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Levelized cost of energy (lcoe) analysis of a low temperature PCM thermal storage combined with a micro-CHP in an apartment block

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Abstract

When Combined Heat and Power (CHP) is applied to the building sector the main driver for the right sizing is the thermal load. The wide range of hourly and daily heating need variations in dwellings represent a key aspect to get the device cost effectiveness and self-sustainability. For those purposes thermal energy storage can be coupled so as to minimize the energy generation cost as much as possible. Furthermore, estimating the cost effectiveness and technical feasibility of a cogeneration plant with a domestic target is very challenging and it should be done only if a comprehensive loads evaluation along with a real cost analysis have been performed. The purpose of the research is to analyze the correct interaction between the CHP using a domestic load and a thermal storage analyzing the differences between classic water storage and one with better performance in PCM. The case study is an apartment block located in Rome, Italy. Moreover, the economic characteristics will be studied by the calculation of the Levelized Cost Of Energy (LCOE) along with the capital costs and the actual technical problems arising from the thermal energy accumulation. PCM (phase change materials) is demonstrated to have a potential wide use since it is more practical, in terms of required technical spaces, especially in constrained environments such as existing buildings.

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Keywords: Low temperature PCM; LCOE; condensing micro-CHP; Technical issues; economic analysis.

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1. Introduction

The feasibility status for a cogeneration plant in apartment block is a critical issue since the incoming loads and the timing of purchasing energy in the electricity market need to be thoroughly analyzed [1,2]. An apartment block located in Italy is chosen as case study. In the 1970s, all buildings with more than 4 apartments had condominium centralized heating systems by boilers. Yet, the technology was not ready to serve effectively all the apartments. Indeed, the flats at ground floor were often too warm while, the ones at higher floors resulted cold. In the 1980s and 90s, starting from this discrepancy, centralized generation was discontinued in favor of single boilers entailing a strong increase of national Natural Gas demand due to the installation of gas boilers with average power of 23kW. Most of the time, the boilers sizing was independent of the amount of heated surface of the flat. This latter is a key point to address when retrofitting interventions are planned for building stock [3] or installation of new energy supplier is considered [4]. With the introduction of Law 10/91 (Italian low), it started to account the energy consumption by favoring system monitoring. Furthermore, Directive 2012/27 / EU was transposed by Legislative Decree no. 102 art. 9 co. V, which requires thermoregulation and individual heat measurement in buildings. Article no. 4 of D.P.R. 59/09 stipulates that centralized plants are preferable for buildings with more than 4 units. Any use of autonomous installations should be subject to technical or force majeure, justified by a specific technical report. This document is very important when new low temperature heating systems feasibility is analyzed [5] as well implementation of innovative solutions such as fuel cells technologies [6], interaction with forthcoming electric private mobility [7], hybrid systems [8] or, even, adoption of eco-fuels in existing energy production facilities [9,10]. Electricity can easily be utilized throughout the day, while the main concern is related to the rational use of thermal energy produced by CHP unit [11]. Winter use allows to optimize hot water both for heating and domestic hot water but, in certain cases, it is advisable to store hot water to make it available during the day. This allocation has to be related to looking for the best economic and energy balance to obtain a CHP more profitable for condominium users [12]. Therefore, involving storage solutions could play a key role in facing all the aforementioned challenges. This study investigates on coupling PCM-based thermal storage and CHP unit to fulfill the case study heating demand.

1.1. Energy storage technologies

Thermal energy storage is mainly divided into two kinds: sensible and latent heat storage. The sensible one is accumulation with water. It is so defined because it can store only the sensible heat in a static manner. While, the latent typology allowing a speed up to 14 times faster than the sensible one [13]. It is remarkable that having an accumulation power 14 times higher, as a consequence, the size will be reduced. For more information about PCM technologies and PCM type see [23]. In solid-solid transformations, the heat is accumulated while in the material a process takes place by a type of crystallization to another. Generally speaking, those transformations have a latent heat release less than the melting solid-liquid transformations but, they have a greater ease of design. The purpose of the research is to analyze the correct interaction between the CHP using an apartment block load and a thermal storage analyzing the discrepancy between conventional water storage and one with better performance equipped with PCM. In Italy, has been made an important step to save electrical energy, the resolution 578/2013/R/eel. An energy production plant can be approved by the GSE as an Efficient Utility System (SEU). Definition of a SEU system "a system where an electricity production plant with a nominal power less than 20 MWe and installed on same location, powered by renewable sources or high efficiency cogeneration, even in the ownership of a Subject It is different from the end customer, it is directly connected, by a private connection without obligation to connect to third parties, to the plant for the consumption of only one final customer and is realized within the property area or in full availability Of the same customer ".With SEU sistem It’s possible to connect the renewable sources directly to the final through a private network, provided that the plant is within the property area or in the full availability of the same end customer. This condition is good for the multiple dweling apllication as if there is a surplus of electricity it is also possible to sel it to third parties or to other neighbors, the selling price can be agreed between private customers surely and can be higher than the sale price of the public network. In the case of a study, it is considered the selling price to the network operator.The economic analysis will be studied by computing the

Levelized Cost Of Energy (LCOE) along with the capital costs and the actual technical issues raised by the heat accumulation.

2. Methodology and materials

The CHP engine prototype consists of a couple of 599 cm^3 single cylinders, based on NG Otto cycle equipped with a 3-way catalyst and lambda probe for pollutants treatment. Two MCHPs were chosen instead of just one to favor the managing stopping one of them in mid-season, optimizing maintenance and prolonging its useful lifespan. The CHP is properly designed for dwelling applications electrically connected to the National Grid by PPPN 400V at 50Hz. The rated power output is equal to 5 kW_{el} each. Recoverable thermal power is 15kW under condensing condition to the liquid to gas heat exchanger. The engine control unit allows to modulate the electrical power output acting on the shaft rotational speed. The electrical generator is connected to a static frequency converter to assure 50 Hz for all of partial load conditions. It is important to point out that part of technical assumptions for performing energy-economic simulations were deduced from experimental campaign carried out in a previous research project [19,20], the difference with the previous measurement campaigns concerns the use of two CHP instead of one.

Table 1. CHP Engine data sheet

CHP Engine Characteristics (single engine)	
Displacement	599 cm3
Number of cylinders	1
Compression Ratio	10
Rotational Speed	1,500-2,100 rpm
Methane Number Required	> 80
Feeding system	electronic injection
Rated electrical power	0.5 – 5 kW
Rated thermal power	5 – 15 kW
Thermal power from fuel	19.2 kW
Electrical Efficiency	26 %
Max heat recovery efficiency	76 %
Max First law efficiency	102 %
Max outlet temperature	70 °C
Max/min inlet temperature	60/25 °C
Water Flow rate	670 litres/h
Oil tank volume	25 litres

Referring to the thermal energy storage device, a PCM array was chosen in order to evaluate its contribution to enhance the CHP/building energy system efficiency. In detail, the salt hydrates type was used for simulations, in particular the sodium acetate water and additives. PCM cylinders based on custom-made plastic containers filled with Phase Change Materials (PCM) solutions which have operating temperatures between +48 ºC and 65°C They can be stacked in either cylindrical /rectangular tanks for atmospheric / pressurized systems for a variety of thermal energy storage applications. For cost-effectiveness cylinders of 70cm length and 7cm diameter were chosen.

Fig. 1. PCM cylinder

The principal physical data is in the following table:

Table 2. PCM data sheet

PCM features	
Phase change temperature	48°C
Maximum temperature	65°C
Storage capacity 45-60°C	95 Wh/litre
Latent heat of fusion	68 Wh/litre
Approx. Specific Heat in PCM	1 Wh/kg/°C
Specific Gravity	1.36 kg/litre
Thermal conductivity	0.5-0.7 W/m/°C

For experimentation, a couple of twin steel tanks have been used, each tank inside have a rack used for position the PCM cylinders, two perforated diffuser are installed to optimize the diffusion of the water. The two tanks are installed in parallel to increase storage capacity; the tank connection diagrams also include a mixing valve that can handle the output liquid temperature. The PCM tank has been calculated using the C48 data sheet considering the storage capacity 45°-60°C (table 2) and the size of cylinder. Every tube have 3.31 liter of PCM liquid and 0.314 kWh/cylinder. The number of cylinder has been calculated considering the maximum daily load. The storage strategy it's 100% full load, for satisfying the load of an entire day. The results of calculation are in the table 5.

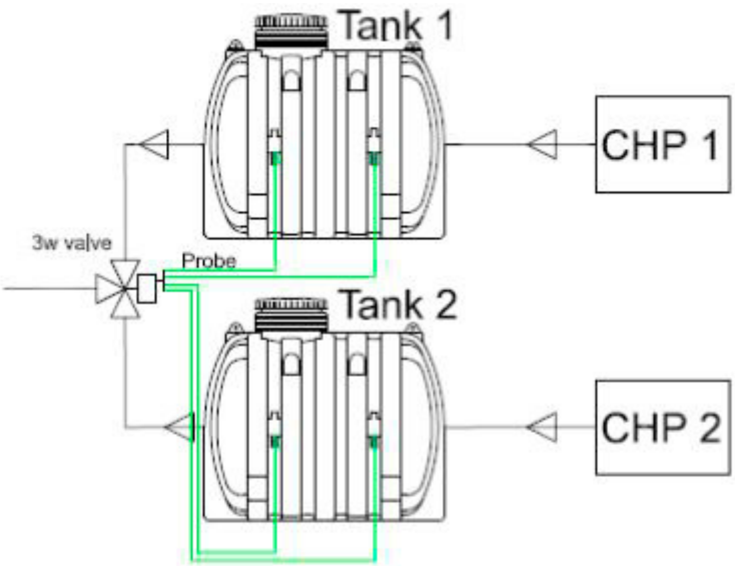

Fig. 2. Tank plant

The LCOE value was calculated considering two scenarios together with the same electrical and thermal loads during winter season. The energy loads belong to an apartment block whit 4 flats, classified as C energy label located in Rome. In the first scenario one sensible storage was included (water), while in the second scenario a latent storage (PCM salt hydrate) was inserted. Having considered in detail the costs related to the purchase of CHP, installation secondary, and the tank, in the scenario with latent accumulation, they were also added to the cost of the PCM and mixing valve.

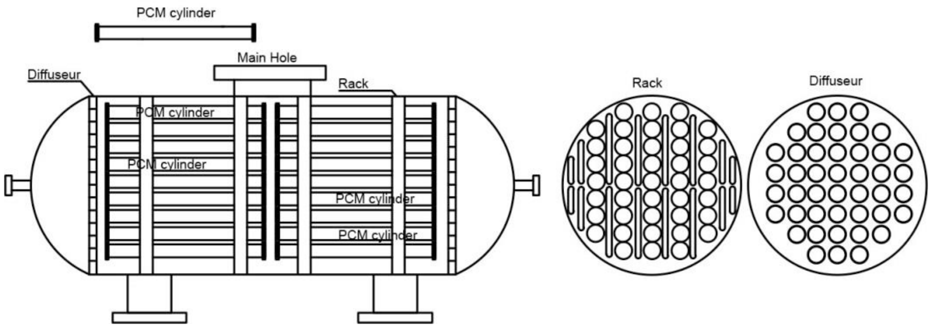

Fig. 3. Tank storage.

As regards the storage strategy for both scenarios was considered that of the 100% full storage, with which it was decided to accumulate all the thermal energy produced by MCHP couple. In the following figure there is the running schedule of CHP, the blue line it's the thermal load, during these time the CHP it's ON, the grey line it's the time necessary for charge the storage; during these time the CHP it's ON and it produce electricity, the yellow line it's a discharge time. During the discharge time the CHP it's OFF, and there is no electrical energy production. The tank it's sized for 175.60 thermal kWh and it's not sufficient to cover a full load and at 10:00 PM the CHP must be turned on for one h more.

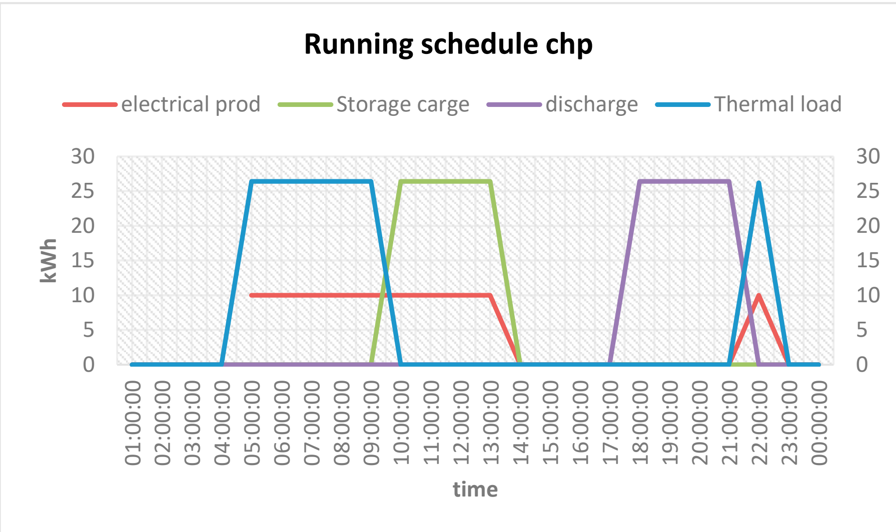

Fig. 4. Running scheduling CHP

Electricity prices for sale and purchase as well as those of the methane gas are updated to the average on the year 2015 AEEG site. The cost of the PCM is real from Finnish supplier. For economic calculation it was considered an amortized over 15 years.

2.1. Technical issues and recommendations

For Technical issues, e.g. the carrier fluid flows inside the tank obtaining the maximum exchange surface around the cylinders filled with PCM and for a correct distribution of the fluid to mount, a perforated foil is recommended [21]. The passage of the fluid in the foil entails uniform distribution giving the maximum heat exchange with the PCM. Non-uniform PCM fluid exchange can generate a cold fluid stream which passes only in a section of the tank not allowing a total storage charge. Temperature sensors and mixing valve downstream help the tank to be charged at 100%. Two probes for each tank are required to handle the temperature of the three-way valve for correct mixing.

Recent demonstration projects are related to biogas thermal pre-treatment to enhance its production by the heat recovered from its burning in boilers or CHP. Integration into urban contexts [22] goes through efficiency improvements such as thermal energy management by means of energy-intensive solution, i.e. PCM-equipped ones.

3. Results and discussions

The economic energy analysis was simulated using the following formula for the LCOE:

$$LCOE = \frac{C_{ann,Tot} - c_{boiler} * H_{served}}{E_{Served}} \tag{1}$$

And:

$$C_{anm,Tot} = \frac{i \cdot (1+i)^n}{(1+i)^N} \cdot C_{NPC,Tot} \tag{2}$$

Table 3. Price table

time slot	price buy	sell back	Buy GAS
	€/kWh	€/kWh	Nm^3
F1	€ 0.168	€ 0.048	
F2	€ 0.163	€ 0.056	0.983
F3	€ 0.163	€ 0.050	

Hence, the following Figures show the Electrical and Thermal energy loads:

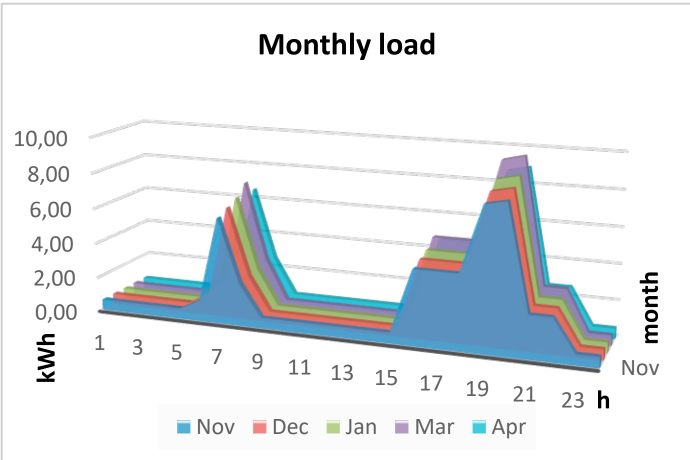

Fig. 5. Electrical monthly load.

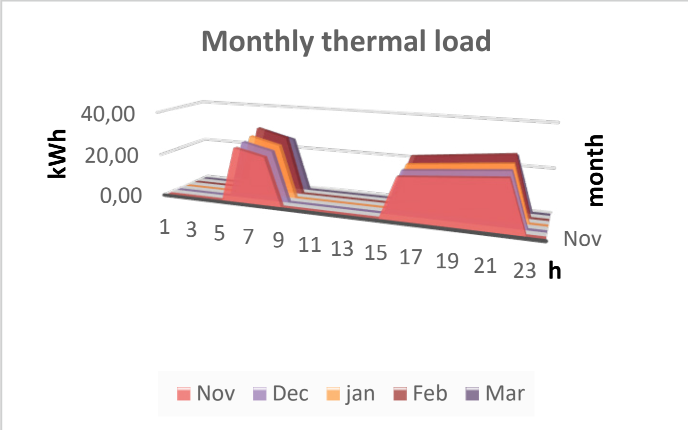

Fig. 6. Thermal monthly load.

Table 4. Annualized costs scenario base sensible storage

component	capital €/year	O&M €/year	Fuel €/year	Electricity €/year	Savings €/year	Total
CHP	€ 1.353,33	€ 203,49	€ 5.840,86	€ 1.675,35	-€ 6,56	€ 9.066,47
Boiler	€ 1.523,49	0	0	0	0	€ 1.523,49
installation	€ 233,33	0	0	0	0	€ 233,33
System	€ 3.110,15	€ 203,49	€ 5.840,86	€ 1.675,35	-€ 6,56	€ 10.823,29

Table 5. Annualized costs scenario base latent storage

component	capital €/year	O&M €/year	Fuel €/year	Electricity €/year	Savage €/year	Total
CHP	€ 1.353,33	€ 203,49	€ 5.840,86	€ 1.675,35	-€ 6,56	€ 9.066,47
PCM cost	€ 843,70	0	0	0	0	€ 843,70
Boiler	€ 202,00	0	0	0	0	€ 202,00
installation	€ 233,33	0	0	0	0	€ 233,33
System	€ 2.632,37	€ 203,49	€ 5.840,86	€ 1.675,35	-€ 6,56	€ 0.345,50

Analyzing the costs above in to the tables, we can see that the cost of the CHP remains unchanged while it varies the cost of the tank. The tank with the latent storage is much smaller than that of the sensible and less expensive, on the other hand there is to add the PCM cost's on the scenario two. The value of LCOE is the following one:

Table 6. LCOE of the two scenarios

LCOE scenario 1 water	€ 0.3344	
LCOE scenario 2 PCM	€ 0.3320	-0.72%

The scenario two with PCM allows a reduction of less than 1%. Further interesting development would cope with the efficiency of those systems, especially when dedicated procedure is adopted for combination with Hybrid fuels.

4. Conclusions

From the point of view of the LCOE's calculation, there is a sensible difference in favour of scenario two with PCM, the real difference and convenience in adopting PCM storage is the tank size.

Table 7. Number of PCM cylinder and costs

storage strategy	**kwh/day**	**PCM type**	**$P_{storage}$ W/l**	**Litres**	
100%	175,60	C48	95	1848,84	
kWh/rod	**vol/rod**	**n° Rod**	**Cost/rod**	**C0-Rod**	**vol/tank**
0.314	3.31	559	€ 22.63	€ 16.655,50	2.961

To obtain the same storage with sensible accumulation a water tank size of 15.084 litres is needed, 7.5 times more voluminous and, consequently, also 7.5 times heavier. This issue does not allow creation of sensible heat storage setting the scenario 2 as more feasible than the 1. Table 7 shows the number of PCM cylinders, the relative cost and the volume of the tank that must contain them starting for storing 175.60 kWh/day.

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