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Demonstration of a residential CHP system based on PEM fuel cells

G. Gigliucci[a,*], L. Petruzzi[b], E. Cerelli[c], A. Garzisi[b], A. La Mendola[d]

[a] *Enel-Ricerca, via Andrea Pisano 120, Pisa 56122, Italy*
[b] *University of Pisa, Pisa, Italy*
[c] *University of Genova, Genova, Italy*
[d] *H-Power, St-Laurent, Quebec, Canada*

Abstract

Fuel cell-based CHP systems are very attractive for stationary energy generation, since they allow production of electricity and heat in a decentralised, quiet, efficient and environmentally friendly way.

As a means of evaluating this new technology, Enel Produzione installed a beta-version fuel cell CHP system, supplied by H-Power, at its experimental area sited in Livorno (Italy), and submitted it to a series of tests. The system is a co-generative unit, converting natural gas into electricity and heat: the former is delivered to local loads using electric load following capability; the latter is delivered to the experimental area hydraulic refrigeration circuit.

Experiments were aimed at assessing the suitability of this kind of system to supply Italian residential customers. Factors such as performances, flexibility and operational requirements were evaluated under all the possible operating conditions, both under grid connected and stand alone configurations.

At the same time, a mathematical model of the FC/CHP unit was developed to allow for the prediction of system performances and operating parameters under off-design conditions. This model can be used as an effective tool to optimise system operation when a particular customer has to be supplied.

Results show that the prototype behaved as expected by a first "proof of concept" system and outline improvements to be achieved in order to satisfy the energy needs of small residential applications.

Keywords: PEM; CHP; Testing; Modelling

1. Introduction

Fuel cell-based CHP systems are very attractive for stationary energy generation, because they are expected to allow high primary energy savings thanks to the high electric efficiency guaranteed by fuel cells in their entire load range and to the co-generation intrinsic benefits. However, nowadays the market offers only prototype units which are used to demonstrate the potentiality of this kind of systems and to optimise their configuration in view of commercialisation in the near future.

Enel Produzione installed a beta-test co-generative system, supplied by H-Power, at its experimental area sited in Livorno (Italy), and submitted it to a test campaign aiming at the assessment of actual and foreseeable performances of the system and as well as operation requirements of this kind of apparatuses.

Moreover, a mathematical model of the entire system was developed, in order to predict technical and economic evaluations of the suitability of FC/CHP systems to the requirements of different customers.

In the present paper, results from the experimental tests are presented together with those predicted by the model. Furthermore, effects of possible system modifications on performances are discussed.

2. System description

The system under analysis is the H-Power RCU 4500v.2, which is a natural gas-fed beta-test co-generative unit able to produce, at nominal conditions, 4 kW of electric power and 6.8 kW of thermal power. The former is delivered either to local loads or to the electricity grid, while the latter is transferred to the user by means of warm water at about 60 °C. The unit is equipped with a set of batteries enabling load tracking and peak loads up to 10 kW for 15 min and 20 kW power spikes.

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[*] Corresponding author. Tel.: +39-050-618-5580;
fax: +39-050-618-5985.
E-mail address: gianluca.gigliucci@enel.it (G. Gigliucci).

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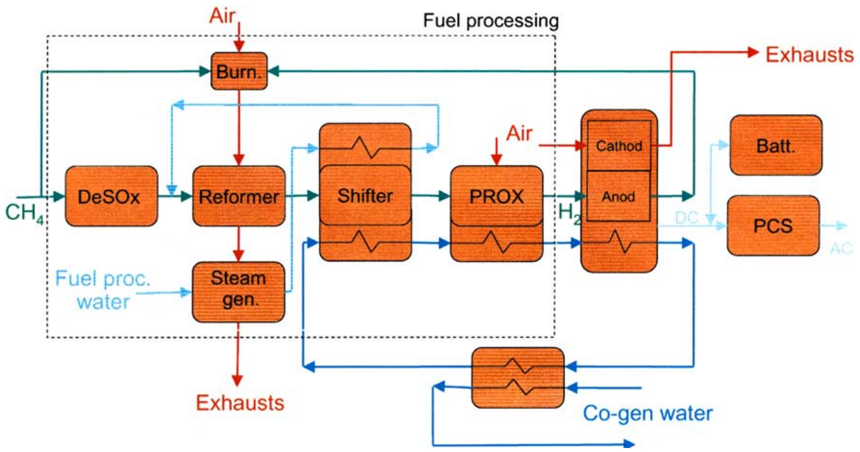

Fig. 1. Sketch of the RCU 4500v.2.

Fig. 1 shows a sketch of the system, which is made up of five main sections:

- the fuel processor, which converts natural gas into a hydrogen-rich mixture;
- the fuel cell stack, which generates dc current from hydrogen–oxygen electrochemical reaction;
- the power conditioning system, which converts the dc current into ac current suitable for grid connection;
- the co-generation system, which transfers the heat generated by the fuel processor and the stack to an external water circuit by means of a liquid-to-liquid heat exchanger;
- the set of batteries, which allows system load tracking and peak power.

In addition, the unit is provided with an industrial PC to take care of data acquisition an recording and automatic control during all the phases of operation.

Finally, the de-ionised water required for steam production is provided by an external de-ionising system.

The fuel processing section is the largest section of the whole plant, due to both the complexity of the fuel conversion process and to the high sensitivity of the polymer electrolyte fuel cells (PEFC) to CO and sulphur compounds. It constituted of the following parts:

- the fuel clean-up section, where sulphur, halogens and ammonia are removed to avoid damages on cell catalysers;
- the fuel reforming section, where natural gas is converted into hydrogen and carbon monoxide;
- the shifter, where carbon monoxide and steam give rise to additional hydrogen and carbon dioxide;
- the preferential oxidation unit (PROX), where the CO residues are oxidised to CO_2, in order to feed fuel cells with less than 10 ppm CO, as required by PEFC technology;
- a condensing cyclone to remove the excess water from the reformed fuel.

System nominal performances are the following:

- Net electric power: 4 kW
- Peak electric power: 10 kW (15 min maximum), 20 kW (few seconds maximum)
- Thermal power: 6.8 kW
- Outlet water temperature: 60 °C
- Net electric efficiency: 18%
- Net total efficiency: 50%

The size of the overall system is 1.6 m × 1.2 m, 1.4 m height and its weight is about 1400 kg.

3. Mathematical model

The steady state model of the whole system was built by integrating a stack model written in FORTRAN language within Aspen Plus®, where the balance of plant (BoP) was implemented considering all the subsystems shown in Fig. 1 but the battery set.

The model aims at the prediction of PEFC/CHP performances along their entire load range, once their behaviour at nominal conditions and their main operating parameters are known. Indeed, this would allow technical and economic analysis on the suitability of a generic system to specific customer's demands (i.e. electric and thermal requirement profiles) to be made.

The stack is described zero-dimensionally, therefore no spatial variation of its physical properties is considered, neither inside a single cell, nor between the 120 different cells. This assumption, which could lead to unreliable predictions in the case of solid oxide cells (SOFC) as highlighted by [1], is not far from reality for polymer electrolyte fuel cells and, in particular, for the one analysed in the present paper. In fact, the stack operates at about 60–65 °C and the cooling water has a difference between temperatures entering and leaving the cell of about 5 °C only.

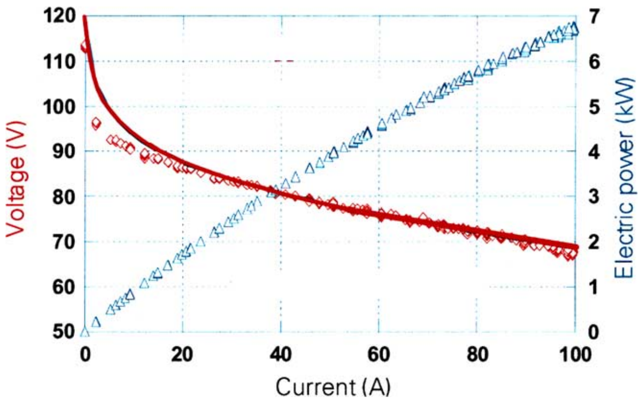

Fig. 2. Stack model validation. Model results are shown using the continuous line.

During the first phases of the work, a two-dimensional stack model was developed in order to evaluate the improvements in prediction capability, but results confirmed that the zero-dimensional approach was able to give the best compromise between prediction accuracy and model complexity.

The other main hypotheses which were adopted to build the stack model are the following ones:

- the stack operating temperature is assumed equal to the mean value between that of the water entering the stack and that of the water exiting it;
- concentration polarisations are neglected, because stack normal operation is far from the region where these phenomena occur.

Input values for the stack model are the following: cell temperature, number of cells, active area of each cell, cathode, anode and electrolyte thickness', cathode, anode and electrolyte resistivity, fuel and air mass flows, fuel composition, generated current.

Using those inputs, the stack model calculates composition of the gases leaving the stack, ohmic and activation polarisations, working voltage, electric and thermal stack efficiencies and fuel utilisation factor.

The stack model was validated using results recorded on the real system: its good accuracy is visible in Fig. 2.

The BoP developed using Aspen Plus® allow the whole system to be simulated, taking advantage of the software ability to work with gases with generic compositions.

The model was tuned at nominal stack operating performances, then off-design performances were predicted.

4. Results

The unit demonstrated the ability to operate autonomously in the entire range of electric load. The electric connection that was chosen is the "grid connected" operation, which allows the electricity to flow only from the grid to the unit when required, but prevents any flow in the opposite direction. Thus, the unit tracks the load when it is lower than the maximum continuous power allowed, while grid support is used in case of higher loads for long periods of time. Thermal power, which is delivered in the form of hot water, was collected by the refrigeration circuit which is installed at Enel experimental area.

In this configuration, system control, especially as far as stack power is concerned, is based on the required electric load and on the battery level, which is kept within a fixed range. In addition, natural gas reforming process is controlled in order to keep the process temperatures within the appropriate levels, since this assures the appropriate fuel quality (i.e. the reactions are thermodynamically controlled).

The main critical parameter for the correct operation is the stack voltage, which must be greater than a minimum safety value depending on the stack current in order to prevent cell damages. Indeed, low voltage can indicate insufficient membrane humidification or lack of hydrogen feeding the cell as well as permanent damages on the membrane itself [2].

Data acquisition is performed by the industrial PC the unit is equipped with once a second. The results shown in the present paper are the mean of the recorded data in the periods (viz. 15–30 min) of stationary operation at electric load values from 1 to 5 kW, which is the entire range of continuous operation.

No noticeable decays in system performances have been observed after about 550 working hours.

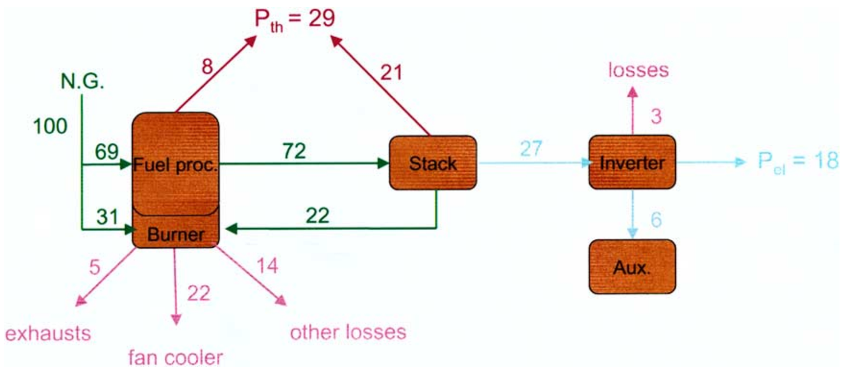

Fig. 3. Power flows at nominal conditions (i.e. 4 kW electric load).

Power flows inside the system at nominal conditions are shown in Fig. 3. The values shown were obtained by field data as well as by energy balances applied to single components.

Power flows highlight large amounts of losses associated to the fan cooler, which is a fan used to cool down the processed fuel leaving the shifter from about 70 °C to about 50 °C in order to condense the steam and remove the water from the fuel. The amount of heat lost is noticeable due to the high steam to natural gas ratio used in the reforming process, which is necessary to allow an almost complete conversion of methane into hydrogen.

In addition, fuel utilisation factor is quite low, i.e. around 70% at nominal conditions, therefore a noticeable amount of hydrogen is recirculated to the burner and feeds the fuel processing unit.

Exhaust gases coming from the burner are released at about 250 °C and some 5% of losses are associated to them.

Stack electrochemical efficiency is quite good as far as a beta-version system is concerned, being around 54% and the largest contribute to co-generation is the heat recovered by cooling the stack.

Fig. 4 shows efficiency curves of both the fuel processor and the stack versus net load generated by the system. Fuel processor efficiency curves, i.e. hydrogen conversion efficiency (FP_{H_2}) and thermal efficiency (FP_{th}), are related to the total amount of energy entering the system (viz. both the natural gas and the recirculated hydrogen are accounted for), while stack electric and thermal efficiency curves are related to the chemical energy of the fuel entering the stack itself.

The figure highlights that almost constant fuel utilisation factor are used within the stack, but when load is decreased down to 1 kW the value falls sharply. This reflects directly on the fuel cell electric efficiency; indeed, when power is reduced the stack becomes more and more efficient thanks to the reduced parasitic losses, but the sharp decrease at 1 kW counterbalance this benefic effect.

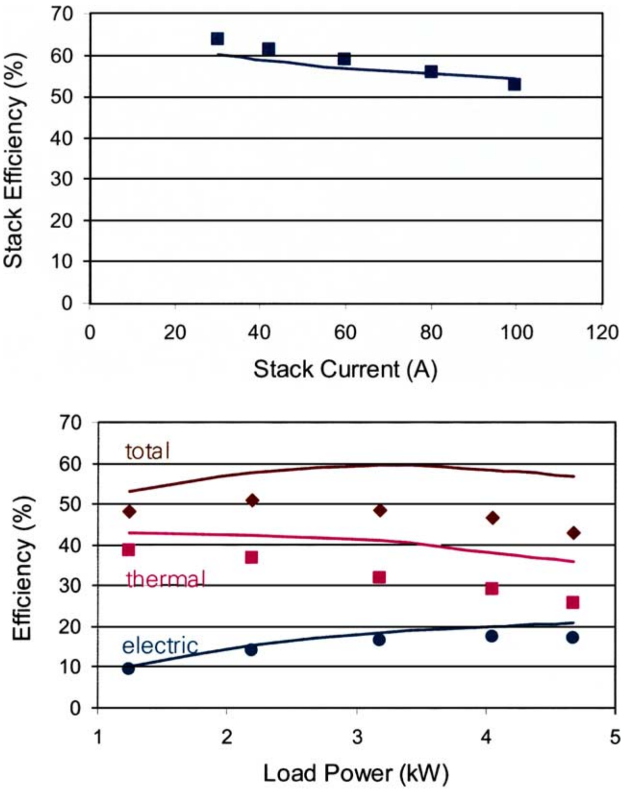

Fig. 5. System global performances vs. electric load.

The higher the electric load is, the better the fuel conversion is performed. In fact, load reductions are controlled by reducing natural gas mass flow, but almost constant steam mass flow is used in the entire load range. This means that the amount of energy required to produce steam is proportionally increasing when power is reduced, causing a decrease in hydrogen conversion efficiency. A portion of the excess steam is recovered and used for co-generation, therefore fuel processor thermal efficiency grows with power reductions.

As far as the stack is concerned, Fig. 5 shows its electrochemical efficiency (i.e. the ratio between the electricity

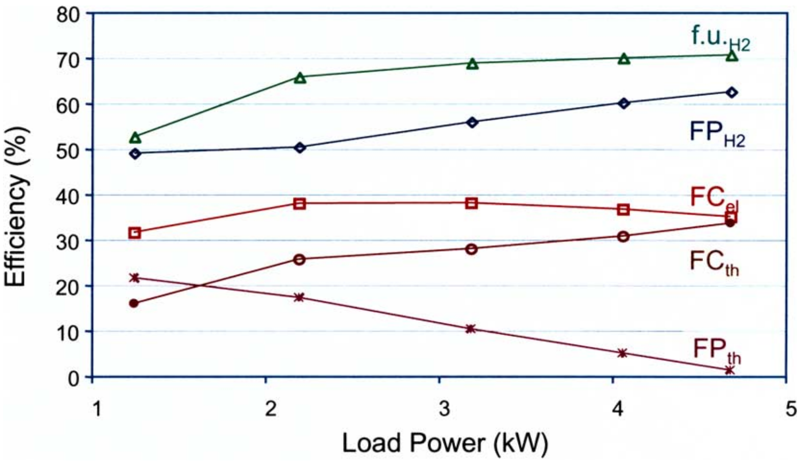

Fig. 4. Efficiency of the main system components at different electric load.

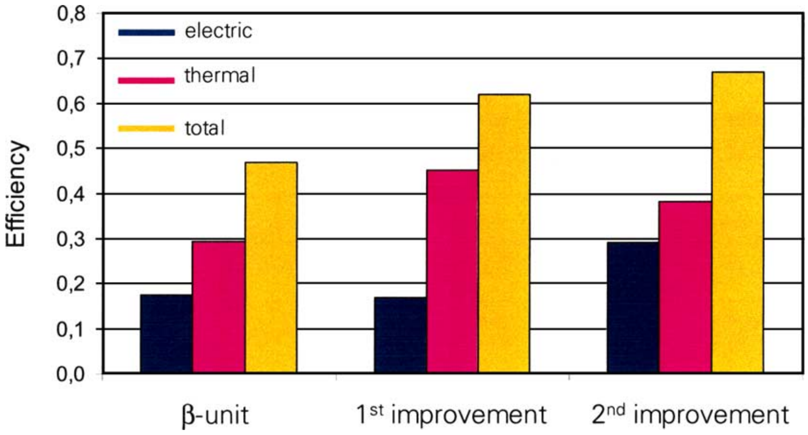

Fig. 6. System global performances following to improvement actions.

generated and the hydrogen consumed) against electric load. Experimental results are shown using points, while model predictions are drawn with the continuous line. Stack electrochemical efficiency at nominal conditions is the value which was used to tune the whole system model.

The assumption of uniform stack operating conditions was verified by means of direct single-cell voltage measurements: in fact, differences between voltages of sets of 10 cells were limited to some 0.1 V.

System global behaviour is shown in Fig. 6, where electric, thermal and total efficiency curves are plotted against load net power, both as for experimental results and model predictions.

System net electric efficiency is almost constant from full load down to 50% load, while at lower power values the decreases in both the fuel processor efficiency and the fuel utilisation factor get global electric efficiency to decrease. Thermal efficiency is increased at low loads, mainly due to the proportionally larger amount of heat recovered by the excess steam introduced in the fuel processor. Thus, system total efficiency slightly increases when the power is reduced.

Absolute efficiency values are quite small, but the results are related to a first “proof of concept” system, which has great possibility to be improved, as shown in the next paragraph.

The mathematical model results shows good prediction capabilities as far as electric performances are concerned, while it is to be improved as for thermal management.

5. Performance improvements

β-Prototype system global performances are quite small, being of the order of 18% for electric efficiency and 30% for thermal efficiency at nominal conditions. However, improvements in those values are achievable by addressing at the main sources of losses described in the previous chapter.

As far as improvements acting on thermal efficiency only are concerned, complete steam condensation and heat recovery from burner exhaust are two possible way of increasing system performances by introducing new components without modifying the existing process.

Firstly, a large amount of heat is lost in the steam condensation taking place in the fan cooler, as shown in Fig. 3. The main portion of this heat can be recovered by introducing an appropriate heat exchanger cooling the fuel down to 30 °C, thus recovering almost all the heat released by water condensation.

In addition, exhaust gases leaving the reforming section are released at about 250 °C. The sensitive heat associated to their temperature is about 1.1 kW, therefore ad additional heat exchanger cooling them down to about 80 °C could recover more than 0.7 kW for co-generation.

Furthermore, actions aiming at increasing electric efficiency can be optimisation of steam to natural gas flow ratio, increase in fuel utilisation factor and hydrogen management optimisation.

As anticipated above, steam flow is almost constant despite any load variation, therefore steam to methane flow ration at part-load reaches very high levels and, consequently, a larger and larger amount of energy is required to vaporise water that is not used in the reforming reactions when power is decreased. A control in the steam mass flow enabling an almost constant steam to fuel ratio at all the operating conditions will therefore allow higher electric efficiency values even at part-load.

Fuel utilisation factor is at present quite low, i.e. around 70% for almost the entire operating range. Nowadays PEFC stacks are able to achieve values around 85%, provided that the appropriate membrane humidification is continuously guaranteed. Therefore, experience earned during tests on β-prototype could allow next units to be operated with higher fuel utilisation, without particular requirements on stack performance improvements.

Finally, a considerable amount of hydrogen is recirculated to the burner, where its chemical energy is used for additional methane to hydrogen reforming. In principle, at least a portion of it could be reintroduced in the anode, thus increasing system electric efficiency, but this modification can be performed provided that the increase in carbon dioxide inside the anode is not detrimental to stack operation.

In order to evaluate quantitatively performance improvements achievable by applying the solutions described above, two improvement actions were considered. The first one took into account increase in heat recovery from steam condensation together with heat recovery from reformer exhausts. The second one summed up the effects of the first action with those related to a reduction in steam to natural gas molar flow ratio down to 3 and an increase in fuel utilisation up to 85%.

Results of the two actions on electric, thermal and total efficiency were calculated by using the mathematical model described above: results are shown in Fig. 6.

It is clear that the first set of improvements acted only on thermal efficiency, whereas the results due to the first and the second sets are a considerable increase in electric power, i.e. from 18 to about 28%, associated to thermal power raising from around 30% up to 38%.

From the practical point of view, steam complete condensation down to 30 °C requires a second co-generation line to be improved, because the mass flow value of the existing one, the water temperature required for the good operation of the stack and the power recovered by additional steam condensation do not match. Indeed, the additional co-generation line would have much lower water flow and could be used as a first stage for external water heating. On the other hand, exhaust heat recovery could be performed by using the existing water circuit with ad additional gas-to-liquid exchanger.

Performance improvements can be usefully evaluated by assessing energy savings achievable by the use of the co-generation plant with the actual performances as well as with the performances due to the improvements with respect to separate generation of electricity and heat from centralised power plants and conventional boilers, respectively.

This can be done taking into account Italian co-generation promotion policy [3], which guarantees fiscal benefits on the natural gas price to co-generation plant provided that they allow at least 10% primary energy saving and that at least 15% of the energy generated is in the thermal form. Energy saving is evaluated using the so called Indice di Risparmio Energetico—IRE (viz. Energy Saving Index), which is expressed as follows:

$$\mathrm{IRE} = 1 - \frac{E_{\mathrm{c}}}{(E_{\mathrm{e}}/(\eta_{\mathrm{e,st}}\,p)) + (E_{\mathrm{t\text{-}civ}}/\eta_{\mathrm{t,st\text{-}civ}}) + (E_{\mathrm{t\text{-}ind}}/\eta_{\mathrm{t,st\text{-}ind}})}$$

where E_{c} is the amount of fuel energy consumed, E_{e} the electrical energy generated, $E_{\mathrm{t\text{-}civ}}$ the thermal energy generated and used for civil purposes, $E_{\mathrm{t\text{-}ind}}$ the thermal energy generated and used for industrial (viz. process) purposes, $\eta_{\mathrm{e,\,st}}$ the standard electricity generation efficiency, $\eta_{\mathrm{t,\,st\text{-}civ}}$ the standard thermal energy generation efficiency in case of civil use, $\eta_{\mathrm{t,\,st\text{-}ind}}$ the standard thermal energy generation efficiency in case of industrial use and p a factor taking into account energy losses due to transmission. All energies are calculated as the total value over a whole solar year. $\eta_{\mathrm{e,\,st}}$ is 0.38, which is the mean electricity generation efficiency of the Italian grid, $\eta_{\mathrm{t,\,st\text{-}civ}}$ w is 0.8, $\eta_{\mathrm{t,\,st\text{-}ind}}$ is 0.9 and p depends on the amount of energy consumed directly on the production site with respect to that delivered to the grid and on the voltage of the grid the system is connected with (viz. high, medium or low voltage). In the case of domestic grid connection without any delivery to the grid p value is 0.935.

The amount of energy savings guaranteed by the CHP system under analysis can be assessed by plotting its operating point characteristics onto an electric efficiency versus thermal efficiency graph together with the 10% IRE lines for the cases of industrial and residential uses of the heat, as done in Fig. 7. In this way, operating points lying above the lines guarantee more than 10% primary energy savings with respect to separate electricity and heat generation, and they would allow fiscal benefits according to Italian legisla-

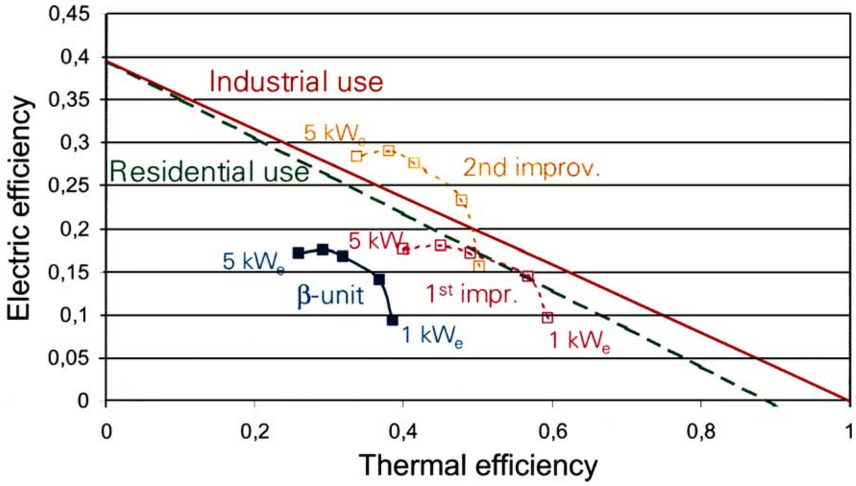

Fig. 7. Primary energy savings of the β-unit tested and predictions following to system improvements.

tion if they represented the mean status of operation over a whole year.

Fig. 7 highlights that the performances of the β-unit which underwent tests do not allow primary energy savings. However, system modifications described above, whose effects are calculated by using the mathematical model developed in the flame of the work, are very effective to increase system performances and allow much more than 10% primary energy savings over the almost entire operating range.

6. Conclusions

To conclude, both experimental results showed that the prototype behaved as expected by a first "proof of concept" system. Indeed, although actual performances are quite low, improvement actions not requiring any significant technological development (i.e. their execution requires conventional components and adjustments in the control strategies) could increase considerably electric as well as thermal efficiencies, so that the system could allow primary energy savings with respect to separate generation much higher than 10%.

The mathematical model developed demonstrated good prediction capabilities, especially as far as electric performances are concerned, and allowed estimation of performance improvements associated to system modifications. In addition, it is an effective instrument to evaluate system suitability to each different customer (i.e. characterised by its peculiar electrical and thermal requirements) in terms of performance expectations and primary energy savings achievable over a whole year.

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