ENVIRONMENTAL PERFORMANCES OF RESIDENTIAL FUEL CELL CHP SYSTEMS UNDER VARIOUS ENERGY DISTRIBUTION SCENARIOS

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Fuel Cell-based Co-generative Heat and Power (FC/CHP) systems are very attractive for stationary energy generation, because they allow co-production of electricity and heat in a decentralized, quiet, efficient, and environmentally-friendly way. So, Enel Ricerca decided to install a natural gas-fuelled polymer electrolyte (PE) FC/CHP pre-commercial prototype, supplied by H-Power, at its experimental area.

The whole PEFC/CHP system has been experimentally analyzed under all possible operating conditions, so that thermodynamic and environmental performances have been evaluated. Using these results, two possible modifications of the PEFC/CHP system configuration to increase its energy conversion efficiency and improve its environmental impact have been highlighted. Then, an energy distribution scenario analysis has been performed. Supposing both a scenario with a large diffusion of the PEFC/CHP systems in the decentralized domestic end-users and a long-term scenario of hydrogen-fed systems connected to fossil fuel derived (joined with CO2 sequestration) hydrogen distribution grids, a global environmental impact comparison between combined and separated generation of heat and power has been executed. This scenario analysis has shown that a wide FC/CHP system diffusion in the decentralized end-users would reap large environmental benefits.

Keywords: CHP, PEFC, Distributed generation, Gaseous emissions, Environmental scenario analysis

INTRODUCTION

Fuel Cell-based Co-generative Heat and Power (FC/CHP) systems are very attractive for stationary energy generation, because they allow co-production of electricity and heat in a decentralized, quiet, efficient, and environmentally-friendly way. Following its distributed generation research framework, Enel — Ricerca installed and tested a Polymer Electrolyte (PE) FC/CHP pre-commercial prototype, sup-

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plied by H-Power, at its experimental area, connected to local loads in grid-parallel operation and to the area heating system (co-generated heat). The two main features that drove the choice of the H-Power system were the use of natural gas as fuel (i.e., not pure hydrogen) and the possibility to connect it directly to the electric grid.

The whole process of the PEFC/CHP system has been experimentally analyzed under all possible operating conditions; thermodynamic and environmental performances have been evaluated.

In this article, the test campaign experimental results are presented, focusing on system global thermodynamic performances and pollutant emissions. The plant behaved as a "first-proof-of-a-concept", and possible solutions to increase its energy conversion efficiency are highlighted. The most critical aspect affecting energy conversion efficiency is system integration.

In fact, a large portion of natural gas feed is needed as a heat source to bring the fuel reforming section to its operating temperatures. Once the temperatures are achieved, heat exchangers among the various fuel cell processor components are used to effectively maintain the vessels at their different working temperatures. Moreover, pollutant emissions are produced at the natural gas burner. Thus, the internal energy transfer process optimization of the system can minimize the amount of natural gas burned for fuel processing purposes, which could maximize system thermodynamic efficiency and minimize its pollutant emissions.

Experimental results are used to analyze the environmental impact that can result from a large diffusion of PEFC/CHP systems, with respect to separated generation from conventional power plants and heat boilers. Specific emissions (i.e., quantity of pollutants per generated energy) are calculated for the PEFC/CHP next generation systems, which will benefit from higher PEFC electric efficiency and better system integration. These values are then compared with emissions associated with electricity generation from the present Italian fossil-fuel and renewable-based electric park and heat production from residential boilers, taking into account the PEFC/CHP system electricity to heat ratio.

Moreover, the same comparison is made assuming a scenario in which hydrogen is generated from fossil fuels with CO₂ sequestration in a centralized large-scale plant, then distributed to residential PEFC/CHP systems to satisfy domestic energy requirements. In this way, the article provides an overview of the global environmental impact that can be expected via the predicted diffusion of residential-scale distributed generation systems, both for natural gas fed systems and for the longer-term vision of hydrogen-fed systems connected to a hydrogen distribution grid.
FUEL CELL CHP SYSTEM

The natural gas fed fuel cell based CHP system (Fig. 1) experimentally studied is the H-Power beta-2 pre-commercial Residential Co-generative Unit, "RCU 4500 V.2", whose nominal electric stack power is 4 kW. It is based on Polymer Electrolyte Fuel Cells and constituted by three main sections, whose functions are fuel processing, electricity generation, and power conditioning, respectively. Moreover, the energy storage of the generated power surplus and the hot water production with the thermal energy from the system are assured by suitable batteries and a heat exchanger, respectively.

Natural gas, which feeds the system, is first de-sulphurized using a chemical trap to prevent fuel cell catalyst poisoning, then mixed with steam at the inlet of the reformer. In this reactor, the methane, which is the main fuel component, is completely converted into hydrogen, carbon monoxide, and carbon dioxide. The reactions that take place are (O’Brien and Hochgreb, 1997)

\[
\text{CH}_4 + \text{H}_2 \text{O} \rightarrow 3\text{H}_2 + \text{CO},
\]

\[
\text{CO} + \text{H}_2 \text{O} \leftrightarrow \text{H}_2 + \text{CO}_2.
\]

The overall reforming reaction is endothermic and occurs at temperatures around 800°C. So, the necessary heat is supplied by the cooling of hot gases from the combustion of both a part of the natural gas and the residual hydrogen coming from the FC stack.

Afterward, in the shifter, most carbon monoxide is shifted to carbon dioxide at about 300°C by following the exothermic water shift catalytic reaction. Be-
cause carbon monoxide would damage the catalyzing layers deposited on PEFC cathodes and anodes, its content must be reduced to values below 10 ppm. This is done in the Preferential Oxidation (PROX) section, where, after air injection, CO is oxidized to CO$_2$ in a catalytic way (catalyst allows the preferential oxidation of CO without involving H$_2$).

The fuel flow, composed of hydrogen and carbon dioxide, feeds the anodic channels of the fuel cell stack, while air is introduced into the cathodic ones. Therefore, direct current is generated via the electrochemical reaction between hydrogen and oxygen.

As the flow exiting the anode still contains hydrogen, it is recirculated to the burner to produce hot gases, which supply heat, not only to the reforming endothermic section, but also to the steam production for the fuel reforming. So, the exhaust gases are released into the atmosphere at about 250$^\circ$C.

Since the FC electrochemical reaction is exothermic, the stack is cooled by a water stream that is also used for the cooling of the shifter and the PROX section. The heat recovered from the CHP system is used to heat external water in a suitable water-water heat exchanger, for co-generation purposes.

The direct current generated inside the stack is delivered to the batteries and then to the Power Conditioning System (PCS), where it is inverted to become alternate with voltage and frequency equal to those of the Italian electric grid. When the CHP system works in isolated conditions, batteries are able to cover peak loads up to 6 kW for 10 minutes and instantaneous peaks of 16 kW. Therefore, the whole system is able to cover demands of 10 kW for 10 minutes and instantaneous peaks up to 20 kW.

The co-generative system can be connected to local loads and the electricity grid using either the net metering mode or the grid parallel mode. In the former, the electric power production is established by the user. Thus, if the user power consumption is lower than the FC/CHP power production, the surplus of electricity is delivered to the grid. On the other hand, in the case of a lack of net power for the end-user, extra power is supplied by the external grid. The grid parallel connection exists in a mono-directional connection to the grid. The electricity can only be taken from the grid, not delivered to it. Consequently, the RCU chases the electric load up to its nominal net power output (4 kW), while the external grid supplies extra power if loads are greater than 4 kW.

A detailed scheme of the RCU power conditioning system, together with the electric flows, is shown in Figure 2. Direct current generated by the stack flows through a DC-DC converter, where its voltage increases, and reaches the batteries. Afterwards, the power required by the AC auxiliaries is supplied by means of a dedicated inverter. From the batteries, the amount required by loads flows through
the System Management Device (SMD), which performs the AC-DC conversion and manages the power exchanges between the loads and the grid. The FC/CHP system tested in Livorno uses a grid parallel connection and can also work if it is disconnected from the grid. The operative conditions of the CHP equipment are monitored and controlled by an industrial personal computer (PC) that can be connected to either a local PC or to a remote PC by means of local area network.

**PERFORMANCES AND SYSTEM OPTIMIZATION**

The experimental activities have been performed coupling the data acquisition system provided with the CHP with an external data acquisition system. Thus, the mass flow and temperature of the streams were measured, enabling the whole process characterization. In addition, a compact emission analyzer, based on electrochemical cells, was used to quantify carbon monoxide and nitrogen oxides contents in the exhaust gases (CO₂ emissions have been calculated) and, consequently, to evaluate the FC/CHP environmental impact. Therefore, the system conversion efficiencies versus electric load at ISO conditions are reported in Figure 3 (Kor-desch and Simader, 1996).

The system shows a nearly constant electric efficiency from the full standard load to about 50% load. This is because, if the power load decreases, the electric losses inside the cells decrease nearly proportionally. At lower power loads, the global electric efficiency reduces because of the performance degradation of the fuel processor and fuel utilization factor. The thermal efficiency behavior can be explained, taking into account the increase of the heat recovered from the fuel processing unit when the electric load decreases. The total efficiency values result quite small in the overall operative range.
Using the results of the experimental analysis reported above, a preliminary study has been carried out to identify some modifications to improve the tested FC/CHP system performances.

The first issue is the co-generation optimization. The β-prototype FC is characterized by a medium level of integration among the inlet-outlet streams of the thermal reactors. The system is not equipped with an exhaust gas heat exchanger and, consequently, the heat associated with the exhaust gas (250°C) at the outlet of the steam boiler is not recovered. Thus, the introduction of a heat exchanger would improve the system's efficiency.
downstream the steam boiler is expected to raise the nominal FC/CHP thermal and global efficiency up to about 45% and 60%, respectively (Fig. 4).

Further optimizing options are related to the FC stack and the hydrogen management concept. In the pre-commercial system, the hydrogen contained in the anode stream and leaving the FC stack is fired in the burner to enhance the thermal power source for the endothermic reformer. A preliminary study shows that it is possible to recirculate a fraction of hydrogen directly to the cell stack, thus obtaining an increase in the system efficiency.

The combination of optimizations of the stack configuration and materials, of the co-generation process, and of the hydrogen management is expected, in the near future, to allow the realization of a FC/CHP plant characterized by about 30% nominal electric efficiency and about 40% thermal nominal efficiency (Fig. 4).

**ACTUAL EMISSIONS OF THE FC/CHP SYSTEM**

Among the most important pollutants derived from fossil fuel combustion, some nitrogen oxides (NO\textsubscript{x}), produced in the combustion of natural gas-hydrogen with air in the burner, whose exhaust gases provide the necessary heat to the reforming process, are the only ones that affect the FC. Indeed, the burner is on-off regulated and the air-fuel ratio is fixed at optimal conditions. From the experimental data collection, the NO\textsubscript{x} content in the flue gases has been lower than 10 ppmV (normalized at 3% O\textsubscript{2} content in gas) in the whole operational range, as shown

![Figure 5: FC NO\textsubscript{x} emissions (@3% O\textsubscript{2}) vs. electric power level.](image-url)
in Figure 5. The CO content in the exhaust gases has been below the instrument
detection limit (1 ppmV) at any operation condition, proving the optimal
burner setting.

ENERGY SAVING WITH THE FC/CHP SYSTEM

Co-generative systems should assure energy savings with respect to the electricity
supplied from the grid and heat production of conventional boilers. To evaluate
the RCU 4500 V.2 FC/CHP system energy-saving performances and its co-gen-
eration behavior, the thermal efficiency versus electric efficiency chart (Fig. 6)
has been constructed. The expected co-generation performances of the hypotheti-
cal optimized PEFC commercial prototypes, as described above, are reported in
Figure 6, too. The thermal and electric efficiency behavior at operative conditions,
far from the nominal point, is supposed to be similar to that of the actual tested
equipment.

In Figure 6, two straight lines indicate the operative conditions where the
combined heat and power production allows 10% energy savings with respect to
a separated supply of electricity and heat, both in industries (continuous line) and
for residential users (dashed line). As the co-generation promotion policy pursued
by the Italian government (DL 16/03/1999 n.79, 1999), primary energy saving has
to be evaluated assuming an efficiency of 38% for the electricity generation (i.e.,
the mean value of Italian thermoelectric power plants) and to 80% and 90% for
heat production in residential and industrial uses, respectively.

![Figure 6: System energy savings under several operating conditions.](image)
The efficiency of the tested FC-CHP system is so low that it does not assure energy saving with respect to the separated heat and power generation (Fig. 6). However, the optimized future FC/CHP will ensure substantial savings with respect to the separated heat and power production. So, taking into account the Italian rules (DL 16/03/1999 n.79, 1999), only the future FC/CHP model can be considered as a co-generation energy device.

SPECIFIC EMISSIONS SCENARIOS

Most Italian residential users get their electrical power from the national grid, and thermal power for house heating from appropriate boilers, which burn either low-sulphur content oil for condominial end-users or natural gas in a single user configuration with later technology equipment.

Supposing a future energy scenario with a wide diffusion of residential FC/CHP systems, the conventional ways of electric and thermal energy supply would be partially replaced. This fact would also imply the partial replacement of specific gaseous emissions. In other words, if a user gets 1 kWh of electricity and 2 kWh of heat from a fuel cell, the gaseous pollutants related to the production of the same energy by centralized power plants and domestic boilers would be partially avoided and replaced by the FC gaseous emissions.

Furthermore, a second energy distribution scenario has been taken into account. With a long term vision, the FC/CHP will be fed directly by hydrogen from a distribution grid. The hydrogen is supposed to be produced in large-scale, centralized, coal gasification power plants (Vierrath et al., 1986) with appropriate CO₂ sequestration options. The oxygen needed for the coal gasification is produced using a cryogenic air separation unit.

Therefore, in order to compare the environmental impacts of residential FC/CHP systems and traditional methods of heat and power separated production, the following hypotheses have been assumed:

- residential PEFC package is equipped with a natural gas reforming system;
- the electrical and thermal efficiencies of the reference FC-commercial model are 30% and 40%, respectively;
- the FC works constantly at full electric load (i.e., 4 kW constant electric load) and, consequently, 6 kW constant thermal load;
- no FC exhaust gas treatment is present;
- the specific emissions per kWh of electricity supplied by the national grid are averaged (weighted by yearly energy production) on every power plant of the electric park, i.e., both fossil fuel-fired ones and renewable ones (ENEL, 2001);
the average NO\textsubscript{x} specific emission from the Italian electric park is 0.8 g/kWh (ENEL, 2001);
the average SO\textsubscript{2} specific emission from the Italian electric park is 2.4 g/kWh (ENEL, 2001);
the average CO\textsubscript{2} specific emission from the Italian electric park is 707 g/kWh (ENEL, 2001);
the distribution grid efficiency is 93% (ENEL, 2001);
the efficiencies of common domestic natural gas-fired boilers and oil-fired boilers are 95% and 90%, respectively;
the FC CO\textsubscript{2} emissions have been calculated referring to the mass balance of the natural gas inlet flow;
the gasification plant uses pure O\textsubscript{2} obtained from a cryogenic air separation unit, with a specific electrical consumption equal to 0.25 kWh\textsubscript{el} per kg of O\textsubscript{2} produced;
the coal/hydrogen conversion efficiency in the gasification plant is 60%;
the CO\textsubscript{2} capture efficiency in the hydrogen centralized production is assumed equal to be 90% (membrane separation).

In Figure 7, the specific emissions of CO\textsubscript{2}, NO\textsubscript{x}, and SO\textsubscript{2} (expressed in g/kWh) from both natural gas-fed and hydrogen-fed CHP fuel cells are compared with the ones caused by the separated heat and power generation for the two kinds of end-users described above. In the same figure, a typical oil-fired boiler user is referred as "USER 1" and typical natural gas-fired boiler user is referred as "USER 2".

![Figure 7: Specific emissions comparisons with the scenario of diffusion of natural-gas/H\textsubscript{2} fed FC/CHP.](image-url)
As in the first assumed scenario, the FC specific emissions are much lower than those from traditional energy supplies. SO\textsubscript{2} emissions from the FC are obviously not present because of the zero sulphur content in the natural gas. Because of its on-off regulation and fixed air-fuel ratio at optimal conditions, the FC burner produces very low NO\textsubscript{x} emissions. Therefore, the overall FC environmental impact is significantly lower than the impact from the conventional electric and thermal energy supply systems.

For the CHP fuel cell systems fed by H\textsubscript{2} produced from coal, the main advantage, from an environmental point of view, consists of the very low specific CO\textsubscript{2} emissions, caused by the centralized sequestration systems. Acid gas emissions (SO\textsubscript{2} and NO\textsubscript{x}) derive only from the air separation unit electric consumption, as H\textsubscript{2} production from coal gasification is an intrinsically clean process. These emissions could be lowered using higher-efficiency thermoelectric plants and renewable primary fonts as well. In any case, the centralized system for H\textsubscript{2} production from coal assures a very low overall environmental impact, compared with current specific emissions scenarios, and, above all, it drastically reduces pollution in urban areas.

CONCLUSIONS

The PEFC/CHP pre-commercial prototype, supplied by H-Power, installed by ENEL Ricerca at its experimental area in Livorno, has been characterized under all the possible operating conditions, in order to evaluate thermodynamic and environmental performances.

The plant was a "first-proof-of-a-concept", and possible solutions to increase its energy conversion efficiency have been highlighted. The most critical aspect affecting energy conversion efficiency is system integration.

Pollutant emissions produced by the natural gas burner have been monitored. CO and NO\textsubscript{x} contents were very low, because of the optimal burner configuration and set-up.

Experimental results have been used to analyze the environmental impact that can result from a large diffusion of PEFC/CHP systems, in comparison with separated generation in conventional power plants and heat boilers. Specific emissions (\textit{i.e.}, quantity of pollutants per generated energy) are calculated for the PEFC/CHP system, assuming characteristics of a next generation system, which will benefit from higher PEFC electric efficiency and better system integration. These values are then compared with emissions associated with electricity generation from the present Italian fossil-fuel and renewable-based electric park and heat production from residential boilers.
Moreover, the same comparison is made assuming a scenario in which hydrogen is generated from coal with CO₂ sequestration in a centralized large-scale plant, then distributed to residential PEFC-based CHP systems to satisfy domestic energy requirements. This overview of global environmental impact showed that a large diffusion of domestic PEFC/CHP systems will allow a major environmental impact reduction, both for acid gases (SO₂ and NOₓ) and for greenhouse gas (CO₂).

The advanced scenario, with an H₂ centralized production using coal as primary font, implies a further reduction of the overall environmental impact, particularly in urban environments. H₂ centralized production from coal seems to represent an interesting medium-term solution for the mitigation of greenhouse and acid gas emissions.

References

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