148	139.3	48.1	55.8	61.6	623	2.498

[a] This case study is the one at 0.35 MPa without intercooling.

Table 6
Pressurisation effect on FCS–MGT (second solution)

FCS–MGT (2), pressure ratio	Post-combustion rate (%)	P/P^*, stack (%)	P/P^*, HS (%)	Cell voltage (V)	TIT (K)	P/P^*, compr. (%)	P/P^*, turb. (%)	η_{stack} (%)	η_{HS} (%)	P_{MCFC}/P_{plant}	T_{ex} (K)	e/q
3.5[a]	21.2	100	100	0.644	1058	100	100	48.6	61.6	62.2	776	2.202
3.5	21.2	99.9	102.3	0.641	1055	94.5	99.5	48.6	63.0	60.7	772	2.873
4.5	27	98.5	106.8	0.638	1083	118.1	119.2	47.8	61.0	57.3	756	2.333
5.5	31.9	98.2	113.5	0.640	1120	133.9	135.9	47.7	60.4	53.8	751	2.474
6.5	35.5	98.4	118.3	0.645	1154	146.5	148.4	47.8	59.7	51.7	753	2.571

[a] This case study is the one at 0.35 MPa without intercooling.

undergoes the contrasting effects of a pressure increase (profitable) and of the consequent cooling (detrimental).

For this reason, its value is almost constant by varying pressure. As for the hybrid system, the higher power supplied by the turbine section does not compensate the greater inlet thermal power furnished for post-combustion; thus efficiency decreases at higher pressure.

8. Comparison

Hybrid systems performance condition has been compared, according to the simulation results. Hybrid systems based on MCFC and gas turbine have shown a different dependence on operating condition if compared with the regenerated solutions. In particular:

- pressurisation by auxiliary fuel and air compressors reduces the stack performance and does not allow a proper exhaust gases exergy recovering;
- pressurisation by turbocharger does not supply an additional power contribution, even if it reduces the disadvantages concerning with the stack pressurisation;
- FCS–GT solution allows a further efficiency increase thanks to the additional net power supplied by the turbine section (without any fuel flow rate increase);
- FCS–MGT solution allows the stack lay out simplification thanks to the cathodic recycle elimination. Both power and thermodynamic efficiency increase. Stack contribution to total net power is about 60% (against 85% of FCS–GT): this involves a significant reduction of plant costs ($/kW) thanks to the MGT section (less expensive than the FCS one);
- post-combustion involves a power (and specific power) increase and reduces the MCFC stack percentage contribution to total net power. FCS–GT plant efficiency decreases since the additional power supplied by turbine does not compensate the greater inlet thermal power necessary for post-combustion; as for the stack section, it is not influenced at all since it is a topping element. Different results have been obtained for FCS–MGT plants: a post-combustion increase involves an improvement of the overall efficiency thanks to greater power supplied by turbine and stack; the latter, in fact, is positively influenced by the TIT increase (through the regeneration);
- pressurisation effects on the stack performance have been analysed at fixed cathode (air) inlet temperature; thus an intercooled compression has been considered in order to increase operating pressure up to 0.65 MPa without compromising the temperature limit feasibility. A pressure increase appears profitable for the greater contribution of the turbine section. As for the stack, no relevant effects have been registered. The voltage increase is about 1.5% and the power increase is exploited for anode pressurisation.

9. Conclusions

With reference to an existing FCS–MCFC stack (100 kW size, Ansaldo fuel cells), a study of pressurisation and heat recovering techniques has been presented and discussed in this paper using the HS-MCFC code developed at TPG, University of Genoa. It is worthy to note that the code HS-MCFC is very useful for MCFC hybrid system off-design performance analysis too as already shown by the authors [4] for one of the hybrid systems presented here (MCFC stack coupled to simple cycle gas turbine).

The main results of the present study are the following.

9.1. Efficiency

In comparison with the standard lay out (FCS plus electrically driven compressors), hybrid systems are characterised by higher efficiency. The standard lay out, in fact, does not allow a proper exergy recovering of the exhaust gases.

In particular, FCS + turbocharger is profitable since the stack exhausts are exploited for the plant pressurisation, but no contribution to net power is supplied. FCS–GT allows a further improvement in performance with an additional power of about 18 kW. The best solution is the one involving the coupling between the FCS and a regenerated microgas-turbine. Efficiency value rises up to 61% and it is noteworthy that a post-combustion increase allows a further improvement, thanks to the stack better performance connected with higher temperature. From an overall plant efficiency point of view, pressurisation is profitable for all typologies of hybrid system considered.

9.2. Specific work

FCS–GT solution is characterised by the greatest value of specific power (net power to air flow rate ratio). Post-combustion effect has been evaluated: rising its value from 0% (design point condition) to 15%, specific power increases of about 90 kJ/kg_{air} while plant efficiency decreases, as shown in Figs. 17 and 18.

Lower values of specific work characterise the FCS–MGT solutions, since a greater inlet flow rate is necessary to substitute the cathode recycle.

These plants (solutions 1 and 2) show an opposite behaviour (if compared with the FCS–GT system) for what concerns the post-combustion influence; an increase of additional fuel involves an increase of both specific power and efficiency (Fig. 18).

9.3. Lay out complexity

From a lay out complexity point of view, FCS plus turbocharger is the more profitable system; if compared with the FCS–GT solution, it does not require any additional control system since no contribution to total net power is supplied by the turbine expander. The FCS–MGT solution has some problems concerning the recuperator reliability;

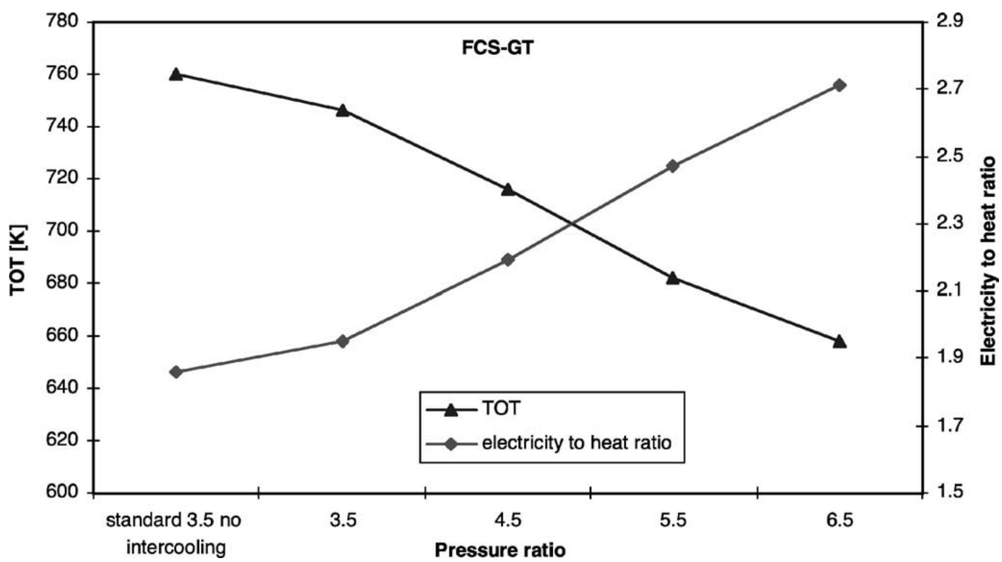

Fig. 17. FCS–GT: turbine outlet temperature and electricity to heat ratio vs. pressure ratio.

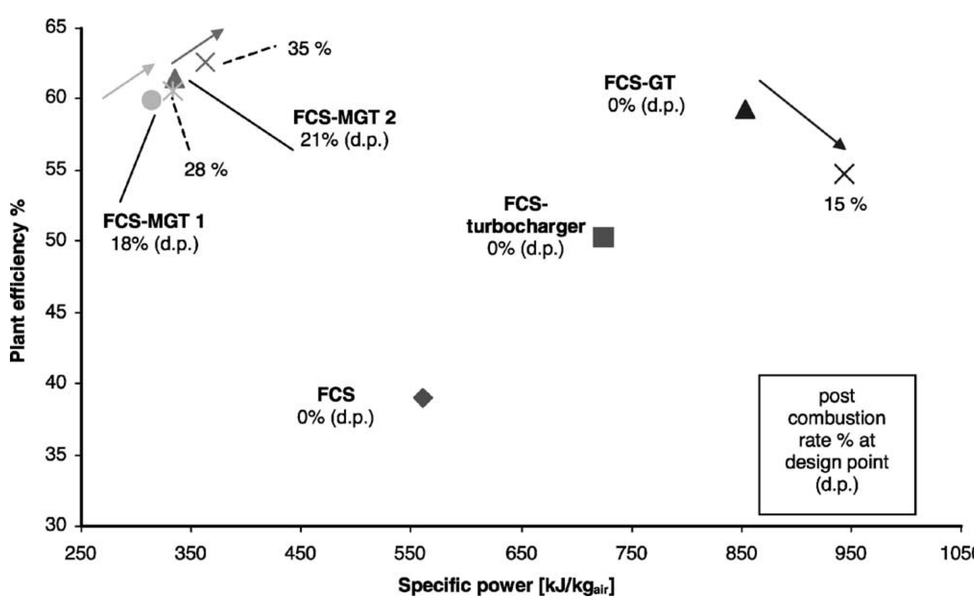

Fig. 18. Post-combustion effects on plant efficiency and specific power: comparison among the different systems.

moreover, an apt integration of the control system is required for the power supplied by the turbine section. On the other hand, the elimination of cathodic recycle involves a simplification of the stack section.

9.4. Technological difficulties

The turbocharger operating temperature (at present time) limits the hybrid system performance, since no post-combustion can be adopted.

Due to the additional power supplied by the bottoming section, and considering the small size of the plants, control system is more problematic for FCS–GT and FCS–MGT; moreover, regenerated systems involve the modification of the stack standard lay out.

9.5. Stack to hybrid system power ratio

If compared with the FCS–MGT solutions, FCS–GT plant is characterised by an higher value of the stack to hybrid system power ratio (83%), as shown in Fig. 10. The presence of post-combustion for the regenerated solutions, in fact, involves a greater turbine contribution (35–40% of the overall net power). According to results of the parametrical analysis, both a post-combustion rate and operating pressure increase from the design point value involves a decrease of the stack to hybrid system power ratio (Fig. 16 and Table 4).

9.6. Electricity to heat ratio

Possible co-generative applications have been evaluated through the electricity to heat ratio. A comparison among the different solutions at design point is shown in Table 3; regenerated hybrid systems are characterised by the higher value of such parameter, since the exhaust sensible heat is recovered in the air pre-heating process to the detriment of co-generative application. Post-combustion influence is different for the considered hybrid systems: it rises with additional fuel for regenerated systems (FCS–MGT) (Fig. 15(a) and (b)) due to greater power supplied: besides turbine, also stack performance improves thanks to the higher operating temperature.

On the contrary, for FCS–GT plants, a post-combustion increase causes a reduction of the electricity to heat ratio. The effect of a TOT rising (involving a greater recoverable heat) prevails upon the power growth one since the turbine only gives a greater contribution.

9.7. Plant costs and cost of the energy (electricity and heat)

As for the plant cost, the turbocharger solution is favourite even if, in future, microturbine cost may become more competitive. Otherwise, since the cost of the turbine power is lower than the stack one, an increase of the turbine to stack power ratio through post-combustion—for example—appears a reasonable way to reduce the plant cost. This opportunity may be considered only for GT and MGT systems, owing to the more restrictive operating limit on temperature for turbocharger.

On the other hand, an economical analysis of the proposed plants should consider also the possibility of co-generation (and thus the cost of the recoverable heat). From this point of view, turbocharger solution is more profitable.

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