Development of a micro-cogeneration laboratory and testing of a natural gas CHP unit based on PEM fuel cells

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1. Introduction

Reduction of primary energy consumption is generally considered as one of the key options to meet the ambitious EU Energy Roadmap target for the year 2050: a decarbonized energy system which reduces its energy-related CO_2 emissions by over 80 percent compared to the 1990 level [1,2]. A recent study shows how only the shift towards a highly-efficient electricity supply system together with the maximum use of advanced technologies allows hitting the target; a substantial portion of the overall energy savings may come from cogeneration and efficient heat generation [3].

Micro Combined Heat and Power (micro-CHP) is a well-known extension of the concept of cogeneration to small-scale applications. Several organizations (ranging from energy companies, gas distributors, independent power producers, and end users) are increasingly looking for environmentally-friendly systems to

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supply energy on a decentralized basis. Micro-CHP systems may fit well the energy demand of diverse types of buildings, such as single as well as multi-family dwellings or small offices [4,5].

One of the central issues in the diffusion of micro-CHP systems is the possibility to rely on efficient, clean and robust units, appropriately designed with respect to a defined load and able to offer a reasonably fast payback time while keeping best energy and environmental benefits. This requires, on one hand, the development of innovative technologies to yield maximum efficiency and lowest emissions; on the other, it requires a numerical estimation and experimental verification of the CHP unit performances to define their potential. This is especially true considering that adequate CHP units should offer sound energy and emissions savings with respect to alternative power supplies, winning the continuous improvement of conventional centralized power plants.

The small size precludes to the majority of micro-CHP prime movers on the market today the possibility to compete in terms of electrical efficiency with large power plants; nevertheless, the landscape may change in the future with the introduction of latest high efficiency fuel cell technologies [6,7]. However, it is already realistic that micro-CHP systems can achieve significant primary energy savings, thanks to the possibility of operating in full cogeneration [4].

In the last years, Politecnico di Milano has dedicated an effort to set up a new Laboratory of Micro-cogeneration (LMC) [8]. The laboratory is a unique structure developed for testing CHP units fuelled by natural gas, hydrogen, synthetic gas or any mixtures of the previous. The laboratory can test also trigeneration or Combined Cooling Heating and Power (CCHP) systems using heat pumps or thermal absorption chillers and boilers, either separated or integrated into a single package [9]. The laboratory is designed to recreate most plausible operating condition, changing independently the water flow rates and temperatures of hydraulic circuits, flow rate and chemical composition of the fuel gas supply, temperature of the ambient air and the electric load. It aims at characterizing a micro-CHP in terms of realistic energy and environmental performance, improving where necessary the control logic; secondly, it aims at developing innovative systems and components in the context of specific research projects.

This work details the plant equipment and laboratory instrument, the types of tests specified, the pattern of the test circuit realized, and, ultimately, reports an example of recent experiments carried out on a PEM fuel cell CHP system with an electrical power capacity of about 20 kW_{el}. Tests have been developed to characterize the processing section and the thermodynamic performances of the overall system. The results are to be compared with other experimental investigations on PEM fuel cell for small CHP applications [10,11], which however have not reached yet the expectations [12].

Table 1
Common infrastructures at LMC laboratory building.

Natural gas pipeline connection and compressor (30 Nm^3/h at 10 bar); external deposit of gas bottles	Condensation boiler (rated at 600 kW) and pump station for hot water primary circuit
Electrolyzer for H_2 production (6 Nm^3/h) and O_2 production (3 Nm^3/h) at 30 bar	Cooling tower (503 kW and 79 m^3/h) and pump station for cooled water primary circuit
Gas distribution network (CH_4, N_2, CO_2, CO, H_2, O_2, compressed air); safety system for gas leakages	Chiller for chilled water production (618 kW screw compressor) and pump station for cold water primary circuit

2. The laboratory

The laboratory basically consists of a set of sensors and units adapt to reconstruct with high precision the mass and energy balances of the unit under test, the operating parameters of the relevant components and the corresponding emissions.

LMC shares with the other adjacent laboratories located in the same building (shown in Fig. 1) a number of common infrastructures. They include a gas distribution network and three water circuits (hot, cooled and chilled water, linked to a dedicated centralized boiler, an evaporative tower and an electric chiller) which are the main sources of heating/cooling used in the laboratory. Details are provided in Table 1.

The gas distribution network includes low pressure natural gas from local distributor pipelines, as well as compressed natural gas from a dedicated screw compressor (up to 30 Nm^3/h at 10 bar); other gases are stored in bottles (CO, CO_2, N_2, H_2, O_2), with the additional possibility of producing hydrogen and oxygen through a dedicated electrolyzer. The latter features a hydrogen flow rate capacity of 6 Nm^3/h at 30 bar, and a connection to a storage system with 1 m^3 pressurized vessels.

The laboratory is divided into three areas:

- the test room, which will be described below (Fig. 2);
- the control room (about 40 m^2, hosting the control panel and data acquisition, as well as auxiliary instrumentations);
- the plant area, placed above the ceiling of the test room, hosting all the hydraulic circuits (Fig. 3), the test room air treatment unit and the electrical panels.

Fig. 1. The building hosting the LMC lab at Milano Bovisa campus of Politecnico di Milano.

Fig. 2. Test room with a prototype CHP plant (PEM FC system by ICI Caldaie SpA).

Fig. 3. Hydraulic plants above the test room.

2.1. *Experiments and functional layout*

LMC is designed to carry out the type of experiments listed below.

a) Low temperature CHP tests. For units with electrical power generation up to 100 kW (grid connected or island mode) and hot water production up to 200 kW and 95 °C.
b) High temperature CHP tests. For units with electrical power generation up to 100 kW (grid connected or island mode) and superheated hot water production up to 200 kW and 150 °C at 8 bar.
c) Cooling generation tests. For compression and absorption/adsorption chillers, with electrical (up to 100 kW) or thermal (up to 100 kW with pressurized water at 150 °C) feeding.
d) Heat pump tests. For the compression and absorption heat pumps, with electrical or thermal feeding (same as above), within a max thermal power output of 200 kW.
e) Boiler tests. Up to 150 °C at 8 bar and 200 kW of useful thermal power output.
f) Trigeneration tests. For combined cooling, heating and power systems (e.g. CHP + absorption chillers and/or heat pumps, with mechanical or electrical drive, with separated or integrated units), according to the CHP and cooling generation specifications given above.

Starting from this requirement, the laboratory has been developed according to a functional diagram able to handle all the heating and cooling requirements involved by the above-mentioned tests. The simplified functional diagram, with the main components of the hydraulic and the air treatment plant, is shown in Fig. 4. The plant is developed starting from three primary circuits for cooled, chilled and hot water, shown on top of Fig. 4 (circuits 01, 02 and 03), that are connected to the hydraulic loops of the laboratory building (specified in Table 1, second column). Three secondary circuits (circuits 11, 12 and 13) interface the hydraulic plant with eight flanges of possible connection with the system under test. The latter are shown at the bottom of Fig. 4 and placed within the test room. The secondary circuits, interposed between the primary loops and the system under test, allow simulating the connection to a cogeneration or trigeneration network.

Tests (cases a–f) are controlled in different ways. Heat recovery for cases a, b, d, e and f is handled (i) at low temperature by circuit 12 (up to 95 °C) or (ii) at high temperature by circuit 11 (up to 150 °C at 8 bar). In the first option, heat is dissipated by circuit 12 through the cooled water primary loop (circuit 01 driven by the cooling tower) and, if the cooled water temperature is not low enough, with the chilled water primary loop (circuit 02). In the

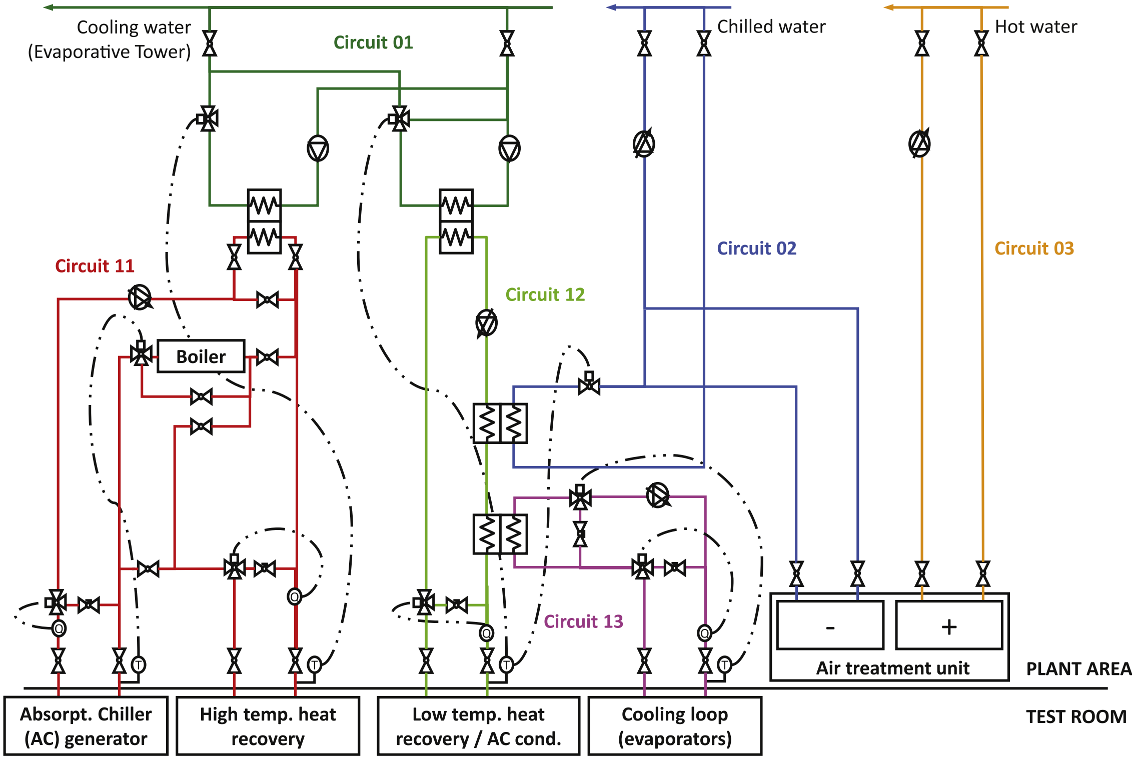

Fig. 4. Functional diagram of the hydraulic and air treatment circuits of the LMC laboratory (AC is the acronym for absorption chiller).

second option, all heat is dissipated by the cooled water loop (circuit 01).

For tests on absorption chillers or heat pumps (cases c and d), heating is produced by a 100 kW-electrical heater that operates in circuit 11. The cooling effect produced by the unit is recovered by circuit 13 to partially cool the condenser and absorber of the refrigerator; the remaining cooling duty being dissipated by circuit 12 with the same possibilities discussed for the low temperature heat recovery case.

Finally, trigeneration tests (case f) require the simultaneous use of all circuits. An example could be an integrated system with a prime mover (e.g. ICE, microturbine or fuel cell) and an absorption chiller that would be connected to circuit 12 for low temperature heat recovery and circuit 13 for cooling recovery, provided that the absorption unit is driven directly by the prime mover heat production. On the other hand, it is also possible to run a test on a prime mover releasing heat both to high temperature and low temperature heat recovery circuits, where the first (circuit 11) would feed the generator of the absorber (bottom left of Fig. 4).

The primary circuits are also used to feed an air treatment unit (right side in Fig. 4) designed to control an air flow rate of 2700 m^3/h between 10 °C and 40 °C. The unit can be expanded to include a humidity control section as well as a refrigeration section to decrease the lower bound of the temperature range. Air can be sent to the test room and/or directly to the inlet flange of the unit under test. Air mass flow rate may be measured by a Wilson grid.

On the electrical side, electricity can be directly sent to the grid with a standard parallel connection or indirectly through an electronic loadbank that simulates island operations as well as grid distortions and failures. The bank comprises two inverters, the first of which emulates the electric load seen by the unit under test, while the second reconverts the electrical output of the previous in order to send the electricity to the grid within requirements. Both inverters are rated at 100 kW in three-phase configuration. The electric load is also capable of being plugged to direct current storage systems to simulate hybrid setups.

2.2. *The test room and control system*

The test room is a 25 m^2 cell where the hydraulic, electrical and gas circuits can be connected to the unit under test. A redundant leakage monitoring system on flammable and toxic gases (CO, H_2, O_2, CH_4), together with a large capacity ventilation system (1200 Nm^3/h) and permanent external openings ensures the possibility to comply with ATEX standard requirements and carry out tests on unclassified units and components. Exhaust gases can be sent to two external stacks (one of which is designed for hot, dangerous and corrosive gases).

Within the cell, the gas lines are organized with a measurement and control section (for pressure and flow rate) yielding the possibility of being mixed for syngas simulation. In that case, dosing is controlled through a closed loop control based on periodical chemical analysis through a micro-gas chromatographer.

This unit (Pollution VEGA-GC) includes two heated sampling systems able to handle up to 18 inlet lines, and is based on three columns and a pre-concentrator for ppm-scale sulphur analysis. The three columns are:

- CP-Sil5CB (length 8 m operating at 40 °C and 90 kPa gauge) for CO_2, ethane and higher hydrocarbons.
- Molsieve5APLOT (length 20 m operating at 90 °C and 180 kPa gauge) for H_2, O_2, N_2, CH_4 and CO.
- PoraPlotQ (length 10 m operating at 60 °C and 110 kPa gauge) for H_2S, H_2O (steam), CO_2 and natural gas odorizers.

Data acquisition and process control is managed through a National Instruments Programmable Automation Controller (with more than 600 signals acquired for process management, supervision and measurements). A graphical user interface on a dedicated PC allows plant management and control (Fig. 5).

3. Testing of a PEM FC CHP unit

In the first period of the laboratory activity test campaigns were carried out on a CHP unit based on PEM fuel cells. The unit, called Sidera 30 and manufactured by ICI Caldaie – partner of Politecnico di Milano in a European Community FP7 project on the development of an advanced PEM CHP unit [9] – is a prototype for distributed generation. It is fuelled with natural gas that is transformed into a hydrogen-rich syngas, which feeds the fuel cell, by a fuel processor (see the simplified system diagram in Fig. 6) based on a steam reformer with shift reactors and a section for CO abatement through preferential oxidation [13].

Heat recovery allows producing 60 °C hot water by cooling the FC and the fuel processor. After installation at the laboratory (Fig. 2), the unit has been tested to verify the general energy balances and emissions according to a research project [14], and to support the enhanced design of internal components (in particular the reactors that make up the fuel processors, the PEM cell stacks and the related heat exchangers circuit for heat recovery).

In all tests, the measured variables are mass flow rate and temperature of the CHP water entering and returning from the machine, where the mass flow rate is controlled through the pump speed and the inlet temperature is kept at 30–45 °C by the PID controller that manages the cooling circuit. Below it is given a description of the main flow and energy measurements carried out during the test.

- Natural gas mass flow measurement is carried out with a low pressure drop Bronkhorst IN-FLOW F106BZ hot wire massic sensor with accuracy 1% of full scale upon calibration with pure methane. The reading is corrected for the actual composition of natural gas. Alternatively, using the high pressure natural gas pipeline, natural gas mass flow rate is measured with another Bronkhorst IN-FLOW characterized by a high accuracy (0.8% of measured value plus 0.2% of full scale) but much higher pressure drop. Pressure is then reduced with a mechanical two stage regulator (Fiorentini Minireg FE6) and measured through a Bronkhorst IN-PRESS P-502CI sensor. Temperature is measured with a thermocouple.
- Air is taken by the laboratory itself, which can be controlled in temperature through a dedicated air conditioning system. Temperature and humidity at the inlet of the unit under test are measured with Pt100 thermoresistances and a hygrometer Testo H1.[1]
- Exhaust gas temperature is monitored with a Pt100 thermoresistance. Exhaust gas composition and emissions are monitored after dehydration (ABB Sample gas cooler Advance SCC-C) via the micro-gas chromatograph and Testo 360 emission control unit (with infrared and electrochemical sensors) for CO, NO, NO_2, SO_2 and O_2 content in the flue gas.
- Electrical power (active and reactive power, exported or imported by the unit under test) is measured by a power analyzer (Fluke Norma 4000 with amperometer transformers type

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[1] The laboratory has been equipped recently with a much more accurate unit by Vaisala for the measurements of pressure, temperature and humidity of the air within the test room.

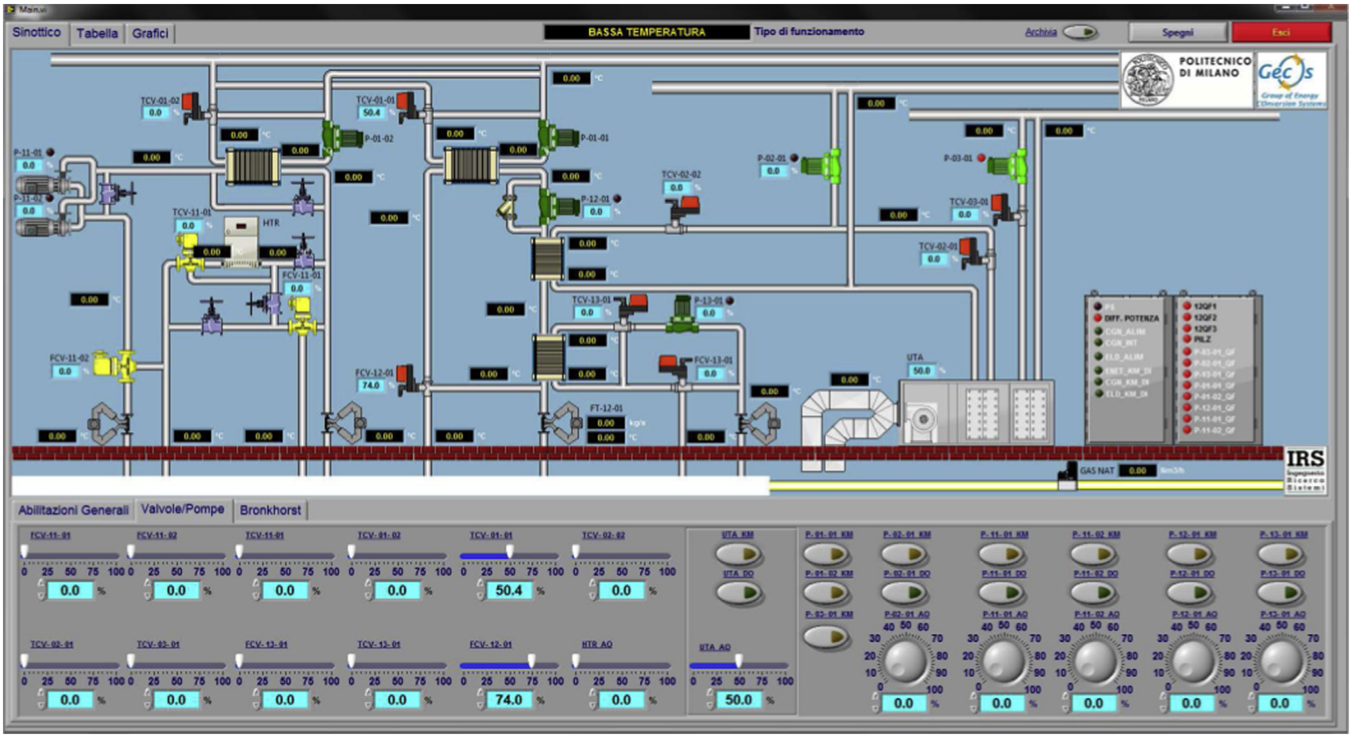

Fig. 5. A screenshot of the control system.

Signaltec MCTS based on Hall effect), with accuracy ±0.1% in all the relevant power range.

- Water mass flow rate is measured by Coriolis sensors (Emerson Micromotion Elite CMF100) with accuracy of ±0.1% of reading; pressure drop is measured by a differential sensor (Emerson Rosemount 2051CF). Water temperature at inlet/outlet of the unit under test is controlled by a PID loop and measured with Pt100 thermoresistances. Water condensation from the flue gases may be measured by a weight scale (Bel Mark 1700) connected to the data acquisition system.

The experimental campaign was divided into two phases. The first stage focused on tuning the control logic of the fuel processor to produce steadily a hydrogen rich synthetic gas with a content of CO below 10 ppm. The second phase aimed at controlling the overall process feeding the synthetic gas to the fuel cell without directing the anode exhaust to the burner. Then, the anode exhausts were utilized in the burner allowing for the minimum consumption of natural gas. At last, the overall control logic was adjusted to increase the electrical production.

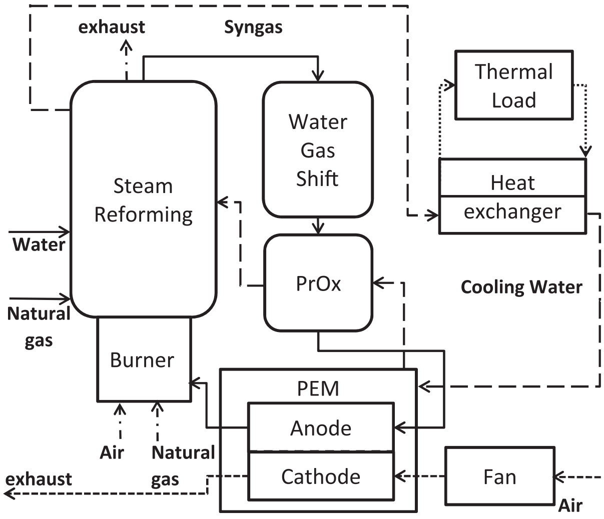

Fig. 6. Simplified diagram of the PEM FC unit: the fuel supplied is natural gas, transformed into the fuel processor in a stream with a high content of hydrogen that feeds the PEM cells.

Setpoints, measures and calculations of the best working condition are here outlined. The main controlled properties are: the mean reformer temperature, the steam-to-carbon ratio, the CHP water inlet temperature and rate, and the fuel cell current. The chosen values are in Table 2.

Moreover, the main measured properties are: compositions of the natural gas as well as of the syngas at the outlets of WGS and PrOx reactors, oxygen content of both the burner and the cathode exhausts, the mass flow rate of the natural gas, the temperatures of the ambient, the exhausts and the CHP water outlet, the electric power generated by the inverter and that consumed by the ancillaries. The measured averaged values are given in Table 3.

Steady state conditions of a test are verified observing the CHP water outlet temperature and the fuel cell voltage. Once the variations are significantly small, a number of properties are acquired with a frequency of 2 s. The acquisition lasts about 30 min. At the end of the test the data are averaged to provide a mean value of each property.

Table 2
Main controlled properties.

Parameter	Unit	Value
Mean reformer temperature	°C	700–740
Steam-to-carbon ratio	–	4–5
Inlet CHP water temperature	°C	44–46
Inlet CHP water rate	kg/s	1.15
Fuel cell current	A	90

Table 3
Main averaged measurements.

Parameter	Unit	Value
Normalized composition (volume dry)		
Natural gas		
CH_4	%	89.53
C_2H_6	%	6.40
C_3H_8	%	1.22
C_4H_{10}	%	0.34
C_5H_{12}	%	0.08
CO_2	%	0.79
N_2	%	1.64
Syngas at water gas shift outlet		
CH_4	%	4.60
CO	%	0.90
CO_2	%	19.10
H_2	%	74.96
N_2	%	0.44
Syngas at preferential oxidation reactor outlet		
CH_4	%	4.28
CO	ppm	6.6
CO_2	%	18.68
H_2	%	68.46
N_2	%	8.58
Oxygen content (volume dry)		
Burner exhaust	%	3.65
Cathode exhaust	%	10.32
Mass flow rate		
Natural gas	g/s	2.04
Temperature		
Ambient	°C	23.0
Burner exhaust	°C	61.2
Cathode exhaust	°C	65.2
Outlet CHP water	°C	57.4
Electric power		
Inverter output	kW	24.95
Ancillaries	kW	4.5

Air, syngas and exhausts mass flow rates are estimated starting from compositions and oxygen contents. Enthalpy flows of exhausts and condensate water are calculated assuming ideal mixing and employing the commercial code Refprop 9 (setting the reference enthalpy of each species equal to their enthalpy of formation).[2] Other energy flows are: the entering fuel (defined with respect to its lower heating value – LHV) as well as the exiting net electric power, thermal power and losses. Table 4 illustrates the numerical values of these flows.

The electric and thermal efficiency are computed from the energy flows as simple ratios. Their values are given in Table 5 and are in agreement with those from other experimental studies [10,11].

All the computed values are subject to uncertainty due to the measurements on: composition and molar flow rate of the natural gas (which combine into the input fuel energy flow of Table 3); temperatures and mass flow rate of the CHP water (output CHP flow); voltage and current entering and exiting the inverter (inverter losses) as well as voltage and current to the ancillary units (net electric); composition of the burner and cathode exhausts; finally, condensate mass weight over time. The combined uncertainty is computed according to the standard UNI CEI ENV 13005. The measurement affecting the most the uncertainty is the natural gas composition. Table 6 reports the calculated values for the electrical and the thermal efficiency.

Table 4
Computed energy flows.

Parameter	Unit	Value
Input		
Fuel (lower heating value)	kW	96.56
Output		
Net electric	kW	20.45
CHP water	kW	53.24
Burner exhaust	kW	11.00
Cathode exhaust	kW	3.48
Condensate water	kW	0.47
Inverter losses	kW	1.88
Other losses	kW	6.04

Table 5
Computed performance indexes.

Parameter	Unit	Value
Electric efficiency	%	21.18
Thermal efficiency	%	55.13
First-law efficiency	%	76.31
PES index	%	6.07

Ultimately, the primary energy savings (PES) index is estimated according to the EU Directive on cogeneration [15]:

$$\mathrm{PES} = 1 - 1/\left[\frac{\eta_{\mathrm{el,cog}}}{\eta_{\mathrm{el,ref}} \times p} + \frac{\eta_{\mathrm{th,cog}}}{\eta_{\mathrm{th,ref}}}\right] \tag{1}$$

where the reference efficiency values for the separate generation of electricity[3] and heat ($\eta_{\mathrm{el,ref}}$, $\eta_{\mathrm{th,ref}}$ respectively) are given in Table 7, reflecting the Italian implementation of the directive [12,13]. It is assumed that 50% electricity generated by the CHP unit is consumed onsite and 50% is injected to the local grid, yielding an intermediate grid efficiency coefficient, p, equal to 0.8925. Based on the current legislation, the resulting overall efficiency (76.31%) and PES index (about 6%) are sufficiently high to qualify for high efficiency cogeneration [16].

Summarizing the test results, the overall energy balance proves encouraging total efficiency and PES, which should be considered satisfactory given the non-optimized layout and prototype integration of the system components. Moreover, the system has shown good stability in the conversion of natural gas to hydrogen and feeding the FC with a stable, low CO fuel.

Future evolution of the system includes using different types of fuel cells, specifically designed for syngas operation, and the exploration of an advanced fuel processing solution based on a membrane reformer using hydrogen separation membranes [10], which should allow reaching much higher electrical efficiencies (over 40% LHV according to theoretical estimates [17]).

4. Conclusions

This work addresses the development and the objectives of a new Laboratory dedicated to Micro-cogeneration systems (LMC), established at Politecnico di Milano. The laboratory aims at developing innovative systems and components within specific research projects and to carry out energy and environmental

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[2] http://www.nist.gov/srd/nist23.cfm.

[3] Reference electric efficiency depends also on average local temperatures in the installation site. The EU Directive allows to adapt $\eta_{\mathrm{el,ref}}$ in each country, including a ±0.1% correction for every ±1 °C of variation between yearly average local temperature and 15 °C. This variation is neglected here for simplicity.

Table 6
Computed combined uncertainties.

Parameter	Unit	Value
Electric efficiency	%	±1.19
Thermal efficiency	%	±1.93

Table 7
Reference values for PES calculation.

Parameter	Unit	Value
Electric efficiency $\eta_{el,ref}$	%	52.5
Heating thermal efficiency $\eta_{th,ref}$	%	90
Grid efficiency (voltage <0.4 kV) p		
- onsite consumption p_{ac}	–	0.86
- electricity sale p_{im}	–	0.925

characterization of micro-cogenerators. It is designed to simulate a number of operating conditions, having the possibility to change independently the temperature and mass flow rate in the different hot and cold hydraulic circuits, the primary fuel chemical composition, the inlet air temperature and the electrical load. Moreover, the LMC is developed for testing hydrogen production appliances, including electrolyzers and fuel processing systems for fuel cells.

Finally, it is outlined an experimental activity carried out on a prototype PEM cogeneration unit, with natural gas feeding and a steam reformer fuel processor, evidencing the functionality of the laboratory. The prototype PEM CHP system under test has shown interesting working conditions, despite its non-optimized layout, and the ability to work with encouraging total efficiency (above 76%) and a positive primary energy savings index (6%).

Parallel activities at the lab have been developed on Stirling engines [18], while future campaigns will focus also on advanced fuel processors [13,17], reciprocating engines, microturbines, or other prime movers, as well as on trigeneration systems.

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Nomenclature

Acronyms and symbols

AC	absorption chiller
CHP	combined heat and power
CCHP	combined cooling heat and power
FC	fuel cell
LHV	lower heating value
LMC	Laboratory of Micro-Cogeneration
p	grid efficiency coefficient (Table 7)
PEM	polymer electrolyte membrane fuel cell
PES	primary energy saving index (Eq. (1))
PrOx	preferential oxidation reactor
WGS	water gas shift reactor
η	efficiency

Subscripts

cog	cogenerator
el	electrical
ref	reference
th	thermal

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