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# Dynamic simulation of a multi-generation system, for electric and cooling energy provision, employing a SOFC cogenerator and an adsorption chiller

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## Abstract

Aim of this work is the dynamic simulation of the operation of a small-scale multi-generation system, based on a Solid Oxide Fuel Cell (SOFC) micro-cogenerator (µCHP) coupled to an adsorption chiller, to provide electric and cooling energy to a telecommunication shelter. The dynamic simulation model has been implemented in TRNSYS environment. The µCHP has nominal electric power of 2.5 kW and its thermal output is used to drive a thermally driven adsorption chiller, with nominal cooling power of 10 kW. The performance of both components were experimentally validated under controlled lab conditions. The developed model allowed to optimize the system configuration and to perform an energy and environmental analysis. This analysis demonstrated the possibility of achieving global energy efficiency up to 63% with a $CO_2$ reduction proportional to the electric and cooling load of the telecommunication shelter.

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*Keywords:* SOFC, adsorption chiller, telecommunication, power and cooling

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## 1. Introduction

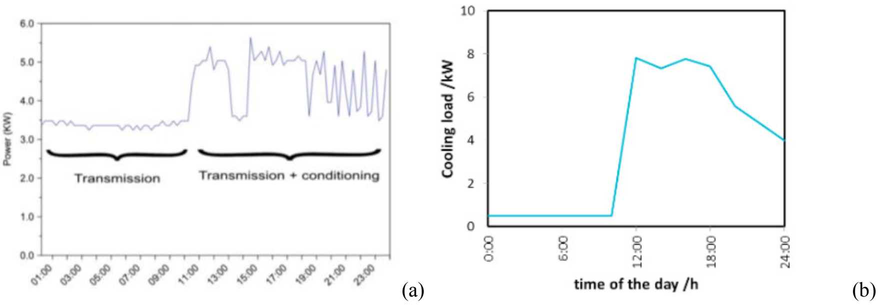
The Information and Communications Technology (ICT) sector is recording a quick growth thanks to the ever-increasing demand for mobile services [1] and datacenters. Indeed, it has to be considered that, in 2009, the ICT sector accounted for about 3% of the overall electric consumption worldwide, and this energy consumption is expected to be triplicated by the end of 2030 [2]. The main power consumption in an ICT installation, base transceiver station (BTS), is due to the air conditioning system [3], which can absorb up to50% of the overall energy required. This represents a crucial aspect in the future development of this technology, both from an economic and environmental point of view. In [4] different methods for reducing the excessive power consumption in air conditioners installed in BTS are discussed: replacement of air conditioner with exhaust fans, improvement of the efficiency of air conditioner systems, building envelope and systems advanced design.

In such a background, the present work reports about the simulation activity of a multi-generation system, employing a micro-cogenerator, based on SOFC technology, coupled to an adsorption chiller for covering power and cooling demand of a BTS. This work is performed in the framework of the EU funded ONSITE project [5].

| **Nomenclature** | | *Subscripts* | |
|---|---|---|---|
| | | boiler | Backup heater |
| BTS | Base Transceiver Station | BTS | Base Transceiver Station |
| COP | Coefficient Of Performance | cool | Cooling |
| E | Energy [kWh] | el | Electric |
| EER | Energy Efficiency Ratio | fuel | Fuel |
| $f_{CO2}$ | $CO_2$ emission factor [$t_{CO2}$/MWh] | grid | Grid |
| PE | Primary Energy [kWh] | load | Load |
| PES | Primary Energy Savings [kWh] | ref | Reference system |
| $\eta$ | Efficiency | SOFC | Solid Oxide Fuel Cell |
| | | sys | Proposed system |

## 2. Reference load and main system components

Since the availability of experimental data on energy consumption of BTS is scarce, in the present work, data from a literature source, based on the monitoring of telecommunication systems in Italy, were used [1]. The available load profile corresponding to the electric consumption of the station over a typical day, is shown in Fig. 1a. It can be divided in a constant base component, about 3.5 kW, representing the consumption of the internal devices inside the shelter/room and a "saw tooth" component, which is mainly due to the consumption of the air conditioning system inside the base. From this data, the cooling load profile reported in Fig. 1b was suggested. It was calculated starting from the electric load evolution of Fig. 1a, considering a reference Energy Efficiency Ratio (EER) for the electric chiller equal to 3.5.



(a) (b)

Fig. 1. Typical daily energy consumption of a BTS [1] (a). Simulated cooling load (b).

### 2.1. SOFC cogenerator

The SOFC cogenerator comprises a hot box containing two SOFC stacks of electrical power 1.25 kW net each, a reformer, a burner, a heat recuperator and a condenser to recover the water for the reforming process. A control and diagnosis board, thanks to numerous sensors that constantly provide readout of all operational parameters necessary for operations and safety, manages the functions of ancillaries (Balance of Plant).

Fig. 2 shows a sketch of the system, which is made up of the following main sections:

- A fuel processor, which converts natural gas into a hydrogen-rich syngas;
- Two fuel cell stacks generating DC current;
- A burner to combust the anode and cathode off-gases;
- A heat exchanger to pre-heat the inlet gases;
- A water de-ionising system;
- A power conditioning system, which converts the DC current into AC current suitable for telecom load (48 VDC) and grid connection (230 VAC);
- A thermal balance of plant, which transfers heat generated to an external water circuit by means of an air-to-liquid heat exchanger;
- A battery pack, which allows system load following.

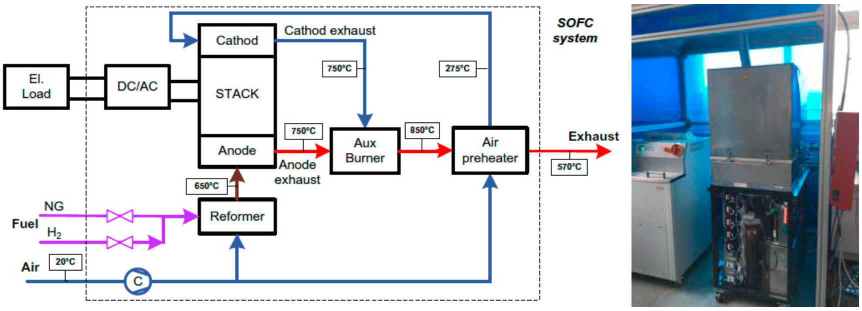


Fig. 2. Schematic diagram of the SOFC cogenerator, left hand side, and installed in the CNR ITAE labs, right hand side.

As variable load (to simulate the BTS power requirements), a DC load bank has been connected to the system DC link. The electrical and thermal efficiency are presented in Tab. 1. At nominal power production, the electrical efficiency reaches 38% while the thermal efficiency ranges between 45% and 50%. Electrical efficiency reached 40% while producing 2,800 W of electrical power.

Fig. 3a reports the experimental correlation obtained between produced electric power and thermal power by tested the SOFC cogenerator. A linear dependency was found, in the electric power range 1.5 - 2.8 kW, which allows to give some flexibility in the cogenerator operation. In Fig. 3b, the correlations between natural gas flow rate (both at the reformer and the burner) and the generated electric power are represented. Also in this case, a satisfactory linear dependency was highlighted.

Tab. 1: Electrical and thermal power comparison at different loads.

| $P_{el}$ [W] | $P_{th}$ [W] | $eff_{el}$% | $eff_{th}$% | $eff_{tot}$% |
|---|---|---|---|---|
| 2000 | 2700 | 38% | 45% | 83% |
| 2500 | 3000 | 38% | 45% | 83% |
| 2800 | 3400 | 40% | 48% | 88% |

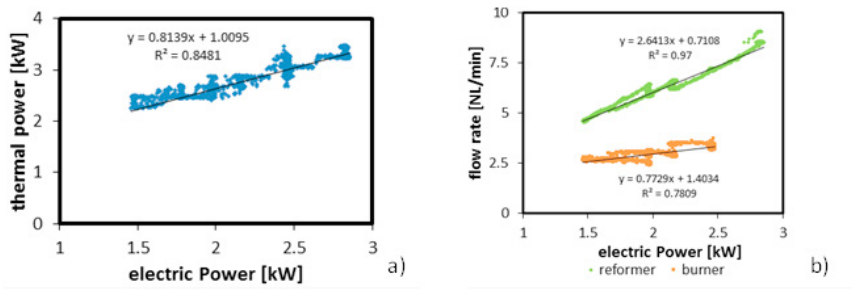


Fig. 3: Experimental correlation between electric and thermal power produced by the cogenerator (a) and between electrical power produced and flow rates at the reformer and gas burner (b).

## *2.2. Adsorption chiller*

The adsorption chiller used in the simulation is a commercial adsorption chiller, employing the working pair silica gel/water, that was acquired and tested in a testing rig located at CNR ITAE labs. Detailed operation features of the test rig and testing procedures are described elsewhere [6,7]. The tests were performed by varying working boundary conditions in terms of driving temperature (e.g. ranging from 65°C to 85°C), heat rejection temperature (e.g. ranging from 22°C to 33°C) and cold water temperature (e.g. 10°C and 15°C). Three main parameters were measured:

- average cooling power produced, $Q_{cool}$,
- thermal COP ($COP_{th}$);
- electrical COP ($COP_{el}$).

$Q_{cool}$ represents the average cooling power produced by the chiller under the defined boundaries; $COP_{th}$ represents the ratio between the cooling energy delivered by the chiller and the thermal energy spent to drive the chiller; $COP_{el}$ represents the ratio between the cooling energy delivered by the chiller and the electric energy spent to drive the auxiliaries of the chiller. In Fig. 4 the obtained results for cooling energy delivered at 15°C are reported as a function of driving temperature and heat rejection temperature.

## 3. Simulation model

Two different configurations were simulated and are reported in Fig. 5. In the first configuration, Fig. 5a, the SOFC cogenerator and the backup heater are directly connected to a water storage, which feeds the adsorption chiller. This means that the temperature inside the storage must be always sufficient to drive the chiller (i.e. at least 70°C). In the second configuration, Fig. 5b, the storage is solely connected to the SOFC cogenerator as heating source, and the backup boiler is in between the storage and the chiller, in order to heat up the water driving the chiller, when the temperature inside the storage falls below the requested 70°C.

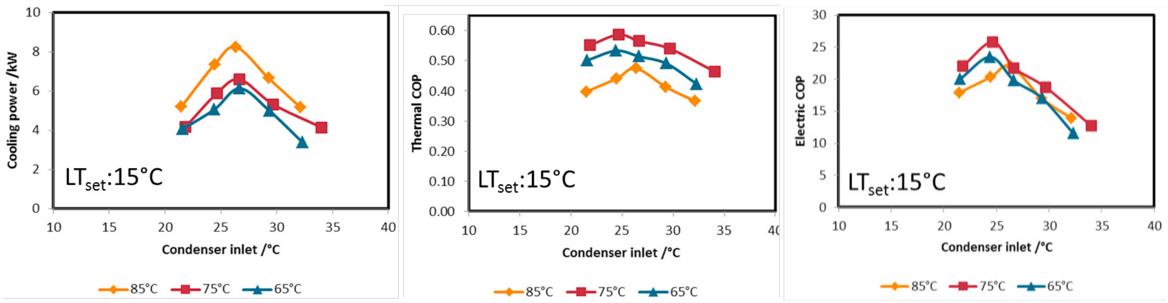


Fig. 4. Experimentally measured adsorption chiller performance in terms of Cooling power, Thermal COP and Electrical COP. The data are reported for cooling energy provided at 15°C, as a function of heat rejection and driving temperature.

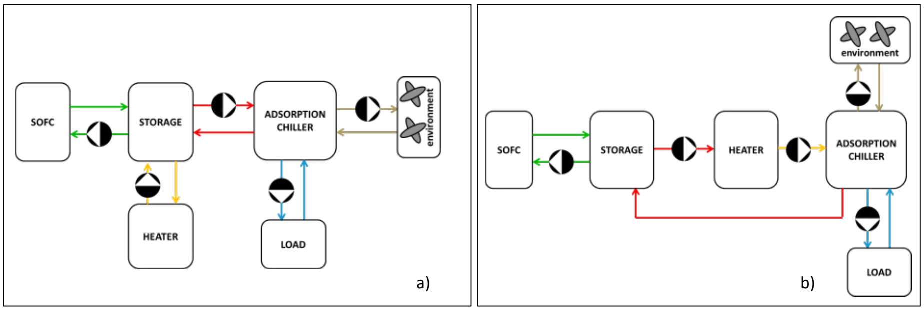


Fig. 5. Simulated multi-generation system configurations. Configuration I (a) and Configuration II (b).

The system simulations were implemented in TRNSYS environment. The SOFC cogenerator behavior was simulated starting from the experimental characterization of the component, by implementing a performance map reporting thermal power and natural gas flow rate as a function of electric power produced by the SOFC, as represented in Fig. 3. The adsorption chiller was simulated employing the TRNSYS Type 909 with the performance map derived from experimental characterization performed at the CNR ITAE lab. The cooling load, as reported in Fig. 1b, was implemented as time-dependent profile, while the weather conditions were taken from the Meteonorm database. The remaining components (e.g. water storage, dry cooler, pumps etc.) were simulated employing standard components from the TRNSYS libraries, properly sizing each one according to the working conditions and simulated loads.

The simulations were performed considering a steady operation of the SOFC cogenerator in terms of electric power production, without implementing any management strategy to either follow the electrical or cooling load.

## 4. Simulation results

Yearly simulations were performed varying the average cooling load, the number of SOFCs and the size of the storage, in order to optimize the system configuration. For the sake of comparison, the main temperatures recorded during three consecutive days of operation for both Configuration I and II are represented in Fig. 6. In both cases, the temperature delivered by the adsorption chiller (T_Ads_LT) to the load is constant, indicating that the system meets the cooling load. Even though the set point of the backup boiler is the same for both configurations (i.e. 70°C), as expected, the dynamic temperatures evolution are quite different. Indeed, for Configuration I, Fig. 6a, the temperature inside the water storage, which is delivered to the chiller, is almost constant fluctuating in the range of about 70°C. Differently, in Configuration II, Fig. 6b, due to the on-off control of the boiler and the inertia of the whole system, the temperature delivered to the adsorption chiller oscillates from 70°C up to 85°C, which makes the operation of the system less stable. From an energy consumption point of view, no clear difference between the two simulated configurations was highlighted. Accordingly, the system optimization was carried out for the Configuration I.

### *4.1. System optimization*

Starting from the reference simulations, a further system optimization was evaluated. For Configuration I, once the electric and cooling loads to be satisfied are fixed, the main design parameters to be optimized are the volume of the storage tank and the set temperature of the electric heater, which affects the adsorption chiller performance. A set of simulations has then been devoted to find out which is the effect of these parameters. The simulations were run in a reference month (July), considering an average cooling load of 3 kW and an electric load of 3.5 kW, employing the load profile reported in Fig. 1. Three different set points of the heater were considered, namely, 60°C, 70°C and 80°C, together with three storage volumes, 0.2 $m^3$, 0.4 $m^3$ and 0.6 $m^3$. In order to evaluate the energy efficiency of each configuration, the ratio between the energy supplied by the backup heater and the total energy needed to drive the chiller, was calculated. Furthermore, the effect of these parameters on the $COP_{th}$ was evaluated. The obtained results are summarized in Fig. 7.

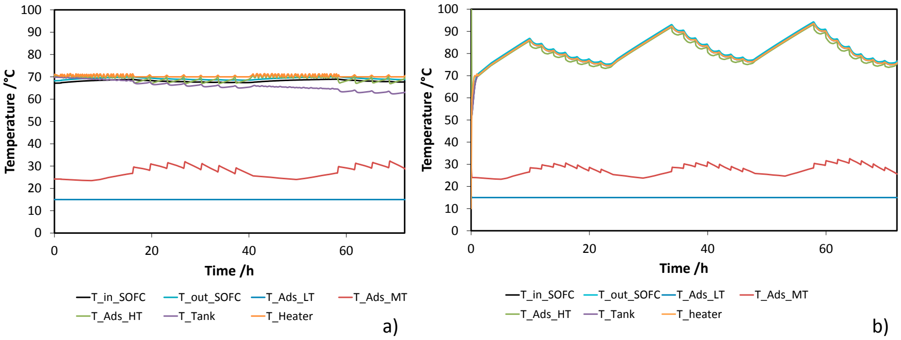


Fig. 6. Main temperatures evolution for a reference simulation of Configuration I (a) and Configuration II (b).

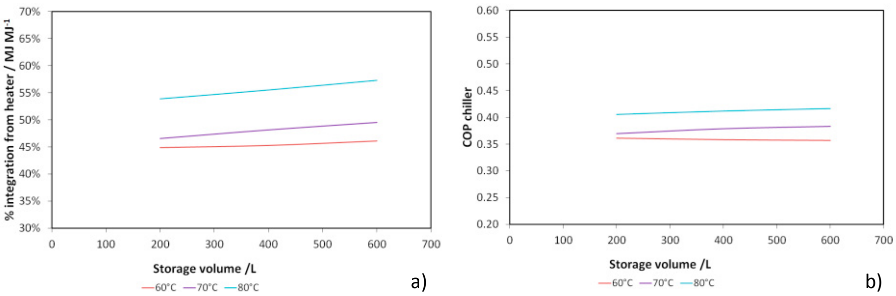


Fig. 7. Effect of storage volume and backup heat set point temperature on the integration from the heater (a) and adsorption chiller COP (b).

The effect of the storage volume is limited: indeed, the variation of the energy consumption of the backup heater and of theCOP$_{th}$, passing from 0.2 m$^3$ to 0.6 m$^3$, is always lower than 5%. On the contrary, the effect of the set-point temperature of the backup heater is more evident: an increase of about 0.12 of COP$_{th}$ is obtained passing from 60°C to 80°C of set point. On the other hand, an increase of energy consumption of the backup heater of about 25% is obtained passing from 60°C to 80°C of set point, which is caused by the need to heat up to a higher temperature level the water inside the thermal storage. Furthermore, also higher thermal dissipation towards the environment causes an increase in energy consumption of the backup heater.

According to the obtained results, the optimized configuration selected for the energy and environmental analysis is based on a thermal storage of 0.2 m$^3$ with a backup heater temperature set point of 70°C.

### *4.2. Energy and environmental analysis*

Some simulations were run, considering a constant electric load, 3.5 kW according to the load profile reported in Fig. 1a, and a variable cooling load, which can be affected by the wheater conditions of the location in which the BTS is placed. The analysis was performed by varying the number of installed SOFC cogenerators, taking into account that the electric power of a single cogenerator can be varied only in a restricted range, from 1.5 to 2.8 kW, as presented in Fig. 3a. Leading design principle of the simulated system was that the system should be able to fulfill the cooling demand, hence the need to install a backup gas heater to integrate the thermal energy provided by the SOFC cogenerator.

Accordingly, the electric power produced by the cogenerator is solely needed to cover the demand of the internal appliances in the BTS (the constant 3.5 kW load). The system is then considered connected to the electric grid, in order to withdraw electricity from the grid in case of insufficient production of the SOFC cogenerator and to feed electricity to the grid in case of overproduction of the SOFC cogenerator.

The obtained simulation results were employed to assess the energetic and environmental performance of the proposed technology. To this aim, the following parameters were calculated:

- The primary energy savings of the overall system:

$$PES = PE_{ref} - PE_{sys} \tag{1}$$

Where the primary energy consumed by the reference system is:

$$PE_{ref} = PE_{cool} + PE_{BTS} + PE_{Grid} = \frac{E_{cool}}{EER_{ref}\eta_{grid}} + \frac{E_{el,load}}{\eta_{grid}} + \left(\frac{E_{el,SOFC} - E_{el,load}}{\eta_{grid}}\right)\cdot f \tag{2}$$

While the primary energy consumed by the multi-generation simulated system is:

$$PE_{sys} = PE_{SOFC} + PE_{boiler} - PE_{Grid} = E_{fuel} + \frac{E_{boiler}}{\eta_{boiler}} - \left(\frac{E_{el,SOFC} - E_{el,load}}{\eta_{grid}}\right)\cdot(1-f) \tag{3}$$

Where, $f$=1 when $E_{el,SOFC}>E_{el,load}$ otherwise f=0.

In both equation (2) and (3) the third term on the right-hand side represents either the electric energy fed to the electric grid, in case of overproduction in equation (2), or the electric energy withdrawn from the grid, in case of insufficient cogenerator production in equation (3).

- The global efficiency of the system:

$$\eta_{global} = \frac{E_{cool} + E_{el,SOFC}}{E_{boiler} + E_{fuel}} \tag{4}$$

- The avoided $CO_2$ emissions:

$$CO_{2avoided} = f_{CO_2} PES \tag{5}$$

Where the efficiency of the Italian electric grid, $\eta_{grid}$, is 0.44, the heater efficiency, $\eta_{boiler}$, is 0.92, the reference EER for a vapour compression chiller is set at a value of 3.5 and the Italian $CO_2$ emission factor, $f_{CO2}$, is set at 0.39 $kg_{CO2}$/kWh [8]. The results of the analysis, for simulations of a reference week, are summarized in Tab. 2. A global efficiency oscillating between 50% and 63% is achieved while PES and avoided $CO_2$ strongly depend on the correct balance between load demand and power delivered by the multi-generation system.

In particular, it is evident that when the system is undersized, with only one SOFC installed, the PES can be even negative, because the integration of the backup heater to cover the cooling demand becomes too high, overcoming the benefit deriving from the self-production of the system. On the contrary, for the system installing 4 SOFCs, there is an increase of PES with the increasing of cooling load. Indeed, the primary energy consumption of the reference system increases with the increasing of cooling load, while the huge amount of thermal energy produced by the cogenerator allows to strongly limit the backup heater integration, keeping the primary energy consumption of the multi-generation system almost unaffected by the cooling load.

Tab. 2. Energy and environmental analysis of different multi-generation system configurations, for a reference constant electric load of 3.5 kW and a variable cooling load.

| No. of SOFC | Ave Cooling load | SOFC Electric production | PESsystem | ηglobal | CO2 avoided |
|---|---|---|---|---|---|
| **-** | **kW** | **kW** | **kWh** | **%** | **[kg/week]** |
| **1** | **0.74** | **2.00** | **8.00** | **55%** | **3.12** |
| **1** | **1.48** | **2.00** | **-40.05** | **59%** | **-15.62** |
| **2** | **1.48** | **5.00** | **94.76** | **57%** | **36.95** |
| **2** | **2.59** | **5.00** | **64.10** | **60%** | **25.00** |
| **2** | **3.70** | **5.00** | **25.49** | **63%** | **9.94** |
| **4** | **1.48** | **10.00** | **62.48** | **50%** | **24.37** |
| **4** | **2.59** | **10.00** | **114.43** | **53%** | **44.63** |
| **4** | **3.70** | **10.00** | **193.00** | **57%** | **75.27** |
| **4** | **4.77** | **10.00** | **302.09** | **63%** | **117.82** |

## 5. Conclusions and future perspectives

In this work, a dynamic simulation model of a multi-generation system for supplying electric and cooling energy to a base transceiver station, based on a SOFC micro-cogenerator and an adsorption chiller, is presented. The numerical simulation model is based on experimental data measured at lab scale under controlled working boundaries for the main components of the system. The simulated model allowed optimizing the system configuration and sizing each component of the system. Finally, the optimized configuration was used to evaluate both energetic and environmental benefits of the proposed technology. First simulation results confirmed that the system can be considered a reasonable option to reduce both energy consumption and environmental impact of BCTs.

Future activities will be dedicated to the implementation of dedicated control logics, in order to simulate different scenarios, prioritizing either the electric or the cooling load satisfaction. Furthermore, also economic analysis will be implemented, to identify optimal system sizing. Finally, system model validation will be performed by means of a lab-scale installation at the CNR ITAE labs.

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