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Economic analysis and technical issues of low temperature PCM thermal storage combined with a condensing micro-CHP

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Abstract

This study is focused on showing technical and economic issues related to the use of low temperature PCM (Phase Change Material) storage system coupled to a condensing micro CHP. That one is a single cylinder engine of rated power and thermal outputs equal to 5 kW and 13.1 kW respectively, equipped with a three-way catalyst to meet the regulations on pollutants emission. Two different system layouts were built and economical-environmental performance was evaluated. Specifically, a traditional water tank and a PCMs array were analysed. A two-family house characterized by a normalized primary energy need equal to 50.523 kWh/m^2 y was assumed as the end user. That energy need is referred to the climatic conditions typical of Middle region in Italy. Finally, the LCOE (Levelised Cost of Electricity), calculated over a system lifespan of 15 years, has been chosen as the main indicator to compare the different options optimizing the CHP switching-on strategies.

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

1. Introduction

It is well known that micro CHPs offer good opportunities to enhance the overall efficiency of several energy systems, such as small industries and buildings, which require both heat and electricity. Even though lower primary energy consumption along with carbon dioxide emissions can be achieved compared with separated generation [1,2], the CHPs deployment depends strongly on their capital costs as well as their operating hours and time matching

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between energy production and demand curves [3]. In detail, when CHPs are applied in building sector the main driver for the right sizing is the thermal load. Furthermore, 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 [4].

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 electricity produced by a residential dwelling is easily usable during the day, immediately profitable the benefits of the micro CHP while thermal energy can be used only in winter condition [5].

The heat energy produced in the form of hot water is a "valuable" by-product; the main use is for heating plant or for domestic hot water production. In some cases the heat produced can be stored for moving the use of the same in the most convenient time slots. A real constraint can be the need of installing new appliances such as storage in existing buildings, especially those ones which are listed due to their historical values. Hence, other heating strategy could be applied such as change in centralized thermal power plant [6,7] or partial fuel substitution [8].

The storage allows to increase the hourly flexibility of the mCHP making it more appealing to domestic users.

1.1. Energy storage technologies

The energy storages are divided into two main categories; sensible and latent. The sensible ones are accumulations with water. They are so defined because they can accumulate only the sensible heat in a static manner. While, the latent component allows to store up to 14 times faster than sensible [9]. It is remarkable that having an accumulation power 14 times higher than the sensible one, also the size will be reduced.

As reported in Figure 1, the phase change materials occur through the solid-solid, solid-liquid and liquid-gas transformations.

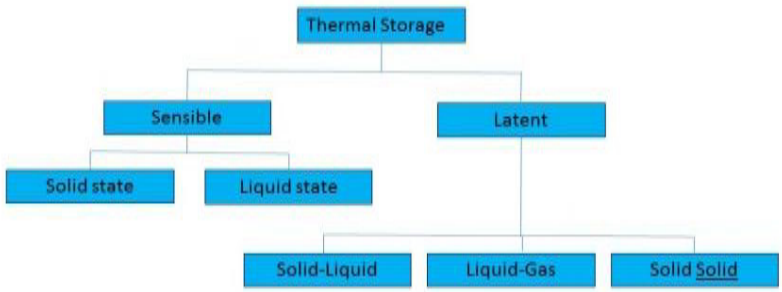

Fig. 1. Thermal energy storage typologies.

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 most common solid solution materials of organic type are the phentaerythritol, Li_2SO_4 and KHF [10].

Changes in liquid-gas phase allow an excellent energy exchange but very high variations of volume, making these changes not available for domestic applications usage. They could be more suitable for other applications such as improving Compressed Air Energy Storage [11] or even applied in the construction of emergency operation centers [12]. The changes of solid-liquid and liquid-solid phase, instead, represent the right compromise for the thermal management with a change of volume about 10%, easily manageable from a technical point of view. The solid-liquid type is divided into two main categories: organic and inorganic PCM. In the first category, the paraffins are the most common materials, whereas, among the inorganic ones, there are the salts hydrates.

Salts hydrates are alloys of salt and water with the chemical formula type AB * nH_2O. They represent the largest category of the PCM used for heat storage. Their benefits are many: the first one is the high latent heat, according to a change in volume in the order of 5/7% and, last but not least, a much lower cost compared to paraffins.

It is remarkable that the inclusion of Phase Change Materials (PCM) in the thermal energy storage of a Solar Domestic Hot Water System (SDHW) has not major impact on thermal energy profitability [13], while when a high temperature source is present; it provides interesting energy recovery performance [14].

The purpose of the research is to analyze the correct interaction between the micro CHP using a domestic load and a thermal storage analyzing the differences between classic water storage and one with better performance in PCM. 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 accumulation.

2. Methodology and materials

The CHP engine prototype consists of a 599 cm^3 single cylinder, based on NG Otto cycle equipped with a 3-way catalyst and lambda probe for pollutants treatment. The CHP is properly designed for dwelling applications and it is electrically connected to the national grid by PPPN 400V at 50Hz. The rated power output is equal to 5 kWel. It is able to recover a maximum thermal power of 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 in order to assure 50 Hz for all of partial load conditions. It is important to point out that all of technical assumptions for performing energy-economic simulations were deduced from experimental campaign carried out in a previous research project [15-17].

Table 1. CHP Engine data sheet

CHP Engine Characteristics	
Displacement	499 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 liters/h
Oil tank volume	25 liters

As regards 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. PCMs based on salts have the best storage capacity; they are more environmentally friendly and cheaper. The PCM box is cylindrical plastic and its dimensions are 70cm height and 7 cm of diameter. The PCM type inside the cylindrical tube is named C48; the main characteristic is 48°C phase change temperature and a storage capacity of 96Wh/liter. Those two parameters are the most important to decide the work fluid temperature and the storage size. For the experimental simulation a steel tank was analyzed. The tank is cylindrical and horizontal. Inside the tank a perforated rack ready for to install PCM cylinder has been designed.

According with the number of PCM cylinders, two or three racks should be installed.

Fig. 2. Cylindrical PCM box.

The main physical features were reported in the following table:

Table 2. PCM data sheet

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

The rack has to optimize and to max the water diffusion for aligning energy charge or discharge. In Figure 3, a sample project of tank is presented. The tank type is horizontal with 4 racks and 2 diffusers. Their sections are shown. The PCM tank has been calculated using the C48 data sheet considering the storage capacity at 45°-60°C, as in Table 2. Every tube has 3.31 liters of PCM liquid and 0.314 kWh/cylinder. The number of cylinder has been calculated considering the maximum daily load. The storage strategy is 100% full load to meet the demand of an entire day. The results of calculation are in Table 5. The LCOE evaluation was performed considering two possible scenarios both with the same electrical and thermal winter loads. The energy loads consider a detached house with 250 m^2 of floor area. They are certified as home C energy class, localized in Rome in accordance with the climate zone regulation in force.

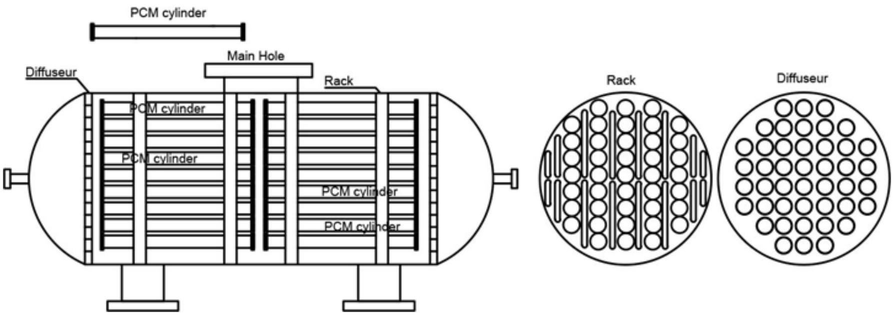

Fig. 3. Design of the tank.

In the first scenario a sensible storage was included (water), while in the second one a latent storage (PCM salt hydrate) was inserted. Having considered in detail the costs related to the purchase of CHP, installation and auxiliaries and, the kettle, in the scenario with latent accumulation, they were also added to the cost of the PCM.

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 the CHP. In Figure 4, the CHP running schedule is shown: the blue line is the thermal load; the green line is the time necessary for charge the storage; during those phases the CHP is switched ON producing electricity. The purple line is the discharge phase. During this latter, the CHP is switched OFF. The tank is sized for 88 kWh_t, not sufficient to cover a full load. Indeed, at 22:00 the CHP must be turned on for one hour more.

Electricity prices for sale and purchase as well as those one for natural gas are updated to the yearly average in 2015 from the AEEG report. The cost of the PCM is real from the Finnish supplier. For economic calculation it was considered an amortization over 15 years.

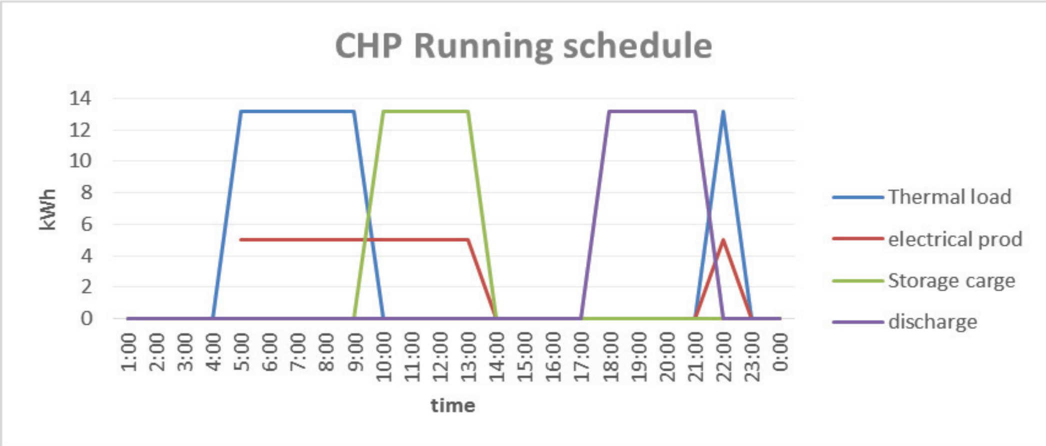

Fig. 4. Running schedule of the CHP.

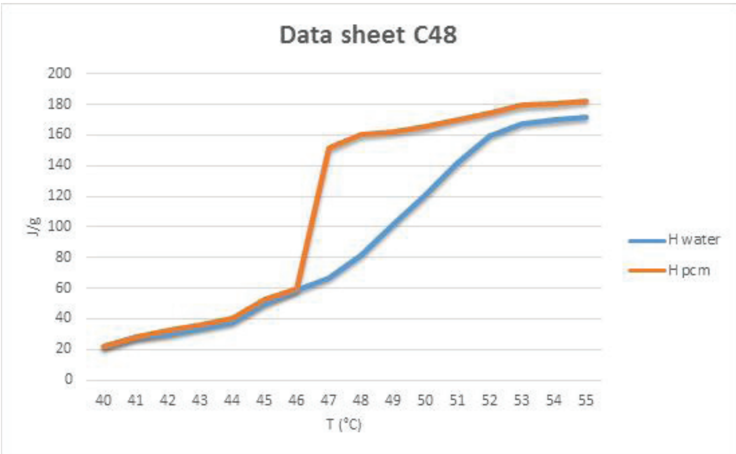

Fig. 5. Data sheet of C48 PCM.

2.1. Technical issues and recommendations

The issues related to the PCM storage is that 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 it is appropriate to mount a perforated foil [18]. The passage of the fluid in the foil allows the uniform distribution of the fluid itself favoring the maximum heat exchange with the PCM. The problem of non-uniform PCM-fluid exchange can generate a cold fluid stream which passes only in a section of the tank impeding a total storage charge. To help the tank to reach 100% of provided thermal energy, it is useful to insert the temperature sensors and a three-way valve at the end of the tank with a recirculation system that starts at the time of signal failure of one of the two probes.

3. Results and discussions

The economic energy analysis was simulated using the following formulas for the Levelized Cost Of Energy:

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

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

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 Thermal and Electrical energy loads:

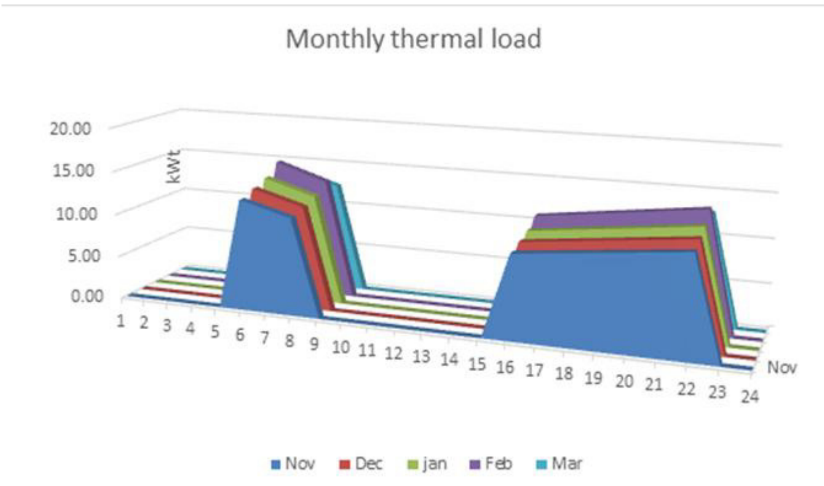

Fig. 6. Thermal monthly load.

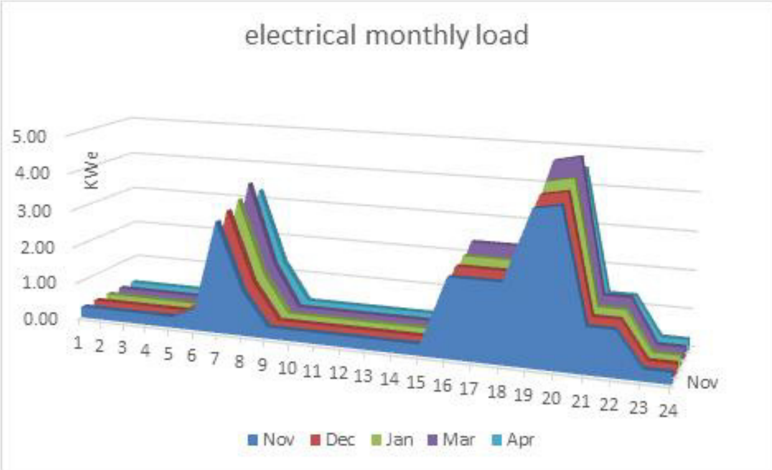

Fig. 7. Electrical monthly load.

Table 4. Annualized costs scenario base sensible storage

component	capital €/year	O&M €/year	Fuel €/year	Electricity €/year	Savage €/year	Total
CHP	€ 676.67	€ 203.49	€ 2,920.43	€ 837.67	-€ 11.08	€ 4,627.18
Boiler	€ 561.90	0	0	0	0	€ 561.90
Installation	€ 143.33	0	0	0	0	€ 143.33
System	€ 1,381.90	€ 203.49	€ 2,920.43	€ 837.67	-€ 11.08	€ 5,332.42

Table 5. Annualized costs scenario base latent storage

component	capital €/year	O&M €/year	Fuel €/year	Electricity €/year	Savage €/year	Total
CHP	€ 676.67	€ 203.49	€ 2,920.43	€ 837.67	-€ 11.08	€ 4,627.18
PCM cost	€ 422.81	0	0	0	0	€ 422.81
Boiler	€ 148.67	0	0	0	0	€ 148.67
Installation	€ 143.33	0	0	0	0	€ 143.33
System	€ 1,391.48	€ 203.49	€ 2,920.43	€ 837.67	-€ 11.08	€ 5,341.99

Analyzing the costs above in Table 4 and 5, it is noticeable that the cost of the CHP remains unchanged while, the cost of the tank varies. The tank with the latent storage is much smaller than that one with the sensible storage and, consequently, less expensive. On the other hand the PCM cost must be added in the second scenario.

The values of LCOE are the following ones in Table 6:

Table 6. LCOE of the two scenarios

LCOE scenario 1	€ 0.1711	
LCOE scenario 2	€ 0.1623	-5.15%

The scenario two with PCM allows a reduction in the value of 5%. Further interesting development would cope with the efficiency of those systems, especially when dedicated procedure is adopted for combination with Hybrid fuels [19] or when the renewable energy supply will change to new emerging technologies such as tidal one [20].

4. Conclusions

From the point of view of the LCOE's calculation, there is a difference of 5.1% in favor of scenario two with PCM. The real difference and convenience in adopting PCM storage is the tank size. To obtain the same storage with sensible accumulation a tank size of 7.552 liters of a water tank is needed, 5 times more voluminous and, consequently, 5 times heavier than the previous one. This technical issue does not allow often the adoption of sensible heat storage setting the scenario two as more feasible than scenario one. In Table 7, the number of PCM cylinders was reported. The relative cost and the volume of the tank that must contain them assuming storage of 88 kWh/day. So, PCM would have wide use since the practical adoption in limited conditions as existing buildings.

Table7. Number of PCM cylinder and costs

storage strategy	kwh/day	pcm type	Pstorage W/l	Liters	
100%	88	C48	95	926.3	
kWh/rod	vol/rod	n° Rod	Cost/rod	C0-Rod	vol/tank
0.314	3.31	280	€ 22.63	€ 6,342.17	1,484.23

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