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SOFC Micro-CHP integration in residential buildings

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Abstract:

SOFC technology has reached many of the performance goals that where indicated by scientific society and is providing several application that permits market penetration. One of the main targets is related to Micro Cogeneration Heat and Power (μ-CHP) for residential application. The integration of this system with a residential house has to be deeply investigated to individuate market targets in terms of costs and efficiency. This study evaluates the Italian market condition and analyzes the integration possibility with both thermal and electrical systems. Different solutions are investigated evaluating thermal and electrical driven logic for □-CHP SOFC based unit and the opportunity of integration with local electrical grid. Evaluation on heat and electricity storage was also considered as integration strategy. The study is based on electrical and thermal loads in typical residential users and the evaluation is based on Italian technical standards and guidelines. Several operating conditions were evaluated and compared to obtain an optimized size and integration of μCHP SOFC based solution.

Keywords:

SOFC, micro-CHP, buildings, emission, energy, sustainability.

1 Introduction

This study introduces preliminary analysis of microCHP system integration providing a feasibility study of economical and energetic operative conditions of a unit installed in a real dwelling. Integration can be realized following different strategies but the final aim is to reach economical and energetic convenience of innovative technology compared with traditional ones. The analysis focuses on an example of real apartment and evaluates the methodology to realize a study of integration between the system and the house.

Literature offers many studies on the integration between microCHP and residential dwellings. This study is important to evaluate the economical convenience in different scenarios differing in house typology, integration and tariff strategies. The results, mainly payback time prediction, individuate the target market for the producers and the economical benefits for the householders. Many of this studies are used by government to select the most effective incentive policy. While some authors focus on economical instruments for combined heat and power support [1,2], there is also a deep investigation on energetic and environmental evaluations [3–5] and many case studies, both model and experimental, that focus on the coupling of the system into the house considering real house load profiles [6–10]. The starting point of the study is the analysis of user typology. In Italy there are 11,1 million of buildings that are used for residential purpose. This buildings correspond to an average of 27 million houses, 22 million of which are regularly lived and heated. Main parts of this houses are individual, single family, while the remaining part, 900.000, is composed of multi-family residence [11]. The user is identify also by: number of inhabitants, dimension and location. The number of inhabitants has a direct influence on electrical and domestic hot water (DHW) requirements and is a parameter used to evaluate annual energy request of the building. Dwelling dimension is used to calculate annual heat demand while the geographical location gives indication on the average environmental temperatures that are usually related to heat loads. Ulterior aspects can be identified to have a more complete description of type of user: for example the type of heating system, the insulation of the house and the typology of householder have an important impact on the utilization of the micro-CHP system. In this preliminary study this considerations are not introduced and can be added in further developments.

The integration analysis is based on information on micro-CHP working conditions and dwelling energy requirements.

2 Dwelling requirements

To produce a feasible study of the integration between building and micro-CHP, is important to correctly evaluate the trends of energy requirements of the building. Three main energy flows inlet a typical residential dwelling: electrical energy, heat for domestic hot water (DHW) and thermal energy for heating system. In addition houses usually have other energy inputs, such as natural gas for cooking purpose, but these requirements are not related with the activity of the micro-CHP but directly with the natural gas net.

The energy flow of an house is strongly dependant from both social and physical peculiarities. The habit of the people living the house can vary dramatically the load profile of all the energy flows while dimension and position of the dwelling has main impact into the heating energy requirement. Moreover the flows are also time depending due to some environmental parameters such as external temperature, season, weather condition, day/night and to some social periodic schedule: weekdays, holydays, Sundays.

The most reliable way to study the consumes of the house is the statistical study of existing data, but this information is not always available. It can be directly measured by the energy supplier or from the distributors if they install innovative instruments that measure instantaneously energy flows. This is not yet diffused in Europe and for new buildings this information cannot be provided and an estimation study has to be performed. For existing building the analysis of bills can be realized but usually there is no daily consume because suppliers calculate invoices every two months. This information can be easily obtained and in following part will be considered. Germany already developed a standard [12] that gives indications on the calculation of reference load profiles of single-family and multi-family houses for the use of CHP systems. There are additional ways to define daily load profile of an house. For example in Italy the Authority for Electric Energy and Gas provides gas standard natural gas consume profile as ratio of annual consume. This tables are divided for climate region and user typology (heating, DHW, both). This values are used by distributors to predict energy consume of standard users and to calculate relative costs but don't offer daily load profile minute by minute but permits to calculate daily requirements of heat and of DHW [13].

The annual heating requirement of an house can be predicted in many different ways. There are several commercial software available based on diffused models that calculate heat requirement depending on building insulation, structural conditions, family members and geographical location. Methods and results of this models are not investigated in this study. In addition in Italy there are several laws and standards that define how to calculate the heating requirements of an house for both heating system and domestic hot water. This standards are used to predict the yearly and monthly house requirements and are used to dimension boilers or alternative integrated system such as solar heating. Main inputs of this calculation are house location and total surface. Finally in literature [14,15] is possible to find many European data that can give an average of what are energy requirements of a standard dwelling.

In this study are considered both Italian and German standards, literature values, gas Authority profiles and some measured values. When possible a compare between different method is performed.

3 Integration study

The scheme of microCHP integration in a dwelling is simply depicted in Fig. 1.

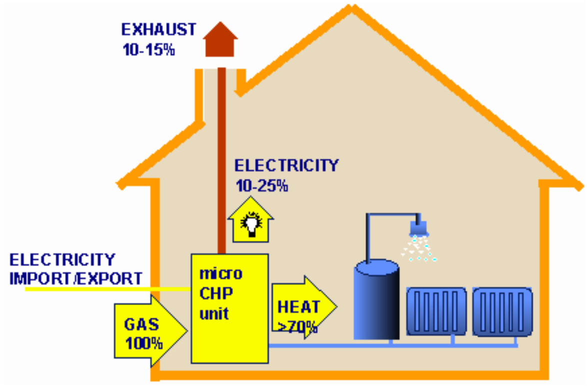


Fig. 1 Integration of micoCHP in the house

The microCHP is integrated in the house as substitution of traditional boiler and supplies energy to the heating system. A secondary boiler, integrated or external, supplies the additional heat required when the microCHP thermal power doesn't reach the building peak requirements. In general the unit supplies heat also to the DHW circuit and a thermal energy storage (TES), similar to a traditional water tank, permits to have a delay between produced heat and used hot water. If correctly dimensioned the TES allows the microCHP to operate at nominal condition most part of time.

A number of CHP operating strategies are present in the reviewed literature. They are mainly related to the tariff contract, to the size of the dwelling loads and to the opportunity of energy storage both for electrical and thermal energy. The two main dispatch strategies are heat led, where the system operates when heat load is required, and electricity led, where the unit operates when electrical load is present. Industries usually develop their products following the heat driven logic in accord also with government lows such as Energy Saving Trust [16] that present electricity as a by-product of microCHP unit heat production. In addition to these simple strategies Hawkes and Leach [17] present a "lead cost" (i.e. optimized) operation where the system is dispatched such as to minimize the cost of operation. The system can also operate so to minimize CO_2 emissions.

Following analysis is realized considering the system operation mode as heat led. The μCHP system operates only to purchase thermal energy when required. This means that there is no need of electricity profiles because all electricity is send to the grid exactly when produced. This choice is related to Italian regulations and grid development stage. The grid connection system can have priority distribution and a net metering tariff scheme. This means that there is no need to produce electricity when required because the balance is realized at the end of the year. If the system consumes all the electricity spent there is no cost for the householder, if the house consumes more electricity of the produced one differences become a cost finally if the production exceeds consumed one the difference can be paid with very small tariff or is add to next year calculation bill. There is no economical convenience in producing more electricity than the consumed one. This means that total year electrical demand is the main border condition when making economical analysis. This consideration is extremely important for selection of system electrical size and corresponding thermal one. Generally this brings to very small scale of plant (1 kWe) that permits also good thermal optimization. If we consider no modulation of the system the unit will operate always in nominal conditions and the total thermal production has to be distributed in operational hours during the all year. Note that this distribution is not required from electricity profile because of priority distribution.

Moreover considering the use of a thermal heat storage, is possible to avoid contemporarily of heat production and consume. The dimension of the storage is related to consume/production delay and total heat produced. In the study a TES able to store all the heat produced daily by the CHP was considered and calculation are realized with 24 hours total heat demand. If this value is higher of total thermal energy produced by the system the unit never stops and operates always at nominal conditions. Without storage the CHP has to go in regulation mode that can bring it to minimum working point (idle) or to shut down. As SOFCs have problems with thermal cycle and have long start-up time the study will focus on reduce on/off cycle. Finally is difficult to imagine CHP system working during summer time when only DHW is required without a storage. DHW consume usually requires high transitional slope with power demand often higher than micro-CHP one. This option is considered as less interesting for this application.

Before analyzing a specific case study some general consideration on the economics and of the integration are performed to investigate the convenience of the system compared to traditional technology. First of all following characteristic are defined:

- η_{eCHP}: microCHP electrical efficiency;
- η_{thCHP}: microCHP thermal efficiency;
- P_e: microCHP electrical power;
- P_t: microCHP thermal power;
- TER: thermal to electrical ratio. This parameter is the ratio between P_{th} and P_e but also between η_{eCHP} and η_{thCHP} as described below;
- OT: operating time. Is the ratio between the year operating microCHP hour and the total one (8760);

If we compare the microCHP with standard production of electricity and heat, we can introduce Primary Energy Save (PES), calculated as the ratio between the primary energy saved over the standard production. Considering:

- E_{CHP}: primary Energy in the CHP (Natural Gas);
- Ee: primary energy for standard electrical energy production;
- Et: primary energy for standard thermal energy production;
- ηe: standard electrical efficiency (50% for Italian standard);
- ηt. standard thermal efficiency (90% for condensing boiler);

and considering following simple equations:

$$E_{CHP} = \frac{P_e}{\eta_{eCHP}} = \frac{P_t}{\eta_{tCHP}} \longrightarrow TER = \frac{P_t}{P_e} = \frac{\eta_{tCHP}}{\eta_{eCHP}} \quad E_e = \frac{P_e}{\eta_e} \quad E_t = \frac{P_t}{\eta_t} \qquad (1)$$

PES calculation follows:

$$PES = \frac{E_e+E_t-E_{CHP}}{E_e+E_t} = 1 - \frac{\frac{P_e}{\eta_{eCHP}}}{\frac{P_e}{\eta_e}+\frac{P_t}{\eta_t}} = 1 - \frac{1}{\frac{\eta_{eCHP}}{\eta_e}+\frac{P_t}{\eta_t}\frac{\eta_{eCHP}}{P_e}} = 1 - \frac{1}{\frac{\eta_{eCHP}}{\eta_e}+\frac{\eta_{tCHP}}{\eta_t}} \qquad (2)$$

Is possible to introduce an equivalent of PES for the economical convenience. Considering:

- €e: electrical energy cost [€/kWh];
- €g: gas energy cost [€/kWh];
- R: €g/€e

Cogeneration Economical Save (CES) is defined as the ratio between the cost saved over the cost of standard solution. Note that electrical energy is valorised after transformation:

$$CES = \frac{€_e{\cdot}P_e+€_g{\cdot}E_t-€_g{\cdot}E_{CHP}}{€_e{\cdot}P_e+€_g{\cdot}E_t} = 1 - \frac{€_g{\cdot}\frac{P_e}{\eta_{eCHP}}}{€_e{\cdot}P_e+€_g{\cdot}\frac{P_t}{\eta_t}} = 1 - \frac{1}{R{\cdot}\eta_{eCHP}+\frac{P_t}{\eta_t}\frac{\eta_{eCHP}}{P_e}} = 1 - \frac{1}{\frac{\eta_{eCHP}}{R}+\frac{\eta_{tCHP}}{\eta_t}} \qquad (3)$$

Table 1 reports PES and CES values of the technology that are the most feasible candidates for microCHP. These are Internal combustion engine (ICE), Stirling engine, polymeric electrolyte membrane fuel cell (PEM) and SOFC based systems. An average indicative value is considered for the efficiencies while R is calculated from Italian electricity and natural gas households price as calculated in Europe Energy Portal [19]. Note that all values are positive, this means that all technologies are more convenient of standard technology both from energetic and economical point of view. Beneath all SOFC remains the most performing solution.

Table 1 PES and CES of different microCHP systems

Technology	η_e	η_{th}	**PES [%]**	**CES [%[**
ICE	0,30	0,60	21	30
Stirling	0,10	0,80	8	13
PEM	0,40	0,50	26	37
SOFC	0,50	0,40	31	42

Finally to evaluate the convenience of the solution the payback time is introduced calculated as the time required to recover with gain the initial cost of the microCHP.

Considering the definition introduced is possible to realize a preliminary sensitive analysis on some of the key parameters. Some of the value, such as initial cost and operating time, are still object of development and investigation, this section aim is only to general consideration on parameters effect. To complete the study three simple parameter referred to building specifics are introduced:

- De: is the dwelling annual electrical consumption;
- Dh: is the dwelling annual heat consumption;
- D_{TER}: is the thermal to electric ratio of the building;

Note that depending on the integration strategies the annual heat consumption can be composed of heating and/or DHW requirement.

To evaluate the optimal size of the microCHP a preliminary study of the impact of operating time was realized. The electrical microCHP size, P_e, was calculated to reach, in operating hours, an annual electrical production of the microCHP equivalent to building requirement. Results are reported in Fig. 2.

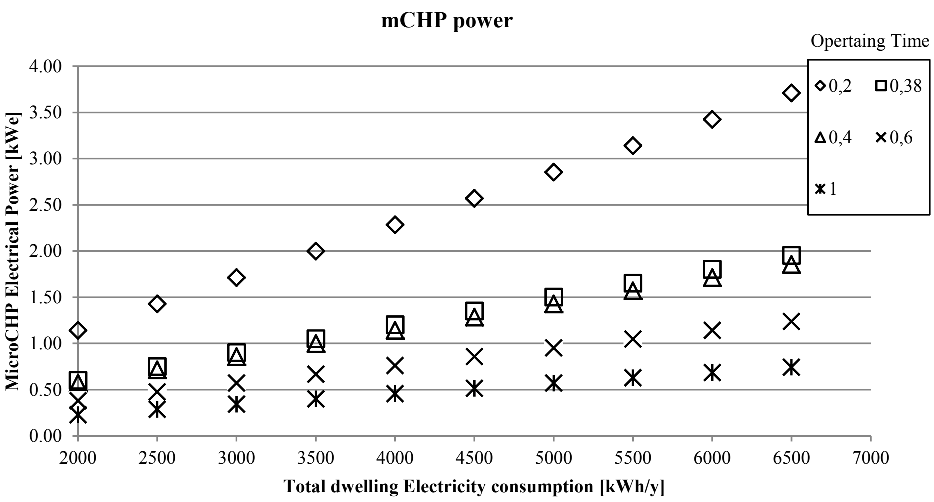
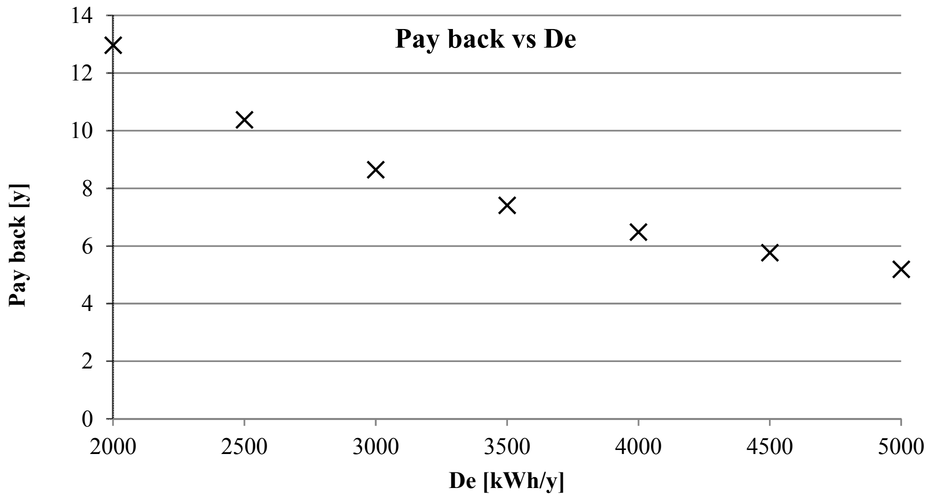


Fig. 2. Electrical power of microCHP for different dwelling consumption and operating time

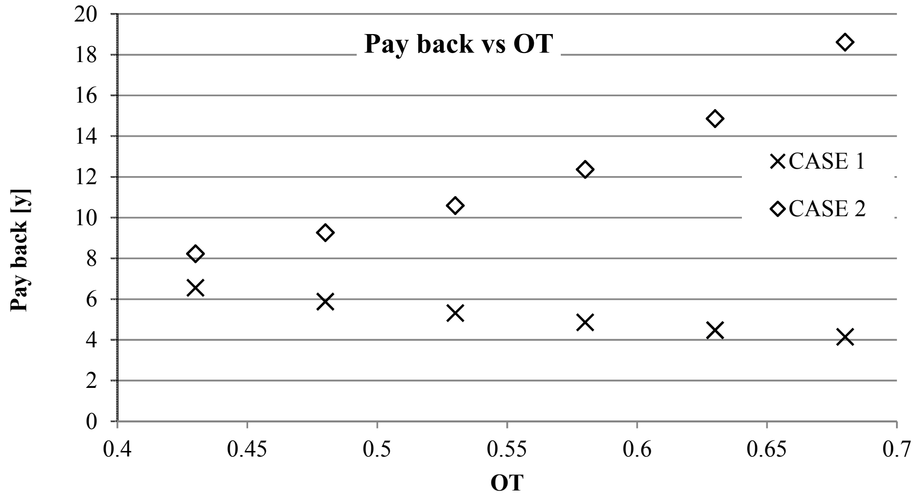
Increasing operating time, the size of the system decreases due to the distribution of electrical production during the all year. Note that operating time of 0,38 is corresponding to the winter season in Italy (128 days), if the system operates 24h a day. Considering that is very unlikely to operate the system full time, OT = 1, the optimal system size is between 1 and 4 kW. If all the heat produced is used a compare between the building and the system thermal to electric ratio has to be considered. In general is better to have an heat production smaller that required one and introduce an additional boiler.

The effect of thermal building request, operating time, initial system cost and electricity cost are described in Fig. 3, Fig. 4, Fig. 5 and Fig. 6, respectively. Under each graph a table reports the values of the parameters that are kept constant. If not specified in the table P_e is calculated as previously described. In Fig. 4 two different cases are presented: in case 1 extra electricity produced is valorised with market cost while in case 2 is considered lost. Is interesting to notice how this aspect strongly effects payback time relation with operating time. If the system operates with no valorisation of current there is no reason to increase operating time that brings to the production of the only heat with η_{tCHP} that is always lower than η_t. This can justify the decision of dimensioning the system with a total electricity value smaller than De. In general the increase of the economical incoming from electricity, via increase of production, increase of electricity value or of operating time, positively changes the payback time. Note that Fig. 6 describes how electricity cost can effect payback time. Same but opposite study refers to gas cost as the ratio between this two values effect the economic analysis [20].



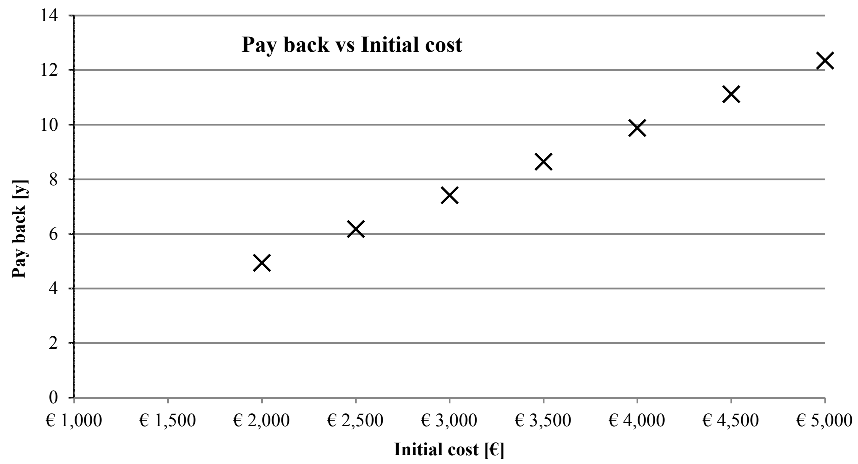
D_{TER}	Uf	TER	ηe	ηt	€e [€/kWh]	€g [€/kWh]	System cost [€]
4	0,38	0,8	0,5	0,4	0,2	0,08	3000

Fig. 3. Pay back vs. Dwelling electrical request



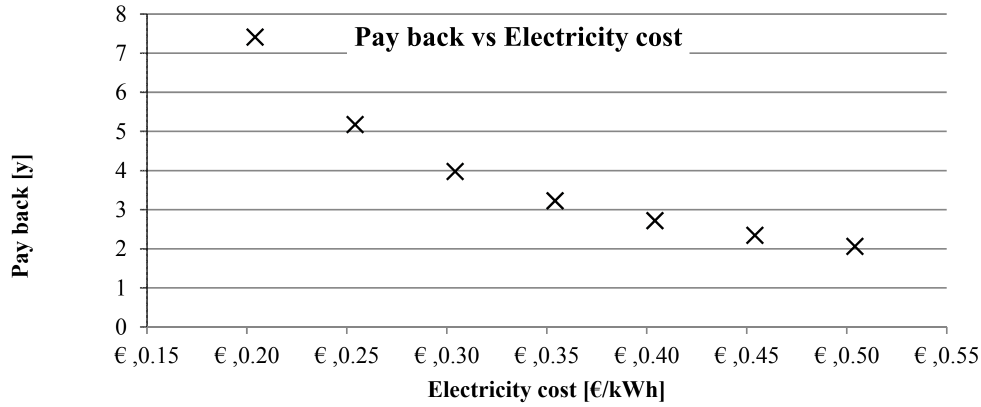
De [kWh/y]	D_{TER}	TER	ηe	ηt	€e [€/kWh]	€g [€/kWh]	System cost [€]
3500	4	0,8	0,5	0,4	0,2	0,08	3000

Fig. 4. Pay back vs. microCHP utilization factor



De [kWh/y]	D_{TER}	Uf	TER	ηe	ηt	€e [€/kWh]	€g [€/kWh]
3500	4	0,38	0,8	0,5	0,4	0,2	0,08

Fig. 5. Pay back vs. microCHP initial cost



De [kWh/y]	D_{TER}	Uf	TER	ηe	ηt	€g [€/kWh]	System cost [€]
3500	4	0,38	0,8	0,5	0,4	0,08	3000

Fig. 6. Pay back vs. electricity cost

4 Case study

Let's consider a single family house, four people, of 100 m^2 located in Italy close to Perugia: climate area C. Total yearly electrical demand, calculated with VDI standard is 1750 x 4 = 7000 kWh/y. Thanks to the study of the bills of a family leaving in the house we can measure a consume of 6300 kWh/y. Both these values appear to be bigger that what is possible to find in literature [21–23]. Following indication of Annex 42 study [21] an electrical consumption of 3500 kWh can be calculated for an European standard household electricity consumption; this value is used in following calculations as the approach is more safe. Domestic Hot Water consume was calculated with several methods obtained from literature [22], VDI and Italian standard. The values are significantly different and vary from the 500 kWh per person per year up to 2000 kWh. To keep a more safe approach, less consume, we consider VDI values of 500 kWh/py with a total of 2000 kWh/y.

Space heating demand is by far the most sensitive data as it varies with the building insulation properties and family living standards. In Ref [15] a study on 193 building of five countries was performed and an average value of 175 kWh/m^2 was calculated. This value can be easily related to this typology of houses and is also consistent with Italian and German standard indications. Total heat demand is 17.500 kWh/y. Main inputs are reported in

Table .

Table 2 Example main inputs

Parameter	Value
Electricity demand [kWh/y]	3500
Domestic Hot Water [kWh/y]	2000
Annual heating energy demand [kWh/y]	17500
D_{TER}	5,6

Trends described by Italian authority was selected for defining demand profile. This data contain the daily percentage of gas average gas consumed for both heating and DHW. Values are grouped for climate area. Considering house location and typology the energy request was calculated as in Fig. 7.

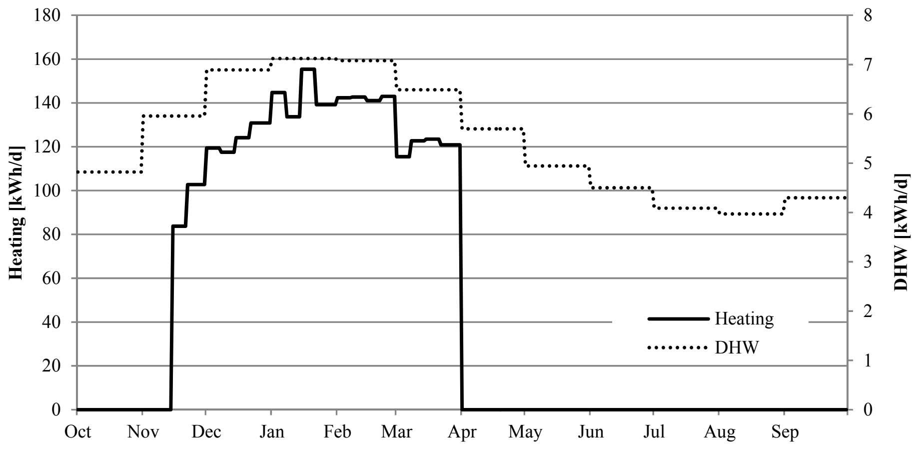


Fig. 7. Heat requirement in one year

The graph shows how the heating period is only during winter time. The exact day are usually defined by local authorities but, in general, are from October 15th to April 1st. Also domestic heat water is not constant during the year and is more concentrated on winter time. Note that in winter time there is a base request of at least 110 kWh/d corresponding to 4,5 kW. Any CHP having a thermal power lower than 4,5 kW can operate continuously during this period. Let's consider a SOFC system, with the efficiency characteristic already presented in Table 1, of 1 kWe and 0,8 kWth. If we consider this unit operating in the house we can build a curve describing operation time during the year. The heat not covered by the CHP is realized with additional boiler. Following graph, Fig 8, presents the load profiles.

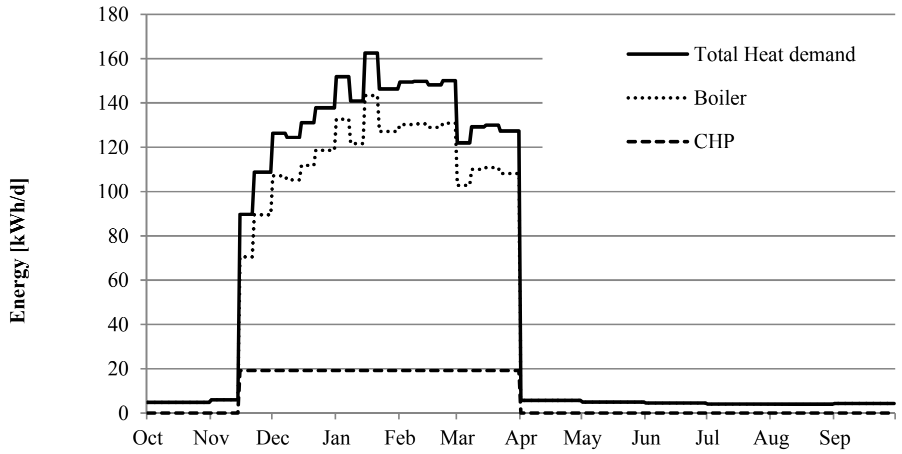


Fig. 8. Load heat profile

We can consider the system operating only during winter time or during the all year following also DHW request. In the second option in summer time the system will operate only the hours necessary to produce required heat that is stored in the water tank. We can imagine that the system operates during the night so that the hot water is ready for daily use. Total operating hours permits to calculate also produced electricity. As previously described this increase of utilization factor gives positive effect only if we give value to extra electricity produced. Table 3 compares three different solutions: only boiler, boiler plus μCHP operating only on winter, and boiler plus μCHP operating all the time. The table introduces a new parameter: ON/OFF cycle, that is calculated as the number of shut down that have to be performed during the all year.

Table 4 Compare of system performances

Annual parameters values	Boiler + μCHP	Boiler + μCHP winter	Boiler
CHP operating hours [h/y]	4.627	3.288	-
CHP heat production [kW/h y]	3.701	2.630	-
CHP electricity production [kW/h y]	3.823	3.288	-
CHP ON/OFF cycle [/y]	229	1	-
CHP operating time	53%	38%	-
Boiler heat production [kW/h y]	15.799	16.870	19.500

This analysis shows how the utilization of winter solution permits to reduce ON/OFF cycles with a reduction of cogenerated heat and electricity. Is important also to notice how the boiler contribution to total heat remains the main one with values always higher of 85% of total energy. Total CHP electrical energy is always smaller than annual consumed.

The economical analysis can be realized considering following:

- Gas cost is evaluated as defined by Italian gas Authority with decreasing cost per unit with increasing quantity [13];
- Boiler is considered with a primary efficiency of 90% as defined for PES calculations;
- Electricity cost is evaluated as the cost of equivalent amount from regulated market as defined by electricity Italian authority [24];

Following Table presents main results. Pay back calculation was realized considering as CHP cost 3.000 € [18]. This is not the present cost of this technology but it is a feasible future market cost.

Table 4 Results of integration case study

Annual parameters values	Boiler + μCHP	Boiler + μCHP winter	Boiler
Annual electricity cost [€/y]	-299	0	1.328
Annual natural gas cost [€/y]	1.256	1.204	2.446
Total annual cost [€/y]	957	1.204	3.774
Annual saved [€/y]	729	482	-
Payback time [y]	4,12	6,62	-
Saved after 10 years [€]	4.228	1.628	-

In the payback time the cost of the additional boiler is not considered because it is a cost also in a traditional solution and is considered in both cases. As expected the best solution is the first one presented in the table but it’s also the farther from the present scenario due to the number of ON/OFF cycle required to the system and the cost equivalence between used and produced electricity.

5 Conclusion

The values of this analysis are extremely interesting and offer an important starting point to perform deeper studies. The aim of this paper was to present a method for projecting the system integration in the building and to give a preliminary evaluation of system convenience. The results are positive and the concept feasibility was demonstrated. A payback time of 4 and 6 years was calculated depending on operating strategies. A deeper study can be realized improving the analysis of house energy demand and of integration logic. Is important also to design the storage and analyze if project working conditions are confirmed. Finally it could be interesting to make a sensitive analysis on the selected value of efficiencies and power and top introduce maintenance costs that can give an additional significant contribution.

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