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Preliminary Investigations on a Test Bench for Integrated Micro-CHP Energy Systems

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Abstract

Micro-CHP (Combined Heat and Power) energy systems are potentially suitable for residential and tertiary utilities, typically characterized by low-grade heat demand and limited electric-to-thermal energy demand ratio values. Different innovative and under development CHP technologies are currently investigated in small scale units, but a standard has not been identified till now. Moreover, depending on the load request, the produced electricity can be used, stored in electric accumulator or in the external net, or integrated with other external sources. Contextually, the available heat can be used, accumulated inside the system or dissipated. The actual convenience of small size CHP systems depends on the demand profiles and the operation management logic.

A test facility is being developed, at the University of Bologna, for the experimental characterization of the cogenerative performance of small scale hybrid power systems, composed of micro-CHP systems of different technologies (such as Organic Rankine Cycles and Proton Exchange Membrane Fuel Cells), a battery and a heat recovery subsystem. The test set-up is also integrated with an external load simulator, in order to generate variable load profiles.

This report describes the main characteristics of the implemented test bench, the selection procedure of the adopted micro-CHP unit and expected performance.

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Keywords: micro-CHP; fuel cell; hybrid; test bench

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1. Introduction

Large scale power production and transmission with high power density network is currently the predominant solution to cover the distributed users power demand in many industrialized countries. Remarkable performance values could be achieved with further improvements of such large scale power plants in the near future [1]. Nevertheless, micro-CHP (Combined Heat and Power) systems are under investigation in the framework of a distributed generation approach, allowing for a reduction in the network losses and for the fulfillment of both thermal and electricity demand of local consumers [2]. Micro-CHP systems have natural potential suitability for different civil, tertiary and industrial applications, such as residential buildings, hospitals, supermarkets, sporting centers, etc., where a significant thermal demand is associated to the user electricity demand, reducing primary energy consumption and also environmental impact [3]. A large market potential for Micro-CHP has been identified since more than ten years ago, as highlighted for example by Dentice d'Accadia et al. in [4].

As shown also in review paper by Kuhn et al. [5] and Bhargava et al. [6], the most promising and available or under development Micro-CHP prime movers are: small Internal Combustion Engines (ICE); Micro Gas Turbines (MGT); Micro Rankine Cycles (MRC); Stirling Engines (SE); Thermo-Photo-voltaic (TPV) [7] and Fuel Cells (FC) systems. These prime movers have different levels of technological development and performance (see [8] for a comparison in residential applications), but till now none of them has reached a significant diffusion or leading role.

Fuel cell systems are innovative prime movers capable to convert the chemical energy of hydrogen into electricity while a fraction of unused energy becomes available as heat. Low temperature FCs such as Proton Exchange Membrane (PEM), operating in the range of 50-90°C, could be feasible distributed energy systems for domestic CHP applications [9] and also for on-board applications [10].

In a previous work [11], a DSP-controlled test facility for the performance assessment of an autonomous power unit based on FC has been developed and preliminary experimental tests have been illustrated, on the electric performance of an installed PEM stack suitable for micro-CHP application.

Key requirements for future distributed energy generation systems are the operation flexibility and the capability to cope with used demand load changes, especially in island connection not involving the external net; indeed, micro-CHP system should face rapid changes and stochastic variations in the demand profiles. In order to fulfill such requirements, the integration between multiple prime movers and with additional energy storage subsystems is a mandatory development of single micro-CHP units. In a previous paper [12], the electric storage potential in CHP applications for domestic applications has been assessed. The adoption of more than one prime mover integrated in the micro-CHP could further enhance flexibility of operation. It is also important to compare advanced CHP systems, such as FCs, with less innovative and more reliable prime movers, such as ICEs or MRCs, which can be fed both with conventional or renewable fuels.

Nomenclature

Acronyms

AC	Alternate Current	MGT	Micro Gas Turbine
CHP	Combined Heat and Power	MRC	Micro Rankine Cycle
DC	Direct Current	PEM	Proton Exchange Membrane
DSP	Digital Signal Processor	PV	Photo Voltaic
FC	Fuel Cells	SE	Stirling Engines
ICE	Internal Combustion Engine	TPV	Thermo Photo Voltaic

1.1. Aim of this work

The aim of this paper is to illustrate a multi-source integrated micro-CHP energy system conceived, designed and almost fully installed at the laboratory of the University of Bologna. Moreover, a preliminary investigation of the expected performance is shown in this study. The paper is organized according to the following points:

- Description of the existing FC-based micro-CHP test bench
- Design of the test bench upgrading by integration with a MRC
- Comparison of commercial MRC units
- Description of the expected micro-CHP performance

The final aim of this preliminary paper is to illustrate a potential design arrangement of a multi-source integrated micro-CHP system, comprising different prime movers, which could be able to fulfill electric and thermal demand of small scale users, in the framework of distributed generation approach. The system will be used in the future to test the micro-CHP system in various operating conditions, by generating demand loads corresponding to "on-field" operation and measuring actual performance and energy fluxes exchanged between the subcomponents.

2. Description of the existing FC-based micro-CHP test bench

A preliminary micro-CHP system was originally implemented in our laboratory according to the layout depicted in Fig. 1. This first system comprises a FC based electric energy generator as main prime mover, a H_2 storage tank feeding the FC, a DC/AC converter, a Photo-Voltaic (emulator) electric energy generator with inverter, an electrochemical storage subsystem and an electric absorber (load emulator). The distributed energy sources and the electric loads are connected by means of power electronic interfaces to a common AC bus. The electric micro-grid shown in Fig. 1 is based on a bidirectional converter, connected to the AC bus and providing maximum flexibility of operation, with FC, PV emulator, battery and, eventually, external net, all connected to the electric load emulator (active and reactive load), in order to be able to cover the imposed load demand. Moreover, the FC cooling system was connected to a thermal energy sink (namely a heat exchanger discharging heat into a large water tank), in order to simulate the thermal load absorption by the user.

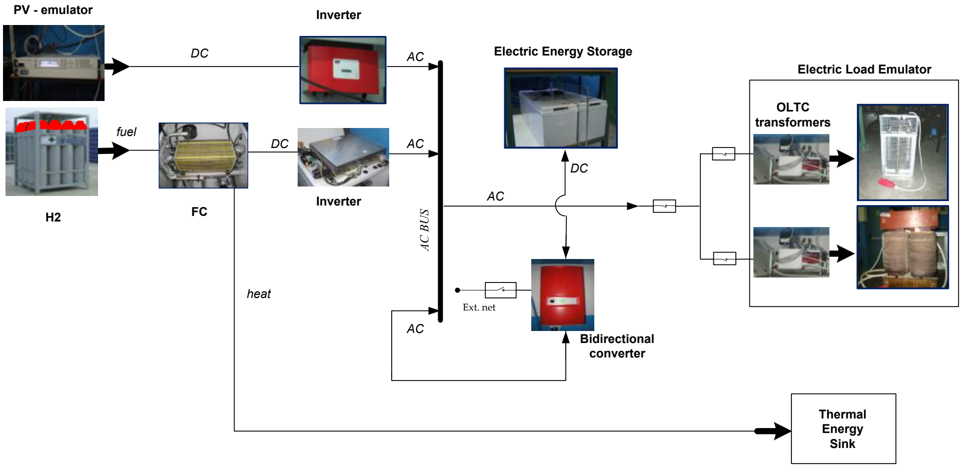


Fig. 1. The existing FC-based micro-CHP system

In order to collect data on the operation of the system described above, a test bench was developed, based on the implementation of real-time embedded microcontroller, namely a National Instrument CompactRIO^{TM} system [13], used to acquire signals from sensors and to control the main input variables of the FC system and of the circuit breakers status. More in details, the sensors implemented to measure electric and thermal power flows are provided in Table 1, while Fig. 2 shows the input/output signal at the microcontroller. In order to simulate the external loads of different kind of users, a dedicated National Instrument control board is employed able to generate different load scenarios.

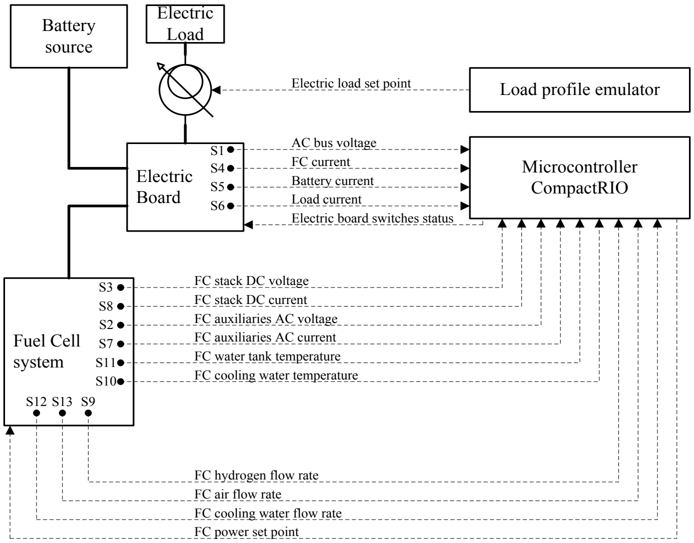


Fig. 2. The test bench and data acquisition system layout

Table 1: installed sensors

Sensor	*Type*	*Measured quantity*
S1	LEM LV25-P voltage transducer	AC bus voltage
S2		FC AC Aux. voltage
S3		FC stack DC voltage
S4	LEM LA100-P current transducer	FC AC current
S5		Battery current
S6		Load current
S7		Aux. current
S8	LEM LA200-P current transducer	FC DC current
S9	BRONKHORST H2 El-Flow thermal flow meter	H2 mass flow
S10	K-series thermocouple	Cooling water ΔT
S11	J-series thermocouple	FC inlet Temp.
S12	McMILLAN Turbine FLO-SENSORS	Water mass flow
S13	GL gx Turbine flowmeter	Air mass flow

By means of the above illustrated test bench system, a 5 kW PEM FC stack has been detailed tested in previous studies of the authors [14,15] obtaining the CHP performance of the system. A summary of performance result and auxiliaries losses is provided in Table 2. This system is capable of a net electric efficiency equal to 36.6% and the maximum recoverable thermal power is equal to 4.5 kW, allowing to obtain a positive PES value, equal to almost 28%. Moreover, part load CHP performance had been acquired in [14], showing positive PES values, for part load conditions up to 30% of the electric load.

The 500 W PV emulator can be switched-on or -off, in order to simulate the perturbation introduced by a PV panel into the grid. The electric energy storage is composed of four lead acid 12 V batteries for a total capacity of 100 Ah. The storage has been introduced in order to compensate the mismatch between load demand and FC-PV production. Nevertheless, flexibility can be further enhanced if additional sources are included, due to limited capacity of the storage.

Table 2: FC power contributions and performance values at design operating conditions

Power contribution @ full load	*Value [W]*	*Performance indicators @ full load*	*Value [%]*
Input fuel power	12056	Stack efficiency	51.7
FC AC output power	4410	Fuel utilization factor	94.3
FC DC output power	5875	Electric efficiency	36.6
FC inverter losses	886	Inverter efficiency	84.9
Auxiliaries power lossses	579	Auxiliaries efficiency	88.4
FC teoric available heat	5492	Thermal efficiency	37.6
Heat recovered	4538	*Primary Energy Saving index*	27.8

3. Design of the test bench upgrading by integration with a MRC

One of the aims of this study is to implement and test multiple innovative micro-CHP systems. In order to improve the existing test bench, by including a different renewable source based on a biomass derived fuel input, the above described system has been further enlarged with the implementation of a Micro Rankine Cycle (MCR). The conceived multi-source system is described in Fig. 3. The connection of a MCR to the aforementioned microgrid requires to introduce an additional inverter, linking the additional source to the existing AC bus in operation. Moreover, additional required auxiliaries are: the biomass boiler providing heat to the MRC; the cooling system allowing to discharge unused low temperature heat, when it is not required by the thermal user or stored in the thermal storage. A thermal energy storage system will be also introduced, to collect residual heat from the FC cooling system and from the MRC condenser.

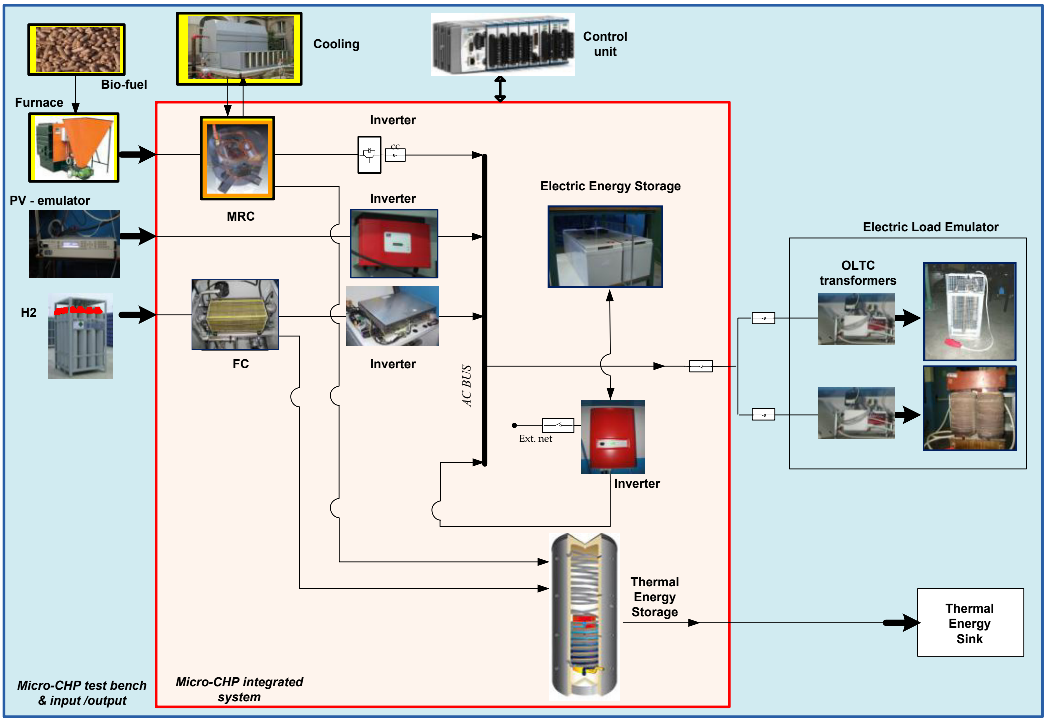


Fig. 3. The conceived integrated multi source micro-CHP system.

The above mentioned components have been sized, in order to fulfill the thermal/electric need of a hypothetic small size user in the civil sector. In particular, a market analysis on commercial/under development MRC units has been carried out, identifying the available systems mainly in the range of power output 1-50 kW, and collected in Fig. 4. Various prototypal or early commercial machines have been identified, characterized by nameplate electric efficiency values ranging between 5% and 13%. For all these MRCs the inlet temperature is quite low, ranging in most of the cases between 80°C and 150°C (Fig. 5) and the expander technology is mainly a volumetric expander or a radial turbine. Among these systems, the MRC selected in this study, consistent with a domestic single user, is a 3 kW unit, capable to be coupled with a 35 kW biomass boiler. The nominal efficiency data provided by the manufacturer is close to 10%.

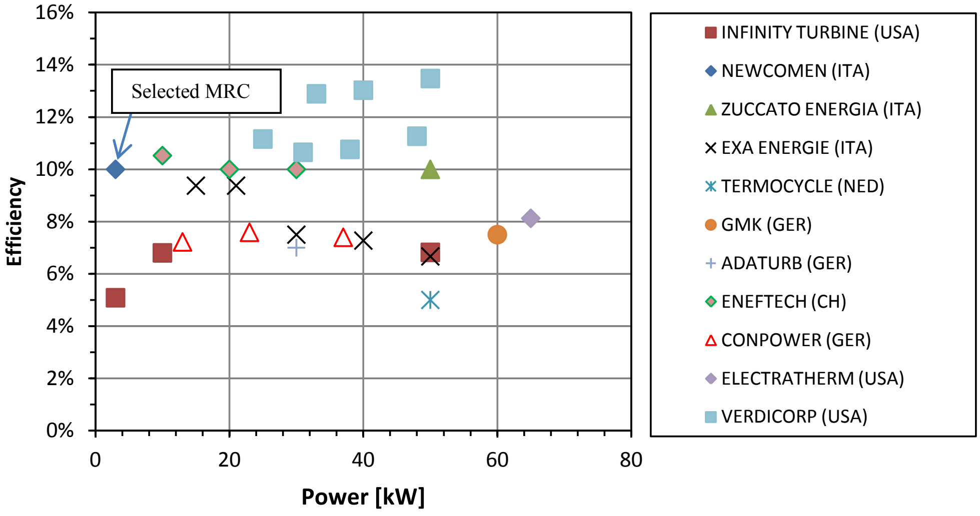


Fig. 4. Overview of commercial MRC units power size and nominal efficiency.

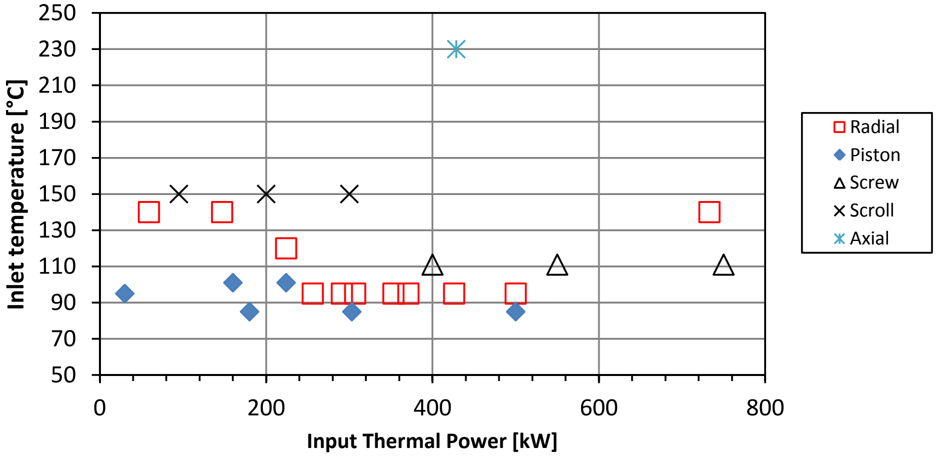
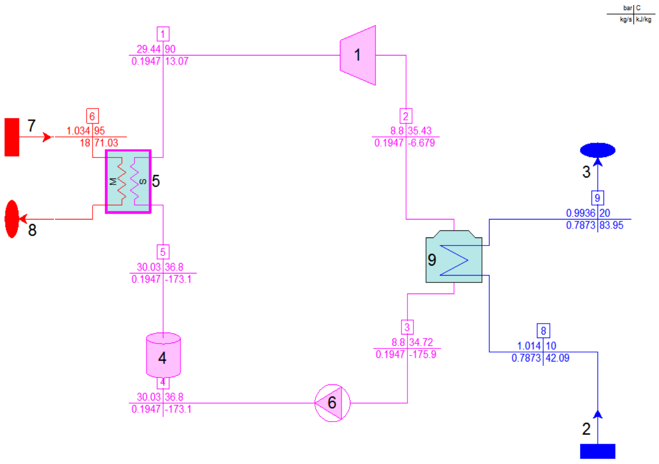


Fig. 5. Overview of commercial MRC units thermal input power and efficiency with different expander technology.

The MRC thermodynamic performance and a calculation of the internal fluid state variables have been simulated with an in-house developed code which makes use of a database of thermodynamic properties for the organic fluids [16]. Moreover, the layout has been implemented into Thermoflex software [17], in order to simulate the thermal balance at the MRC components and to obtain the main sizing parameters of the heat exchangers. The key components of the MRC are the expander, the evaporator, the condenser and the circulation pump of the internal fluid. A MRC performance estimation has been carried out on the basis of available data from the manufacturer and reported in Table 3. In particular, the operating fluid is R134a, and the evaporation and condensation pressure of the organic fluid have been set taking into the expander inlet temperature of the vapor equal to 90°C and the condensation temperature equal to 35°C. Other data not available have been assumed: the organic fluid superheating has been set to 5°C, the expander isentropic efficiency and the pump efficiency have been estimated in line with larger ORC units. Figure 6 shows the schematic layout and calculated flow thermodynamic properties in key sections of the MRC plant and the corresponding T-s diagram is shown in Fig. 7.



	1	2	3	4	5	6	7	8	9
bar	29.44	8.8	8.8	30.03	30.03	1.034	1.013	1.014	0.9936
C	90	35.43	34.72	36.8	36.8	95	93	10	20
kg/s	0.1947	0.1947	0.1947	0.1947	0.1947	18	18	0.7873	0.7873
kJ/kg	13.07	-6.679	-175.9	-173.1	-173.1	71.03	69	42.09	83.95

Fig. 6. Layout of the considered MRC and thermodynamic values

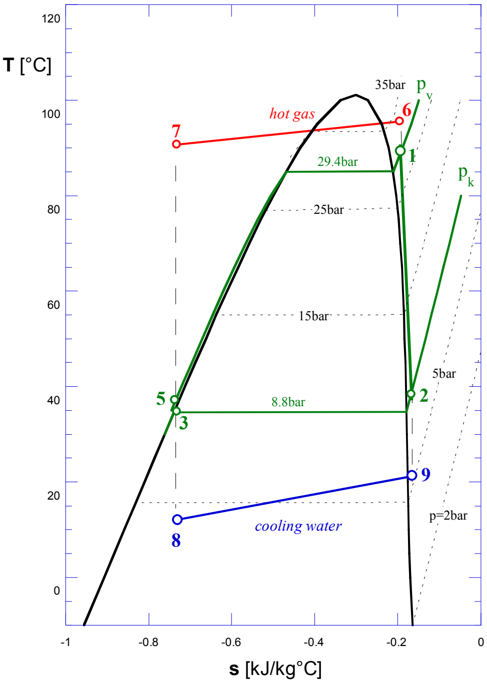


Fig. 7. T-s diagram of the cycle – fluid is R134a

Table 3: MRC thermodynamic simulation main input/output data

input	*Value*	*Output*	*Value*
Evaporation pressure	29.4 bar	Expander power	3.81 kW
Condenser operating pressure	8.8 bar	Input thermal power	36.2 kW
Expander inlet temperature	90 °C	Pump required power	0.579 kW
Expander isentropic efficiency	85%	Generator power loss	0.131 kW
Pump efficiency	85%	Net power output	3.10 kW
Mechanical efficiency	99%	Net electric efficiency	8.5 %
Generator efficiency	96%	Organic fluid mass flow rate	0.195 kg/s
Heat exchangers heat losses	1%	Thermal power to condenser	32.96 kW
Heat exchangers pressure drop	2%	Condensation water mass flow	0.787 kg/s
Condensation water ΔT	10°C		

A simple parametric investigation has been carried out on the effect of the cooling water temperature on the MRC performance. This is an important investigation for the test bench in study and for the future application, as the available cooling water parameter could change depending on the season. Moreover, the effect of the expander efficiency, not yet identified experimentally, has been changed in the simulations. Results are shown in Fig. 8; according to this investigation, the expected actual MRC performance can change significantly around the previously obtained efficiency value equal to 8.5%, with ±3 percentage points of excursion. In the following of this paper, the mean value of the MRC efficiency has been considered.

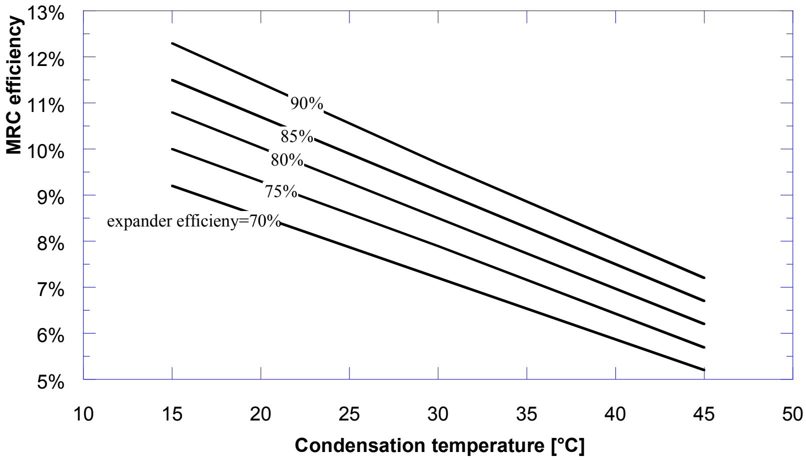


Fig. 8. Parametric investigation on the MRC condenser temperature and expander isentropic efficiency

4. Expected operation and performance of the integrated micro-CHP system

The above described multi source micro-CHP system performance has been simulated in a simple case, considering a specific application scenario, corresponding to a group of residential users. The daily electric load profile of the users is shown in Fig. 9, from [18,19].

This demand has been considered fulfilled by the different sources available in the test-bench, according to a simplified management logic, in order to decide the source operating mode. A calculation routine has been developed to simulate the system operation and the energy flows between components. More in details, the FC and the MRC are considered operated in on-off mode, avoiding part load conditions, and the PV-emulator reproduces a simplified realistic daily solar production, with peak production in the central hours of the day, considering central Italy during winter period. In this preliminary study, the assumed simplified management logic, considers to fulfill the difference between the user electric demand and the PV production profile, by using: (i) the FC, (ii) the battery, (iii) the MRC and (iv) the external net. This is the order of priority in generation, in order to fulfill the power demand. If a power surplus occurs when the FC or the MRC are switched on, then the residual electricity is stored into the battery and secondly provided to the external net. If the battery State of Charge is lower than 100%, then the surplus of FC and/or MRC are used firstly to charge the battery.

The actual contribution of each source to the user electric demand is shown in Fig. 10. In particular, the demand is covered mainly by the FC, than by the battery and finally by the MRC. The contribution of the PV is limited and not programmable, while a small contribution from the external net is required. The developed routine, introduced here and briefly described, will be used to test different operating sequence with various priorities and to optimize the system performance.

Conclusion

A complex multi-source micro-CHP system has been implemented in our laboratory. The system is available and it will be further improved, as described here, for different test campaigns The management system is under development, in order to define the optimum operating logic. A preliminary performance investigation has been carried out and limited results here shown will be extended in the near future.

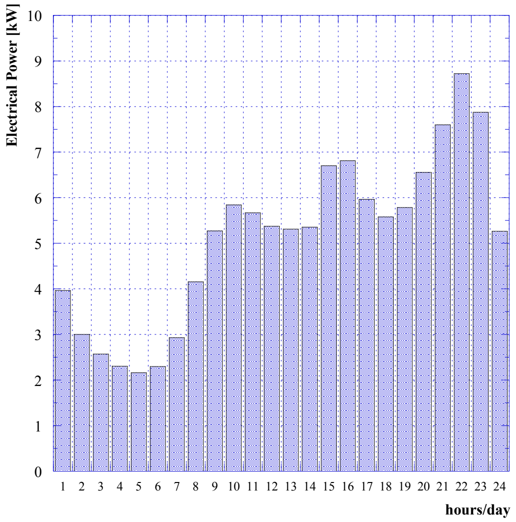


Fig. 9. User demand profile

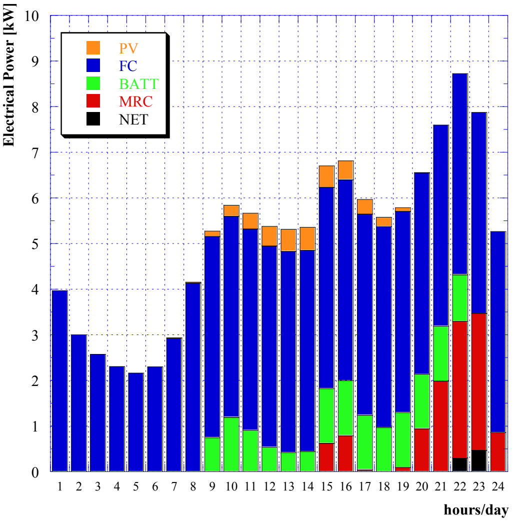


Fig. 10. Operation of the different sources – daily profile

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