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THE COMBINATION OF SOFC AND MICROTURBINE FOR CIVIL AND INDUSTRIAL COGENERATION

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Abstract

Recent studies have shown the possibility of obtaining extremely high electric efficiencies in distributed electric power generation with small capacity advanced plants based upon the combined technologies of solid oxide fuel cells and microturbines. This paper investigates the potential energy savings achievable by the application of this novel technology to cogeneration.

Due to the high electrical efficiency of these systems (approaching 65% LHV), their heat/electricity ratio is unusually low. The addition of a heat pump can dramatically increase the heat/electricity ratio as well as add flexibility to the system. The application of these systems to distributed electricity generation connected to residential heating is discussed. Detailed results are presented, in terms of annual energy balances; they indicate high primary energy savings and reduction in emissions of carbon dioxide.

Nomenclature

Ex_{fuel}	specific exergy of fuel (kJ/kg)
Ex_{Qth}	heat exergy (kW)
Fuf	fuel utilization factor (eq. 2)
L_{GT}	gas turbine organic, electric and inverter losses (%)
$L_{I,SOFC}$	SOFC DC/AC inverter losses (%)
L_{th}	thermal losses (%)
L_{em}	heat pump electric motor losses (%)
m	mass flow rate (kg/s)
p	pressure (Pa)
P_{el}	electric power (kW)
Q_{th}	thermal power (kW)
T	temperature (K or °C)
η_{II}	II law efficiency (eq. 3)
η_{el}	electric efficiency (eq. 1)
η_{th}	thermal efficiency

Subscripts

amb	ambient
el	electric
ref	reference

Acronyms

COP	coefficient of performance
DC/AC	direct / alternating current
FC	fuel cell
GT	gas turbine
HE	heat exchanger
HP	heat pump
IRR	internal rate of return
LHV	lower heating value (kJ/kg)
PER	primary energy ratio (eq.4)
S1, S2	scenarios for separate generation of electricity and heat
SOFC	solid oxide fuel cell

1. INTRODUCTION

Solid Oxide Fuel Cells (SOFCs) have already been considered for integration with gas turbine cycles, projected to achieve extremely high efficiency for electric power production (Bevc et al., 1996; Veyo, 1996; Massardo and Lubelli, 1998; Campanari and Macchi, 1998). The recent proposal of high efficiency recuperated microturbine units generating 50-200 kW and projected to achieve net electrical efficiencies approaching 30% (LHV) (Camdö et al., 1998; de Biasi, 1998; Kim et al., 1998; Anon., 1998), together with the recent successful operation of a 100 kW SOFC plant (Veyo and Forbes, 1998) offers the basis for considering the integration of these two technologies in small size plants.

Based on the predicted performances of these kind of plants at full and part-load conditions (Campanari, 1999), this paper deals with the application of this technology to cogeneration. Due to the high electrical efficiency of these systems (approaching 65% LHV), their heat/electricity ratio is unusually low, if compared to that of other cogeneration systems based upon lower electrical efficiency prime movers. The addition of a heat pump can dramatically increase the heat/electricity ratio as well as add flexibility to the system. In the proposed SOFC-GT system direct current output is generated both by the fuel cell and by the microturbine (rectified after high frequency AC generation), and the system DC output is transformed into AC electricity by an inverter unit; The availability of variable frequency AC electricity, inherent to this configuration, enables a variable speed driving of the heat pump compressor, thereby ensuring highly efficient part load control of the heat pump.

In the first section of the paper two plant configurations, without and with heat pump respectively, are presented, together with the most relevant technical assumptions and predicted energy balances. Calculations are performed based on a simulation model including

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state-of-the-art performance of small turbomachinery and based on the most advanced SOFC tubular technology, with natural gas feeding and internal reforming. Subsequently, the application of these systems to distributed electricity generation connected to residential heating is discussed, covering cases where either the electricity generation or the ultra-high-efficient heat generation are predominant. Detailed results are presented, in terms of annual energy balances and proposed electricity and heat generation. They indicate high primary energy savings and reduction in emissions of carbon dioxide. Eventually, a preliminary economic analysis of the most viable configurations is presented in various tariff scenarios.

2. PLANT CONFIGURATION

Figure 1 shows the first proposed basic plant configuration: it is substantially a recuperative gas turbine cycle, where the combustor is substituted by the fuel cell system, fed with preheated and compressed air and with natural gas as a fuel. The fuel cell generates about 80% of the overall electric power output (259 kW at 15°C), the remaining 20% being left to the gas turbine. The exhaust gases leave the recuperator at 235°C and enter an economizer, where a thermal power of 83 kW is recovered for cogeneration purposes. The predicted net electrical efficiency of such a system reaches 65% (LHV), with a fuel utilization factor of about 86%. System's performance remains also attractive at partial load, mainly due to variable speed operation of the gas turbine and to the fuel cell intrinsic efficiency increase at reduced current output. As already pointed out, the system's heat/electricity ratio is so low (about 32% as compared to about 200% for a typical conventional gas turbine), to assign a marginal role to the heat generation.

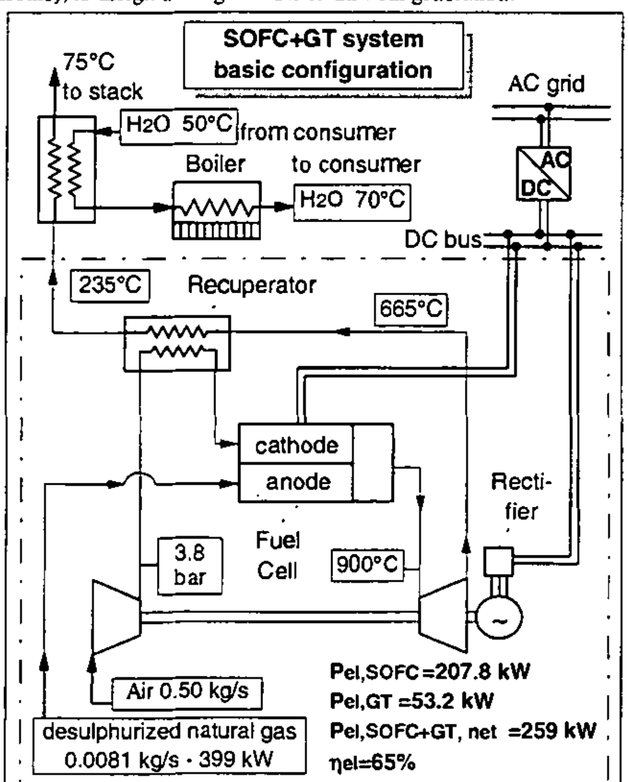

Figure 1: Proposed SOFC+GT plant basic configuration (T_{amb}=15°C; fuel LHV=34.06 MJ/Sm^3, density 0.694 kg/Sm^3 at 15°C, 1.013 bar).

An interesting possibility of increasing the heat/electricity ratio is the adoption of a heat-pump, as indicated in Fig. 2. In the plant configuration shown in Fig. 2, the SOFC+GT system is the same of Fig. 1, but part (or all) of the DC electricity output is used to drive the compressor of a heat pump, that generates heat. In order to consider a widely applicable solution[1], the selected heat pump uses ambient air as heat source and generates heat at relatively high (50-70 °C) temperatures, using water as heat carrier medium[2]. Water is heated in sequence by (i) the heat pump condenser, (ii) the gas turbine economizer and, when required, by (iii) an auxiliary boiler.

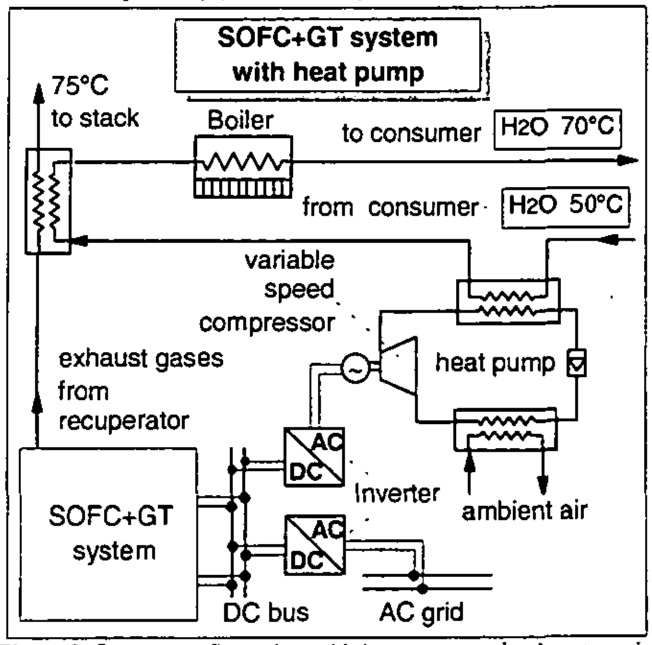

Figure 2: System configuration with heat pump and exhaust gas heat recovery; inverter for AC grid is required only if electricity is exported to the grid (Case 2a).

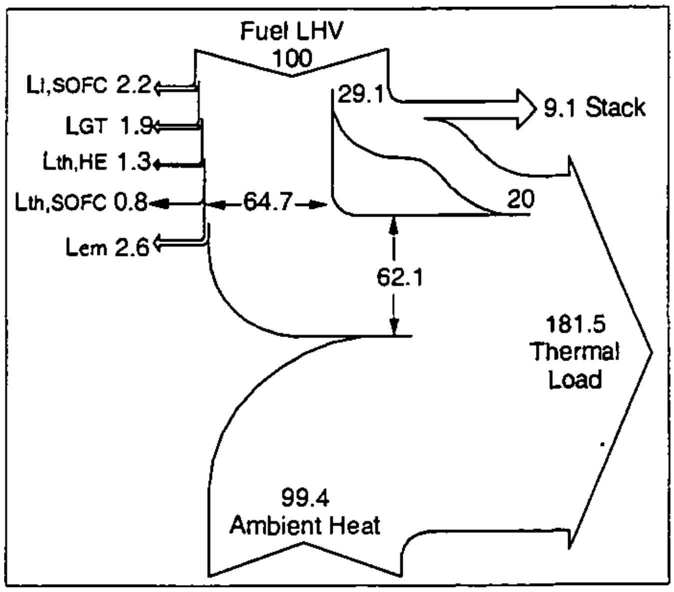

Figure 3: Flow diagram for the energy balance of the SOFC+GT+HP system of Fig. 2 at T_{amb}= -5°C.

[1] The assumption of water or ground as a heat source would yield much better coefficients of performance and avoid penalties related to frost formation on evaporator heat transfer surfaces.

[2] The use of low-temperature – say, 30-40°C - residential heating system, certainly feasible and recommendable for new buildings using heat pumps, could also dramatically improve heat pump COP.

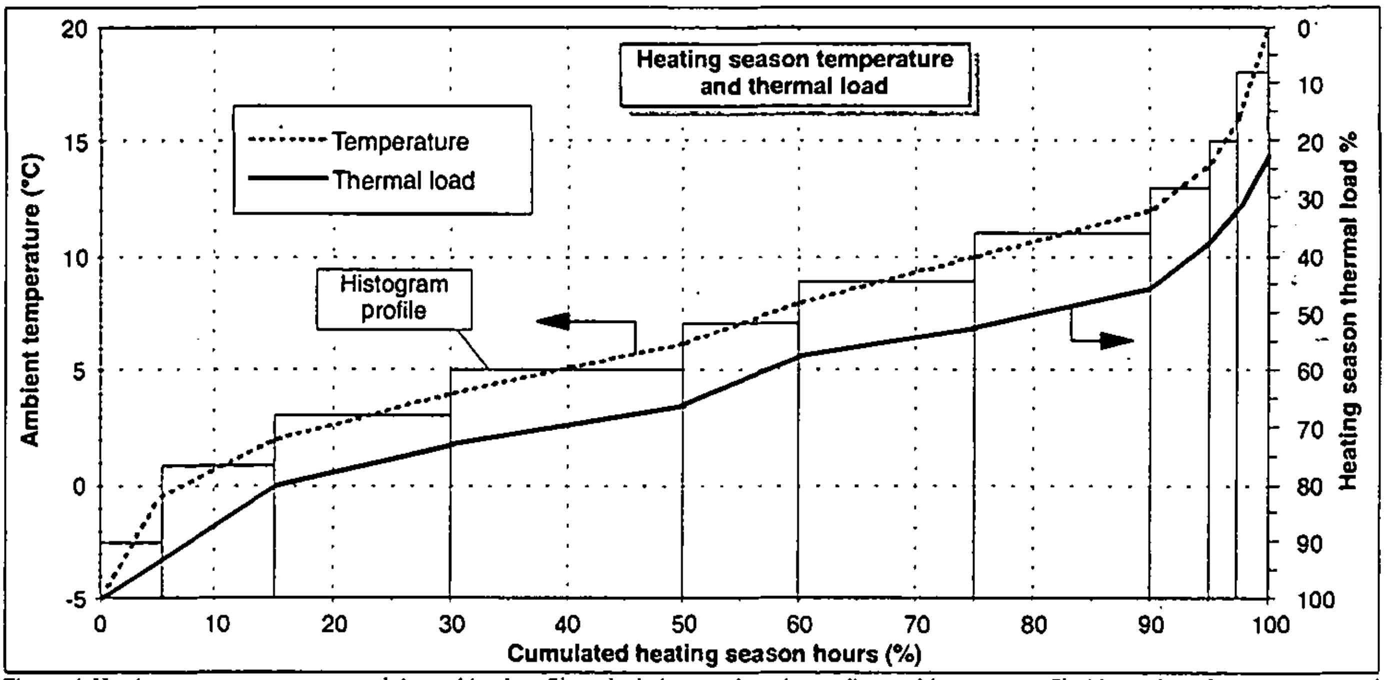

Figure 4: Heating season temperature and thermal load profile; calculations are based on a discrete histogram profile (shown here for temperature only).

Figure 3 shows the predicted energy balance at design condition (T_{amb}= -5°C) for the plant configuration in Fig. 2, with the hypothesis that the entire generated electricity (271 kW) is used for driving the heat pump, without considering the use of the auxiliary boiler. In spite of the conservative hypotheses assumed for the heat pump and the temperatures of heat generation, the system is able to generate the same amount of heat with a fuel consumption of about 50% that of a 90% efficient boiler.

3. SYSTEM APPLICATIONS AND ANNUAL ENERGY BALANCES

3.1 Thermal load

It is considered to apply the systems to a mid-European town environment, with yearly average temperature of 15°C, minimum winter temperature of -5°C (daily average) and maximum summer temperature of 30°C (daily average). The heating season ambient temperature profile, together with the adopted thermal load curve, is shown in Fig. 4. The heating period lasts 200 days for this simulation.

The thermal power demand variation with ambient temperature is represented in Fig. 5, showing that some heat requirement (for hot water domestic uses) is stipulated also for high ambient temperatures. Figure 5 indicates also the repartition of the generated heat among the various sources: in all cases, it is assumed that the thermal power output of the SOFC+GT+HP plant covers 50% of the overall thermal peak demand, leaving the remaining 50% to the auxiliary boiler. In presence of variable thermal loads, this solution is cost effective, since it decreases dramatically the investment costs, with relatively small penalizations on the annual energy balance. For plant #1 (simple cogeneration, without heat pump), the heat generated by the plant is almost constant with the ambient temperature, therefore the auxiliary boiler is required up to ambient temperatures around 10°C; above this temperature, a significant portion of the recuperated heat must be wasted. For plant #2, the heat pump contribution increases with ambient temperature, due to the COP increase, so that the auxiliary boiler is not required for temperatures above 7°C. The heat recovered by the gas turbine is never wasted, and the heat pump heat generation follows the demand: as will be discussed in more detail later, this behavior can be achieved either acting on the heat input of the SOFC, or exporting to the grid the excess electricity.

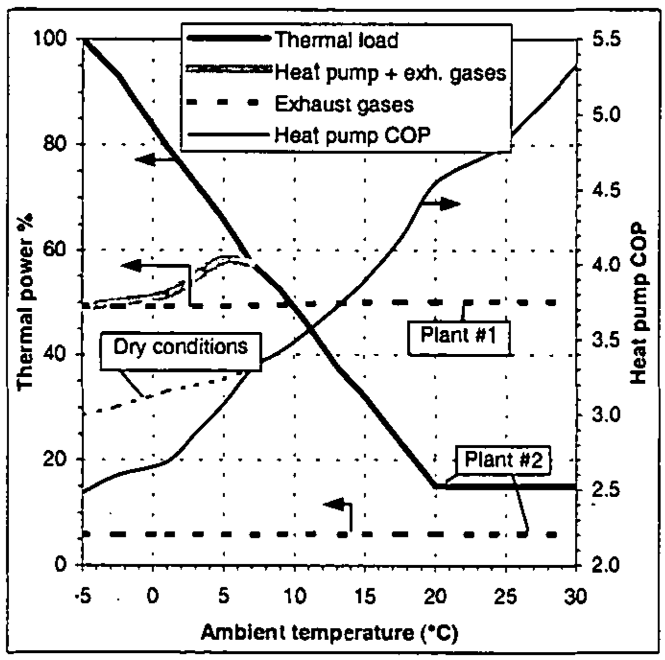

Figure 5: Thermal load repartition between exhaust gas recovery (plant #1) and heat pump+exhaust gas recovery (plant #2) and auxiliary boilers (left scale), and heat pump COP (right scale).

At temperatures below 5°C an inlet air preheating system on the gas turbine is adopted, with a de-icing effect below 0°C; the SOFC+GT system power gain at lower temperatures is then limited to the 5°C value. Figure 5 shows also the heat pump COP variation with ambient temperature: besides the influence of evaporation and condensation temperature, the COP is strongly influenced by the energy penalization caused by frost formation[3].

3.2 Annual Energy Balances

The performance parameters adopted to evaluate the system efficiency include the net electrical efficiency, the fuel utilization factor, the II law efficiency and the Primary Energy Ratio, respectively defined as following:

$$\eta_{el} = \frac{P_{el}}{m_{fuel} \times LHV_{fuel}} \quad (1)$$

$$Fuf = \frac{P_{el} + Q_{th}}{m_{fuel} \times LHV_{fuel}} \quad (2)$$

$$\eta_{II} = \frac{P_{el} + Ex_{Qth}}{m_{fuel} \times Ex_{fuel}} \quad (3)$$

$$PER = \frac{\dfrac{W_{el}}{\eta_{el,ref}} + \dfrac{Q_{th}}{\eta_{th,ref}}}{m_{fuel} \times LHV_{fuel}} \quad (4)$$

where $\eta_{el,ref}$ and $\eta_{th,ref}$ are reference values for the separate generation of electricity and heat. We will consider two different scenarios, the first (S1) referred to a realistic average present situation in most industrialized countries (fuel-to-grid electric efficiency taking into account the grid losses of 35% and yearly average boiler efficiency of 75%) and the second (S2) referred to state-of-the-art technology (electric efficiency of 52% and average boiler efficiency of 85%).

The system electric efficiency, as well as all the other parameters (Fuf, η_{II}, PER), account also for both the heat production and the fuel input of the auxiliary boilers. All the annual balances are calculated for a 90% SOFC+GT system availability (when the SOFC+GT system is out of service, all heat is generated by auxiliary boilers).

Case 1

This plant configuration allows the system to work at full electric power output all over the year, cogenerating 50% of the maximum winter heat demand, and all the summer residual thermal load. As the maximum available heat output (including auxiliary boiler) is only 60% of the electric output, the system is mainly an electrical generator with tail heat recovery.

The most likely application of this plant can be foreseen in distributed electricity generation by a Municipality, providing both gas and electricity distribution network. The recovery of heat from the system, even if it is small, adds significant advantages in terms of energy saving and system economics.

A very high average electric efficiency is reached because of full electric load operation; the system generates 82 kW of thermal power (Tab. 1), satisfying, as anticipated in 3.1, all the thermal load at ≈10°C.

The profiles of the efficiency parameters for Case 1, represented in Fig. 6, show that the system PER decreases at ambient temperatures below 10°C, due to auxiliary boiler operation and GT de-icing at lower temperatures. The value of PER and Fuf decreases at ambient temperatures higher than 10°C due to a waste of recoverable heat.

Gas turbine performance reduction at increased ambient temperatures causes only a slight decrease in the system electrical efficiency at higher temperature (about 1% at 30°C), thanks to the prevailing contribute of the FC (not affected by ambient temperature variations) on the system power output.

Case 2a

We refer now to the system schematic represented in Fig. 3. In this case, since the main plant output is thermal, the system could be used by any thermal consumer (say, a residential or commercial building) exporting to the electric grid all surplus electricity generated. As in Case 1, the system works at full electric power output and high efficiency all over the year, but can export electric power only when the heat demand is lower than the maximum heat generated by the heat pump and the exhaust gases. As shown in Fig. 5 this occurs at ambient temperatures higher than 7°C. During the summer, the system generates mainly electricity, covering all the residual thermal load. Since the peak thermal demand is almost ten times larger than in Case 1, the heat recovered by the exhaust gases is never wasted.

The heat pump works with ambient air as heat source and water as hot fluid; the design condition is set at ambient temperature –5°C; the temperature difference between inlet air and the working fluid at the evaporator is set to 8°C at design conditions, and changes at partial loads according to the evaporator thermal duty.

The heat pump compressor is driven at variable speed utilizing the inverter variable frequency output. Two inverters are employed to generate both a variable frequency output and a grid frequency output for excess electric power exportation. The electric motor driving the compressor has a nominal power of about 280 kW, with a design-point efficiency of 96%, reduced at partial load according to the efficiency curve for variable speed operation proposed by Campanari, 1999 (the efficiency at 30% load is about 75%).

The "dry" COP is reduced by 15% for ambient temperatures below 0°C and with a linear decrease by 0 to 15 % for ambient temperatures ranging from 7°C to 0°C, to simulate losses due to frost formation and defrosting; the resulting COP profile, as a function of the ambient temperature, is shown in Fig. 5.

Table 1 shows the yearly electric and heat production of the system. With the same fuel input as for Case 1, this configuration would generate nine times more heat and 42% electrical energy. Even if the main system output is low-temperature, low thermodynamic value heat, the yearly average II law efficiency is still about 37%, demonstrating a very good system thermodynamic design. The fuel utilization factor exceeds 100% because of the heat pump operation.

The system works with an average heat pump COP of about 3.41 (weighted by heat production), generating useful heat and electric power for a total amount which is 1.39 times the used fuel input.

The profile of the efficiency parameters vs. ambient temperature is represented in Fig. 7, showing a PER (scenario 1) behavior much more influenced by ambient temperatures: at low ambient temperature the effect of auxiliary boiler is much stronger, and yields PER lower than in Case 1, while when the heat is generated by the heat pump the situation is in favor of Case 2a. If we refer to scenario 2, the energy gain related to electricity decreases, and Case 2a is better at all ambient temperatures.

Case 2b

A third case has been investigated, with the SOFC+GT system generating only thermal power by exhaust gas cooling and heat pump operation, following the thermal load and without electric energy export. Since no connection to the electric grid is required, the system could be applicable to any heat consumer, and its validity as energy saving device holds in any electric generation scenario. The system is operated only in the heating period (200 days), with ambient temperatures below 20°C. The schematic for this configuration is the same of Fig. 2, but the second inverter for grid frequency generation (lower part of the figure) can be eliminated.

[3] Frost formation on heat transfer surface causes a decrease of evaporator temperature, due both to the reduced air flow and added thermal insulation. Moreover, frost must be periodically removed, by means of energy demanding procedures.

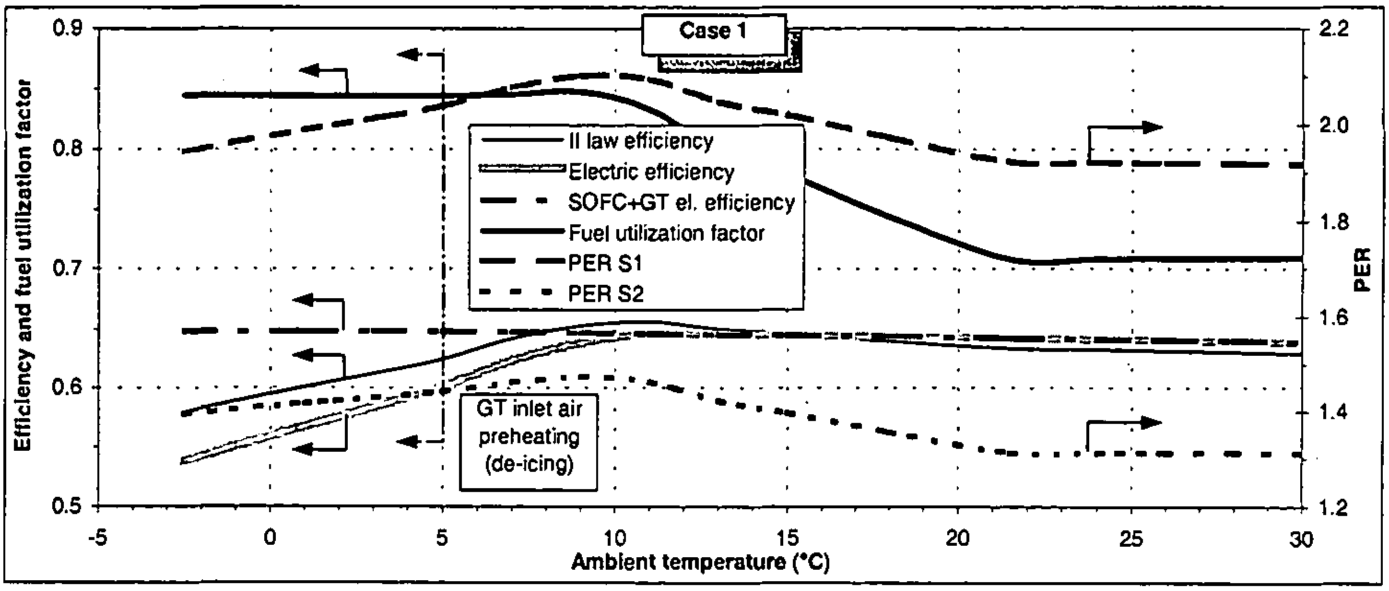

Figure 6: System performances for Case 1.

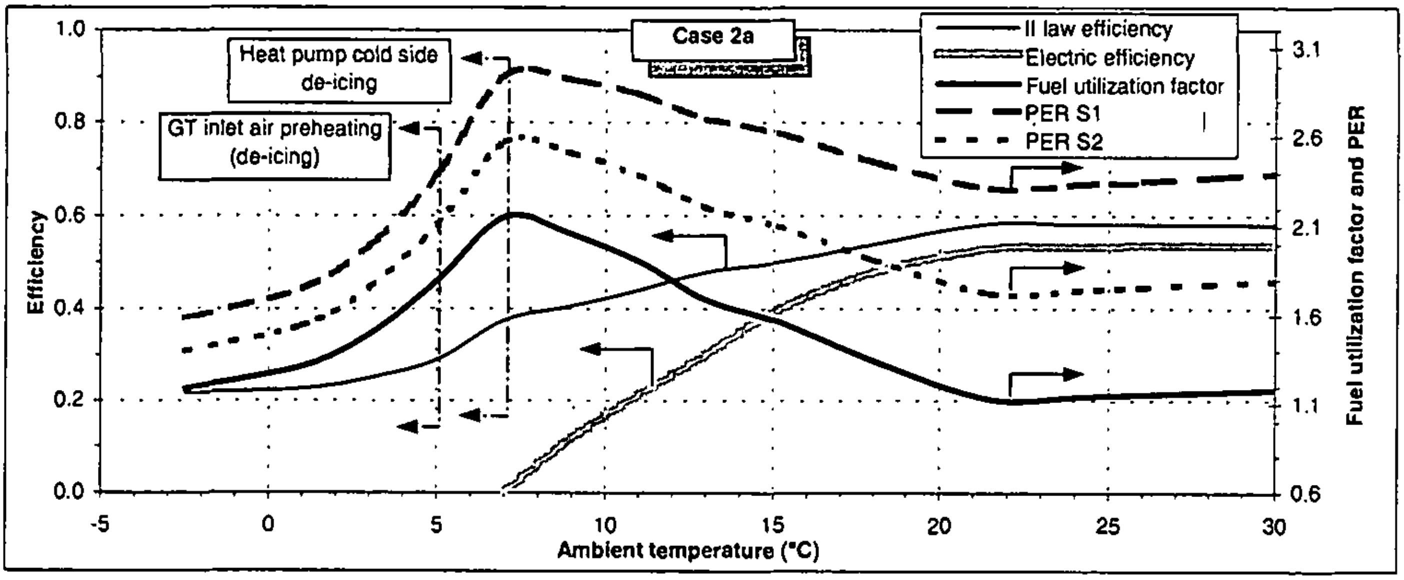

Figure 7: System performances for Case 2a.

This system is configured for a maximum thermal power output covering 50% of the maximum heat demand; hence, it will operate for about 80% of the heating season at partial load generating an electrical output which is a function of the ambient temperature, of the heat pump COP and of the thermal load.

The SOFC+GT system efficiency variation with the electrical output at part-load and with the ambient temperature is discussed in Campanari, 1999. The average heat pump COP is lower than in Case 2a due to the lower average ambient temperatures of the operating period considered.

On the basis of the yearly average Fuf calculated (see Tab. 1), the system acts as a heat generation unit capable of delivering an average of 1.56 kWh for each kWh of fuel calorific value consumed: this very high efficiency index is reached thanks to very good system performances at part-load and to the advanced thermodynamic design of the SOFC+GT cycle.

The profile of the efficiency parameters vs. ambient temperature is represented in Fig. 8: it can be seen that SOFC+GT electrical efficiency maintains high values also at part-load operation. Even if the SOFC+GT system operates at full load, all system quality parameters decrease below 7°C, due to heat pump COP decrease and to auxiliary boiler operation.

3.3 Comparison of the three considered cases

Table 1 compares the annual performance of the three cases considered. The results are obtained by integrating the plant operation over the entire year, according to the selected thermal load vs ambient temperature distribution (Fig. 4). For all cases, the plant availability was set to 90%. SOFC+GT+HP system electric and heat output are consequently reduced, while auxiliary boiler heat is increased to cover the entire thermal demand during plant unavailability.

With the same "prime mover", the three systems have different energy output: Case 1 generates almost 2000 MWh_{el} , Case 2a less than 1000, while Case 2b has no electricity generation.

The heat generated is small for Case 1 (less than 600 MWh, which is less than one third of the generated electricity), while is over 5000 MWh for Case 2a. The yearly average PER, if referred to "conventional" present scenario (S1) is close to 2 for all three cases,

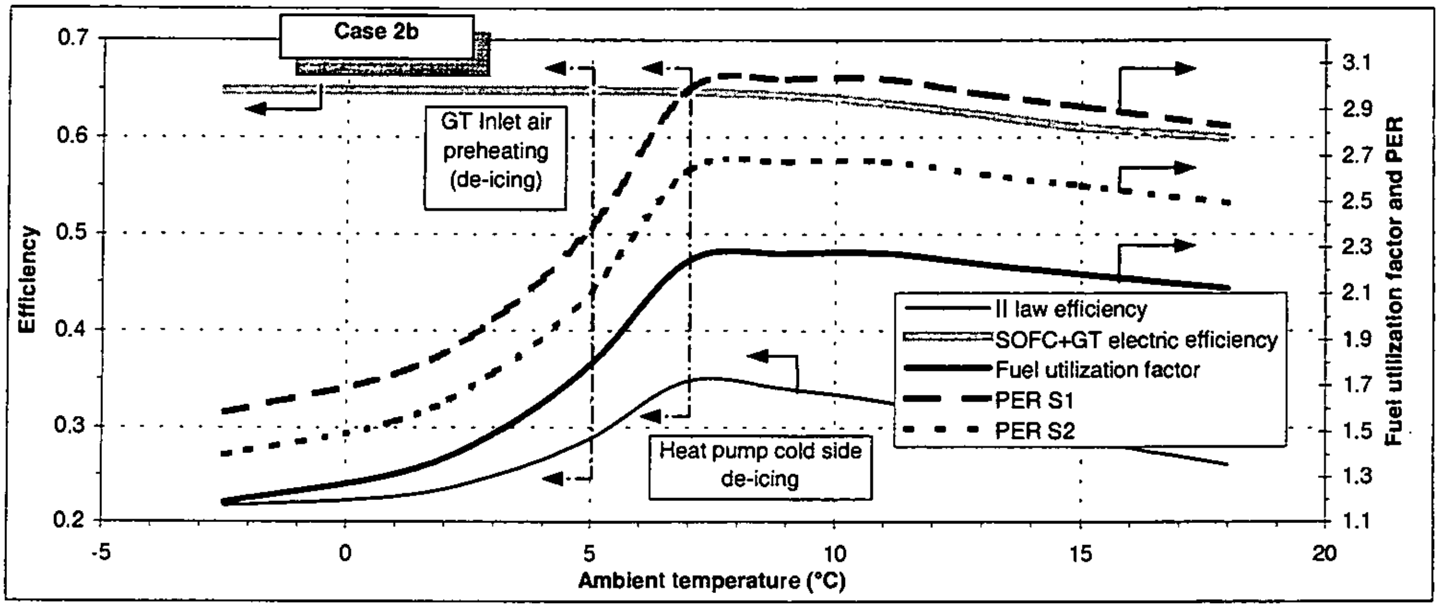

Figure 8: System performances for Case 2b.

Case	1	2a	2b
Plant maximum electric output (kW)	271	200(1)	0
Net electric production (MWh/year)	1998	852	0
Nominal (T_{amb}=-5°C) SOFC+GT+HP thermal power output (kW)	82	760	760
Peak thermal demand (kW)	164	1520	1520
System (SOFC+GT+HP) useful heat production (MWh/year)	427	4166	3355
Auxiliary heat requested (MWh/year)	154	1137	1047
Total heat production (MWh/year)	581	5303	4402
Heat production exergy (T=60°C; MWh/year)	89.4	816	721
SOFC+GT fuel input (LHV) (MWh/year)	3100	3100	1593
Total fuel heat input (LHV) (MWh/year)	3281	4437	2824
Total fuel exergy (MWh/year)	3367	4553	2899
Yearly average net electric efficiency	0.622	0.224	-
Yearly average fuel utilization factor	0.786	1.39	1.56
Yearly average II law efficiency	0.62	0.367	0.249
Yearly average PER (S1)	1.98	2.14	2.08
Yearly average PER (S2)	1.38	1.78	1.83
Average heat pump COP	-	3.41	3.17
Primary energy saving (toe/year), S1	275	436	262
Primary energy saving (toe/year), S2	107	298	202
Carbon dioxide reduction (CO_2 t/year), S1	1226	990	570
Carbon dioxide reduction (CO_2 t/year), S2	251	695	476

(1) For ambient temperature of 22°C.

Table 1: Case 1, 2a and 2b system performances; for Case 2b the yearly average is calculated only on the winter period (200 days); CO_2 reduction is calculated for scenario 1 with emissions of 600 g/kWh for electric generation (carbon+oil+natural gas fuel mix) and 72 g/MJ for heat production (natural gas+naptha fuel mix) ; for scenario 2 the emissions are calculated by an electric efficiency of 52% and a heat production efficiency of 85%. (natural gas only).

and the best perfnrmance is always achieved by Case 2a. If reference is made to "state-of-the-art" scenario (S2), best performance is achieved by the Case 2b, that is not affected by the reference electric grid efficiency.

The analysis of primary energy saving and CO_2 reductioo of the three cases leads to similar conclusions: in particular, the great sensitivity of the results of Case 1 to the reference scenario of electricity generation should be emphasized.

4. ECONOMIC ANALYSIS

On the basis of the plant performances discussed above, a preliminary economic analysis can be drawn.

The assumed fuel cost, together with the electricity, heat and operation & maintenance costs are listed in Tab. 2. The O&M cost is expressed with reference to the SOFC+GT system electrical power generation. The resulting cash flows are gross pre-tax values.

System configuration	Low costs ($/kWh)	High costs ($/kWh)
Case 1 - Electricity	0.05	0.07
Case 2a - Electricity	0.035	0.05
Case 1,2a,2b - Heat	0.02	0.045
Case 1 - O&M	0.006	
Case 2a/2b - O&M	0.008	
Case 1,2a,2b - Fuel	0.015	

Table 2: Cost assumptions for the economic analysis.

Two different hypotheses are considered, the first with low valorization of the heat and electricity production, the second with a 40% higher electricity remuneration and with a 2.25 fold increase of the heat remuneration. The first case is representative of situations where avoided cost criterion dictates the electric tariff of grid exported electricity. The second case includes the situations where "green" policies are adopted in favor of energy-saving. The different electricity valorization adopted for Cases 1 and 2a accounts for the different "quality" of the electricity generated by the two systems. As far as heat valorization is concerned, the "low" hypothesis makes reference to the "industrial" fuel cost (say, the natural gas cost that would be paid by a Municipality), while the "high" hypothesis assumes values more representative of the costs paid by "commercial" users.

Assuming a plant life of 15 years, and a plant specific cost of 2000 $/kW_{el}$, Tab. 3 shows the investment Internal Rate of Return (IRR) for the proposed configurations. It is possible to note that an adequate remuneration of the plant electrical (for Case 1) or heat output (for Cases 2a and b) is essential to achieve satisfactory return rates.

System configuration (Investment cost=2000$/kW, plant cost 515,000 $)	IRR (15 years)	Yearly Cash Flow ($)
Case 1 C_{el}=0.05 – C_{heat}=0.02	5%	50,300
Case 1 C_{el}=0.07 – C_{heat}=0.045	19%	104,800
Case 2a C_{el}=0.035 – C_{heat}=0.02	6%	53,390
Case 2a C_{el}=0.05 – C_{heat}=0.045	38%	198,780
Case 2b - C_{heat}=0.02	1%	37,470
Case 2b - C_{heat}=0.045	28%	147,530

Table 3: Internal rate of return and yearly cash flows (gross pre-tax values) for the investment in Cases 1, 2a and 2b plant configurations.

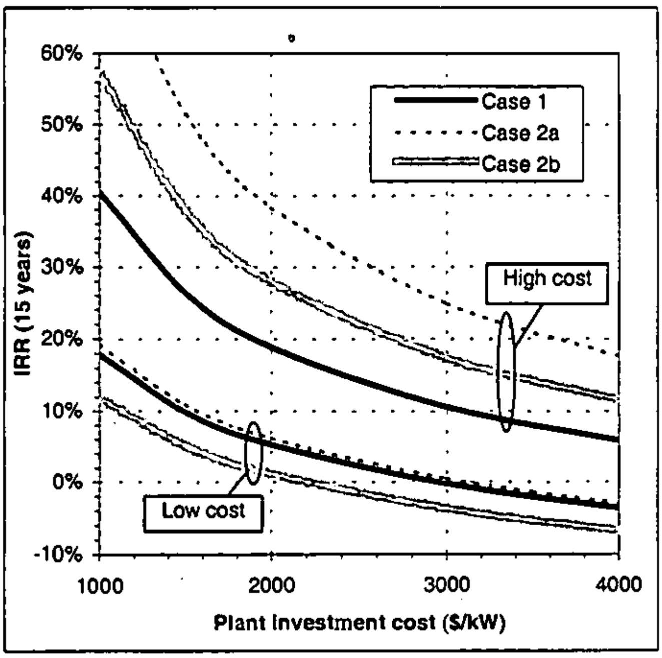

Figure 9: Internal rate of return for Cases 1, 2a and 2b.

The influence of the plant specific cost on the investment IRR is shown in Fig. 9 for the two tariff hypotheses. The best plant configuration is found in Case 2a for both hypotheses: the superiority of Case 2a over 2b is not surprising, since marginal costs of electricity generation are low enough to justify full load plant operation also without heat demand. Comparison between Cases 1 and 2a is not so straightforward, since the result would depend upon the electricity/heat tariff ratio. The detailed annual cash flow repartition among electricity and heat production, O&M costs and fuel cost is shown in Fig. 10 and 11 at low and high heat and electricity costs respectively.

The better economic profile offered by Case 2a can be explained by the following circumstances:

- the yearly fuel consumption, not considering the auxiliary boiler contribution, is the same for Case 1 and 2a (Tab. 2): the corresponding heat+electricity income is higher for Case 2a, as the tariff mix prizes the very high heat production achieved by this plant configuration;
- surplus electricity export during summer operation, though remunerated at lower values with respect to Case 1, gives a positive income not present in Case 2b;
- a significant heat production is made outside the heating period of 200 days to whom Case 2b operation is limited, without auxiliary boilers and with high heat pump COP and very low marginal costs.

The importance of the heat remuneration is confirmed by the circumstance that Case 2b achieves higher IRRs and annual cash flows with respect to Case 1 when the high heat and electricity cost scenario is adopted.

5. CONCLUSIONS

The SOFC+GT technology is currently at the R&D level, with first prototype testing already projected by some manufacturers for the late 1999, and with a commercial availability foreseen for the year 2005 (Veyo and Forbes,1998). SOFCs on their own are still dealing with heavy problems of manufacturing cost reduction, but they have already achieved performance degradations below 0.2%/1000h (Singhal, 1997), whose effects are anyway not considered in this study.

The considered SOFC+GT combination is a highly efficient, low-polluting cogeneration unit. The addition of a heat pump to the system makes the plant more flexible and yields more favorable heat/electricity ratios.

The best application of these systems is probably a situation intermediate between Case 1 and Case 2a considered in this paper, i.e. with a heat pump electric power always lower than the SOFC+GT electric output. In this case the system is able to supply heat and electricity all over the year, following the thermal demand and exporting, when economically justified, the excess electricity to the grid. The presence of cooling (not considered in the paper) in addition to heat demand, a situation quite common in residential and commercial buildings, would make the application ideal. The proposed SOFC+GT+HP plant would in fact result as an extremely high performance "tri-generation" unit.

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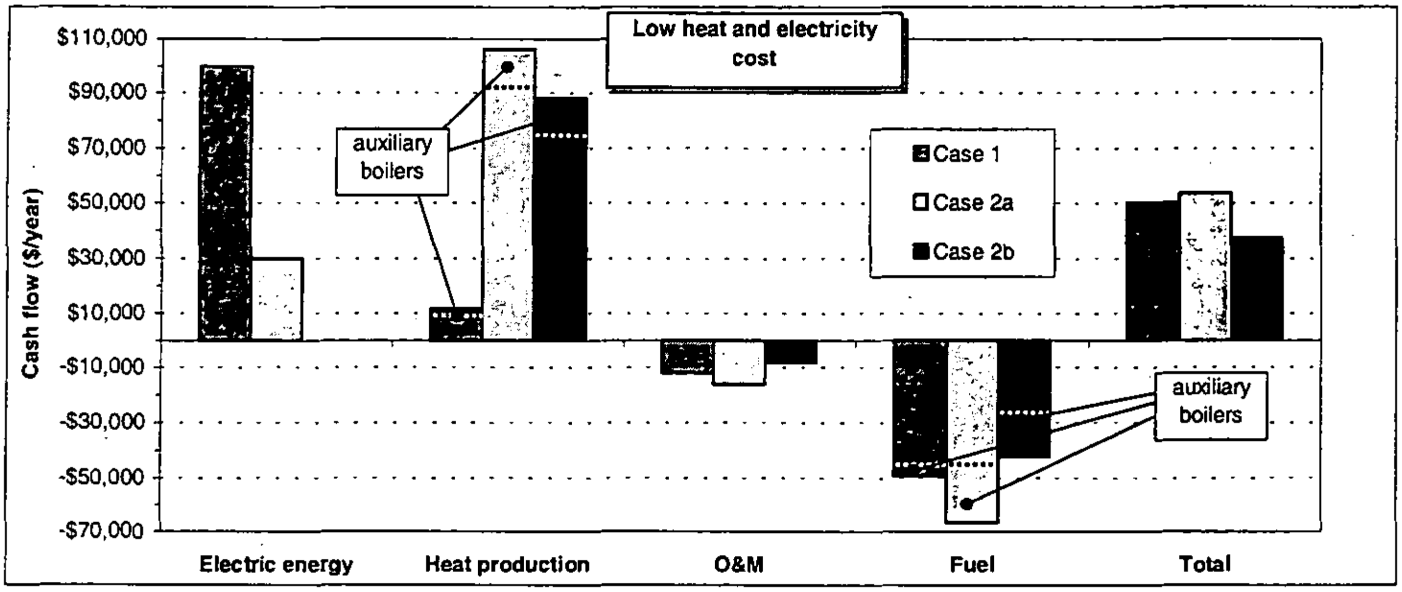

Figure 10: Yearly cash flow for Cases 1, 2a and 2b with low heat and electricity costs.

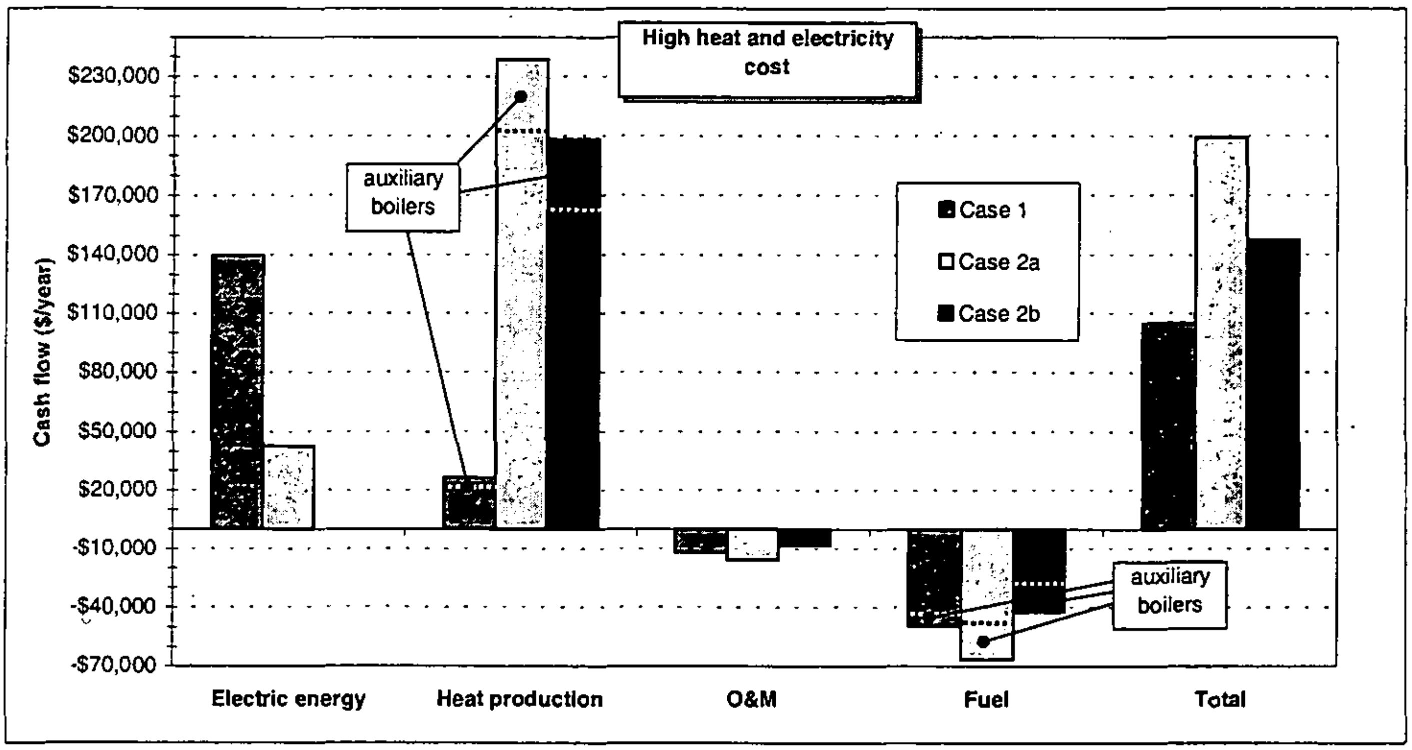

Figure 11: Yearly cash flow for Cases 1, 2a and 2b with high heat and electricity costs.