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Innovative Hybrid CHP systems for high temperature heating plant in existing buildings

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Abstract

This paper deals with the potential role of new hybrid CHP systems application providing both electricity and heat which are compatible with the building architectural and landscape limitations. In detail, three different plant layout options for high temperature heat production along with the electricity generation were investigated and compared each other. To do so, conventional natural gas CHPs and back up boiler, two-stage Electric Heat Pumps (EHPs) and trans-critical CO_2 electric heat pump (CO_2-HP) have been considered as reference technologies to build hybrid systems. In addition, hybrid solar collectors (PV/T) thermal output, along with the recovered low-grade heat from CHP exhaust gas, flowing to the stack, have been used as the CO_2-HP low temperature driving source.

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Keywords: Building refurbishment; Hybrid Heating Systems; CHP; CO2 Heat pump; PV/T; Energy Efficiency.

1. Introduction

A great challenge for building specialists is the energy refurbishment of existing buildings when already part of urban identity or even listed by Restoration Authorities [1]. Furthermore, the call for climate change adaptation

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measures to create more healthy and livable urban environment [2,3] entails more deep analysis for integrating low-energy solutions [4].

A first attempt was done by improving performance of external surfaces of buildings in terms of optic-energy effects [5,6] as well as focusing on large residential building complexes already part of consolidated cities [7,8]. Nevertheless, the subsequent need for integrating higher share of renewables calls for further constraints at territorial level in terms of risk analysis and administrative issues [9]. Indeed, when the building is located in a protected area, harvesting the local renewables is a further critical issue [10].

Starting from that, other research lines are moving towards a partial or total decarbonization of energy production by means of cutting-edge devices [11], installation of forthcoming hydrogen-based systems at building level [12], solar technologies at urban planning scale [13] or more the so-called heat planning [14]. As regards this development, the authors believe that a low-impact strategy is the intervention on the production side. As demonstrated in [15], better energy performance can be reached without modifying the distribution system in the building. Conventional reduced interventions demonstrated long pay-back period since the reached energy efficiency level is low [16]. As aforementioned, the renewable energy sources integration in such buildings is either very often not permit-ted or strongly limited for landscape issues, even if the plants installation is feasible from a technical point of view. So, an alternative solution to overcome those constraints and to efficiently meet the building energy needs is to implement new adequate heating and electricity production systems. The crucial difference with the mentioned other research lines is to preserve the heating temperature level in order to maintain the same distribution systems and terminals without stressing them since they are sized for this heating purposes. In detail, changes in composition of the hybrid systems for high temperature heating were analyzed in this study as well as evaluate their performance in supplying more sustainable energy. One of the author already applied this strategy for nZEB building [17]. Here, retrofitting potential is investigated by evaluating four performance indicators discussed in the study.

2. Methodology and materials

The aim of this paper is basically to provide a short overview on viable options and potential energy strategy dealing with the building plants refurbishment, so as to mainly reduce their PEC.

As a matter of fact, the energy performance analysis of new hybrid CHP systems are evaluated and discussed on the basis of four main indicators such as Primary Energy Consumption (PEC), Primary Energy Saving (PES), renewable energy fraction (f_{RES}) and renewable heat delivered to the end-user.

To do so, the energy balance equations have been implemented in MATLAB SIMULINK environment and a model for each energy scenario has been built. In accordance with the subject of the study, the PEC is identified as the objective function for the optimization process in yearly normalized energy balance of all plant solutions. Additionally, the renewable energy fraction has been calculated as further meaningful indicator as requested by the updated version of Building Energy Performance Certification.

Moreover, PES, renewable heat fraction and TESHP are reported as additional indicators. So, the correlation between the achievable energy saving and the foreseeable integration of Renewable Energy Sources (RES) in existing buildings has been discussed.

Referring to the Figure 1, the conventional Separated Generation layout is com-pared to three different systems gathering the following well-known technologies: Boilers, CHPs, 2-stage HPs, trans-critical CO_2-HPs, hybrid solar collectors and an integrated electrical heater in a thermal storage device to keep as much as possible under control the hot water temperature for CO_2-HPs cold sink. In detail, the first energy scenario consists of a CHP including a traditional boiler as back-up. The second one is composed by a CHP which can drive totally or partially the 2-stage HP electrical need depending on system boundary conditions.

Finally, the third one consists of coupling the CHP to a CO_2-HP, similarly to the second scenario, and a PV/T array is added so as to produce renewable electricity as well. Moreover, the low temperature driving source for CO_2-HP comprises the thermal output of hybrid solar collectors, along with the recovered low-grade heat from CHP exhaust gas flowing to the stack. Thus, an electrical heater, within a thermal storage de-vice, provides the required energy once the PV/T heat production curtailment occurs due to shading or rainy days.

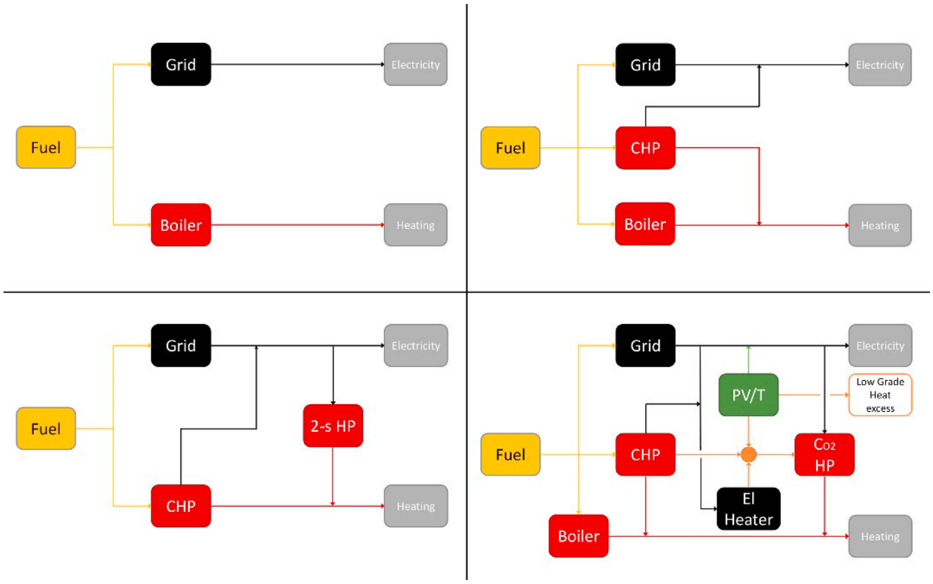

Fig. 1. Simulated Energy Systems lay-out. a) Separated Generation; b) Traditional CHP and Boiler; c) Combined CHP and 2-stage HP system; d) Combined CHP, CO2 - HP, PV/T and Boiler system.

Having said, the energy balance over one year period has been calculated for each system having fixed the same normalized electric and heating needs. It is important to point out that the fundamental assumption is the implementation of Net Metering option for electricity flows through the Grid. Thereafter, a normalized energy distribution for a reference building, in terms of power and heat demand, is assumed according to a previous European research project. Indeed, data from the so-called TABULA project (Tabula EU research project) was used to understand the most com-mon heat and electric energy needs of real buildings related to their different typologies. In such a way, it was possible to identify the typical average value of end-user PTHR for an existing building on the basis of benchmark provided by the aforementioned project. According to the TABULA outcomes, the reference normalized values for electricity and heat have been set equal to 20 and 80, respectively. Those values entail a building PTHR equal to 0.25. In order to perform simulations of all reference scenarios, technical assumptions on each device efficiencies are made and they are summarized in Table 1.

Table 1. Characteristic efficiency values of system components.

Calculation parameters						
	η_{el}	η_{hr}	η_h	ε_{chp}	PTHR	COP_{HP}
CHP	0.3	0.5	-	0.65	0.6	-
Boiler	-	-	0.9	-	-	-
2-Stage HP	-	-	-	-	-	2.5
CO2 HP	-	-	-	-	-	3.2
PV/T	0.14	0.3	-	-	0.466	
Electric Heater	-	-	0.8	-	-	-
National Grid	0.42	-	-	-	-	-
Calculation parameters						

As regards the required receiving surface assessment of PV/Ts, an array of rated electrical output equal to 10.08 kW_p has been simulated by HOMER.

In detail, the POWER HYBRID 240 was chosen as reference module for technical data, assuming then the slope and Azimut equal to 45° and 10°, respectively.

Furthermore, the DNI (Direct Normal Irradiation) data for calculations are referred to the city of Rome in Italy. The yearly electric and thermal energy capabilities have been calculated by the simulation tool, splitting them into winter and summer productions in accordance with the requirements of current Italian regulations for heating plants operation.

The Specific Receiving Surface (SRS), in terms of squared meters per unit of heat, is identified as a key indicator to evaluate technical feasibility of hybrid CHP systems involving PV/Ts. Indeed, the suitable PV/T array size has to match the available roof surface as well as building architectural constraints and environmentally protective restrictions. It is remarkable that the SRS is computed having considered only the winter low grade heat generation from PV/Ts, since, these latter, drive partially the cold sink of trans-critical CO_2 heat pump. As a consequence, the SRS will be high due to the fact that the heat production in winter season is approximately one third of the yearly one. For that reason, the PV/T array is oversized and a low-grade heat excess occurs especially during the summer time. Nevertheless, that energy amount can be either dissipated or partly used for domestic hot water production. Anyway, that case is not discussed here because it is out of the article aim.

In the end, a sensitivity analysis is carried out to find which and when a layout option is more effective with respect to one another, by varying the following energy driers:

- The End-user PTHR, which is defined as the ratio between the electrical energy consumption and the thermal one for the building. It ranges between 0.05 and 0.67 for all system layouts;
- The PV/T heat fraction (f PV/T) which denotes here the array energy contribution to the total required low grade heat of CO_2-HP. It ranges from 0.2 up to 0.8 for system layout d) as depicted in Figure 1.

In this way, it is possible to determine some threshold values of End-user PTHR, where each system layout is competitive and meets the building energy needs more efficiently.

3. Results and discussions

In this section, the outcomes of performed simulations have been presented and discussed. All of results have been determined by an optimization process based on the GRG non-linear optimization algorithm by minimizing the objective function i.e. systems PEC. The fundamental parameter to change, in order to solve the energy balance equations matching the analytical constrains, is the CHP yearly electricity production.

So, four different energy systems have been computed for the reference PTHR value, while forty-nine more case studies have been simulated to perform the sensitivity analysis.

3.1. Reference Scenarios

Since the aim of this paper is to explore the opportunity to apply a new hybrid CHP system, the authors found that the best solution is the combination of CHP with CO_2-HP, PV/T and the back-up boiler. According to energy balances reported in Figure 2, it emerges that last energy system (i.e. the layout d)) is the most efficient, showing the lower PEC even though the PV/T heat fraction is limited only to 0.2. Therefore, that system layout is strongly suitable for existing building characterized by a reduced roof sur-face availability. It is noteworthy that the national grid contribution to meet the electricity need is null for each CHP-based scenario.

Hence, CHP and PV/T are able to completely drive the CO_2-HP and the electric heater as well. In addition, comparing layout c) with the d) one, the electrical energy provided by CHPs is almost the same (i.e. 30 and 29.217 respectively). Consequently, it can be stated that layout c) and d) are basically equivalent from the energy point of view, but the first one shows a lower energy performance despite of having a higher f_{RES} value than the second one. Nonetheless, the layout c) can be considered as the most suitable option when solar energy technologies cannot be integrated in buildings. More-over, the CHPs size are practically the same but the layout d) has a more complicated architecture which could affect the whole system reliability. For that reason, an investigation on changes of PV/T heat fraction was required.

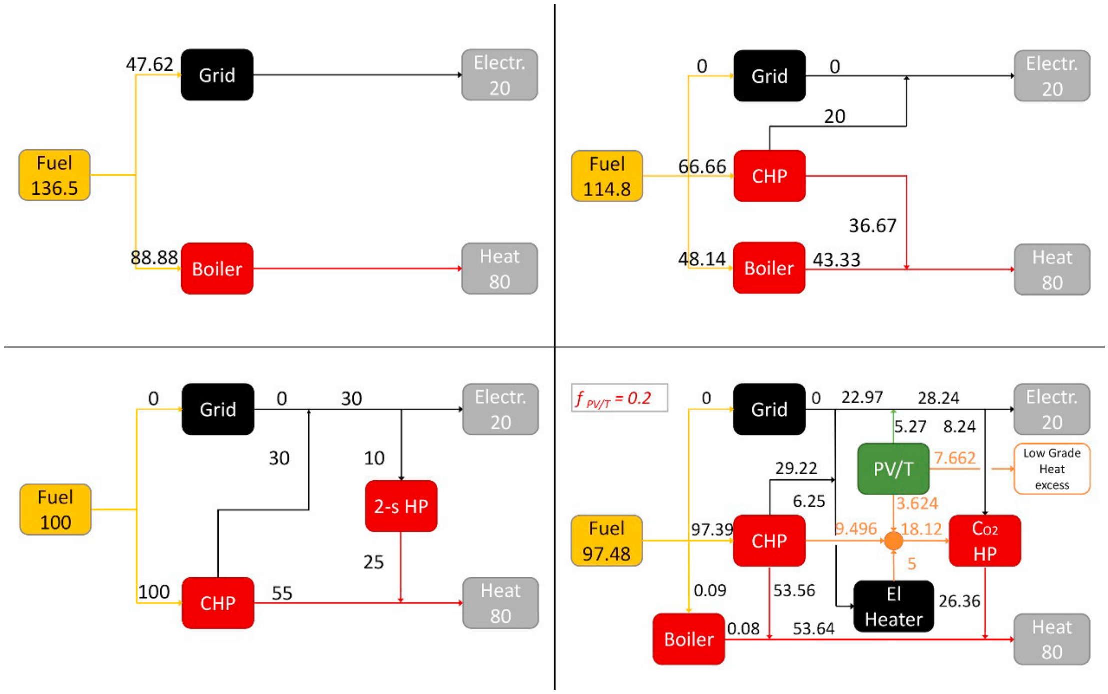

Fig. 2. Energy balance of system layouts. a) Separated Generation; b) Traditional CHP and Boiler; c) Combined CHP and 2-stage HP system; d) Combined CHP, CO2 - HP, PV/T and Boiler system.

In this way, the modules receiving surface assuring a further system PEC reduction can be evaluated. Identifying a minimum threshold value for fPV/T, which allows to up-hold such a complex option related to the marginal benefit, is left to the further development of this study.

As regards the SRS assessment, the outcome of HOMER simulation on the reference PV/T array, leads to a thermal energy production in the winter season equal to 10.894 MWh. It entails a SRS of 6.39 m^2/MWh since the overall array surface is 69.6 m^2. For instance, referring to the energy balance in Figure 2, part d) and considering MWh as unit of measurement, the required receiving surface is equal to 23.16 m^2 and the low- grade heat is approximately 3.6% of total energy need. Obviously, changes in DNI owing to the building latitude as well as changes in slope and orientation imply a larger SRS value.

Having said, energy balances with varying f PV/T values are shown in Figure 3.

From data, it emerges that as the PV/T heat fraction increases from 0.2 to 0.8 the corresponding primary energy consumption diminishes more than 56%. It is remarkable how the low-grade heat used to drive the CO_2-HP is approximately seven times higher than the reference layout one. Additionally, the larger the PV/T heat, the lower the CHP energy production as well as the higher the boiler contribution are. It means that, under the current hypothesis on building PTHR, when larger PV/T arrays are suitable, the energy system changes, in a step-wise fashion, towards highly electrified system which is HP technology-based.

Thereafter, the normalized primary energy consumption as a function of system layouts is depicted in Figure 4. Here, the achievable energy saving adopting the different options, compared with separated generation, can be immediately evaluated.

In order to investigate on correlation between the achievable energy saving and the foreseeable integration of RES within the energy systems, both PES and f_{RES} indicators are presented. The first one has been calculated according to Equation 1 as required by the current international regulations (Directive 2004/8/CE):

$$PES = 1 - 1 / [(\eta_{el,CHP} / \eta_{el,Grid}) + (\eta_{hr,CHP} / \eta_{h,boiler})] \quad (1)$$

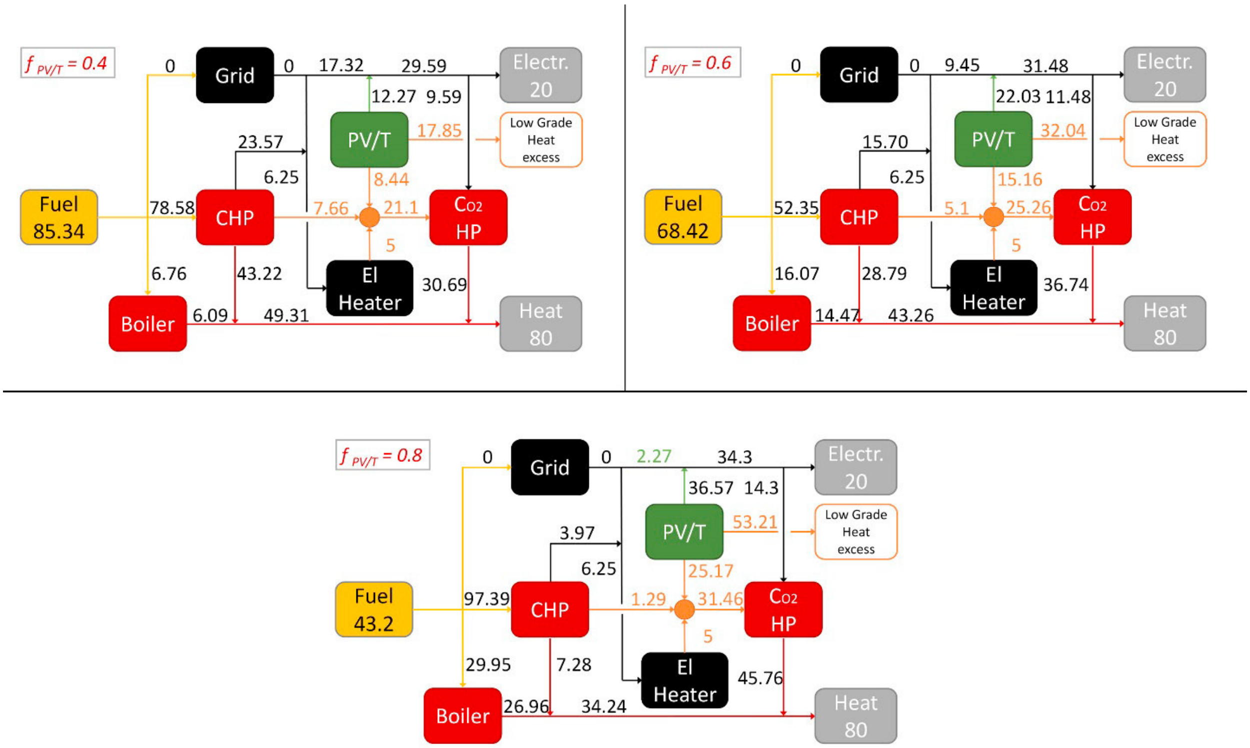

Fig. 3. Energy balance of Combined CHP, CO2 - HP, PV/T and Boiler system with changes in PV/T heat fraction. d1) $f_{PV/T}$ equal to 0.4; d2) $f_{PV/T}$ equal to 0.6; d3) $f_{PV/T}$ equal to 0.8.

Where $\eta_{el,CHP}$, $\eta_{el,Grid}$, $\eta_{hr,CHP}$ and $\eta_{h,boiler}$ denote the CHP system electric efficiency, the national grid electric efficiency, the CHP system heat recovery efficiency and the conventional boiler thermal efficiency respectively.

The second one indicator (Equation 2) reads generally as follows:

$$f_{RES} = (E_{el,PV/T} + E_{h,PV/T} + E_{aerothermal,HP}) / (E_{D,el} + E_{D,h}) \quad (2)$$

That parameter takes into account the overall applied renewable energy sources within the hybrid systems, including the aerothermal energy used by the 2-stage HP.

Hence, in accordance with Equation 2, f_{RES} denotes how much the renewables con-tribute to the End-user energy needs. It is worth of highlighting how a large renewable energy fraction does not lead to a proportional enhancement of PES value.

Indeed, looking at Figure 5, the f_{RES} trend with changes in system layouts is superimposed in the same chart related to PES. In detail, considering the CHP+2 stage-HP system, its f_{RES} is equal to 15% and it corresponds to a PES value of 26.74%.

Conversely, when the CHP+CO_2-HP+PV/T with $f_{PV/T}$ equal to 0.2 is adopted, a slight increase in PES occurs (i.e. from 26.74% to 28.59%) although only 8.89% of green energy is used.

Furthermore, as the $f_{PV/T}$ increases, both PES and renewable energy fraction curves increase, but they are characterized by a different slope.

Consequently, on the basis of data analysis, it is possible to generally state that a large renewables integration within the hybrid systems does not necessarily correspond to same amount of primary energy saving.

In addition, PES values of Figure 5 are always higher than the f_{RES} ones entailing a sort of leverage ratio on the overall system efficiency. It is noteworthy that all of those values are computed for the End-user PTHR equal to 0.25.

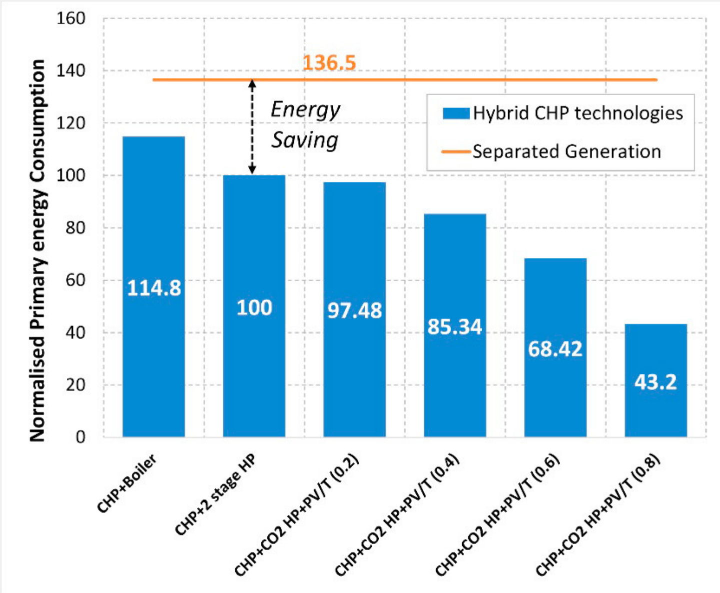

Fig. 4. Normalized PEC vs. system layout options with reference PTHR equal to 0.25.

Therefore, when PTHR varies, both PES and f_{RES} trendlines might change as well. For that reason, the same chart associated to the minimum and maximum PTHR are presented in the next sensitivity analysis. Finally, the renewable heat delivered to the end-user is dis-cussed. That indicator has been calculated by the Equation 3:

$$RH = (E_{ren,HP} / E_{D,H}) = (E_{h,PV/T} + E_{ren,EH} + E_{aerothermal,HP}) / E_{D,H} \quad (3)$$

Seeing that it is defined as the HP renewable external source to system heat demand ratio, it takes also into account the renewable electricity fraction to drive the electric heater which is connected to the cold heat sink of CO_2-HPs. So, Figure 6 summarizes in a comparative overview how the different devices contribute to meet the building total energy need (i.e. power and heat) along with the renewable heat fraction.

For instance, comparing data reported in Figure 6 relative to the b) scenario with the c) one, the renewable heat fractions are equal to 18.75% and 10.78% respectively.

However, even if the renewable heat is higher, the electricity produced by PV/T array significantly contribute to accomplish better energy performance. Then, as the $f_{PV/T}$ enhances up to 0.8 the renewable heat fraction increases largely up to 63.45% at the expense of CHP heat production. Indeed, the HP technologies show a growing energy share ranging between 22.73% and 37.96%. Furthermore, the corresponding TESHP values are equal to 31.25% for 2-stage HP and 57.2% for CO2-HP @0.8. The calculation of that parameter is done by means of the Equation 4:

$$TESHP = E_{h,HP} / E_{D,H} \quad (4)$$

Finally, it is important to point out how the role of CO_2-HPs becomes prevalent in heat production, as the $f_{PV/T}$ is higher.

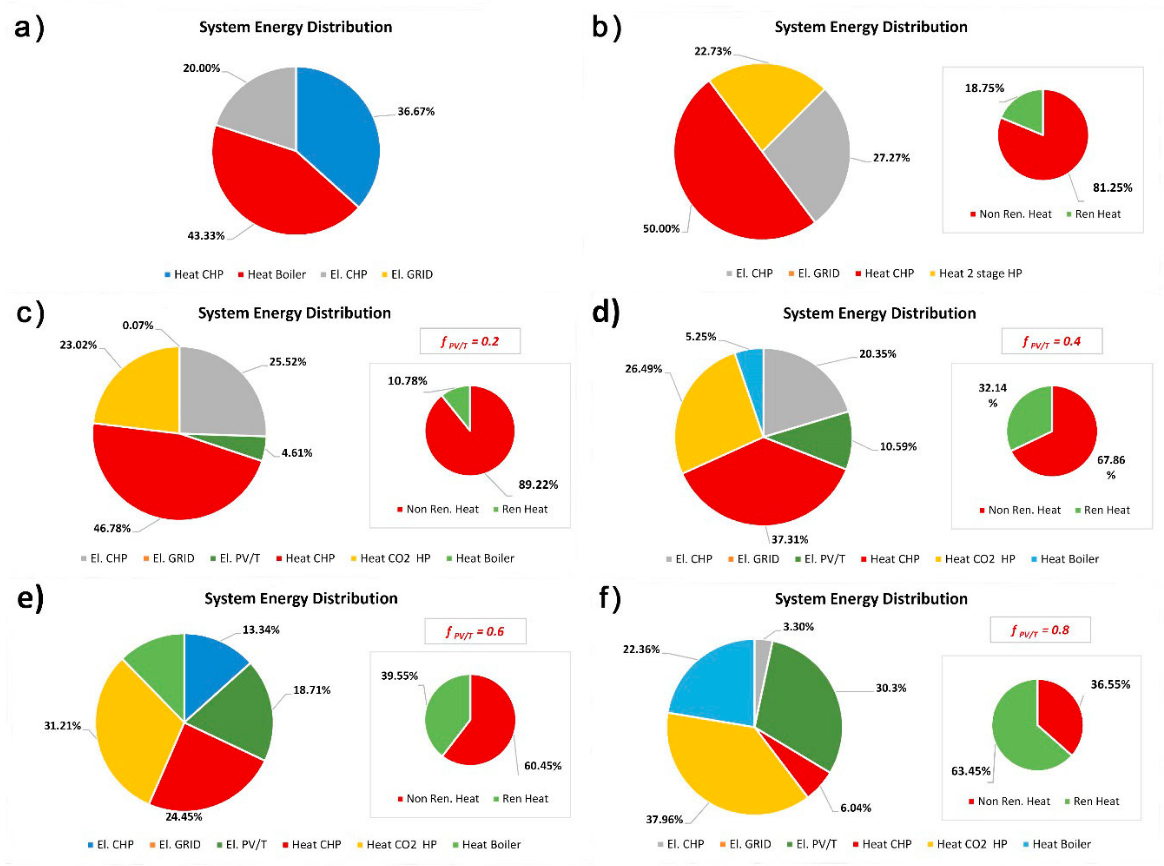

Fig. 6. Hybrid System energy distribution and renewable heat fraction. a) Traditional CHP and Boiler; b) Combined CHP and 2-stage HP system; c) Combined CHP, CO_2 - HP, PV/T and Boiler system with $f_{PV/T}$ equal to 0.2; d) Combined CHP, CO_2 - HP, PV/T and Boiler system with $f_{PV/T}$ equal to 0.4;e) Combined CHP, CO_2 - HP, PV/T and Boiler system with $f_{PV/T}$ equal to 0.6; f) Combined CHP, CO_2 - HP, PV/T and Boiler system with $f_{PV/T}$ equal to 0.8.

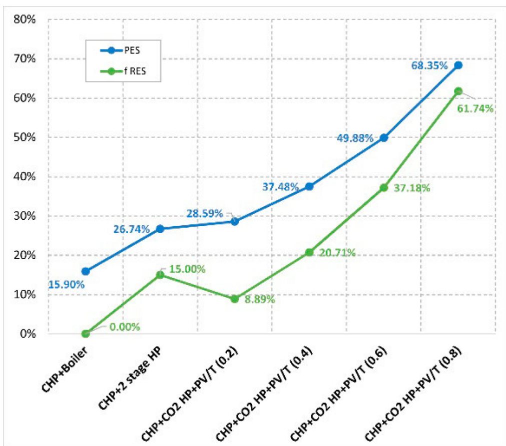

Fig. 5. Equivalent CHP primary energy saving indicator and renewable energy sources fraction vs. system layout options with reference PTHR equal to 0.25.

3.2. Sensitivity analysis

In this section, the outcomes of sensitivity analysis with varying the PTHR of each energy scenario is presented and discussed by the use of the main indicators. As a matter of fact, by this methodology it is possible to find the external boundary conditions affecting the system layouts competitiveness in comparison to the traditional energy production technologies (i.e. separated generation and CHP+Boiler). Figure 7 depicts the normalized primary energy consumption and the PES values associated to hybrid CHP plants as a function of building PTHR. Looking at the first chart (i.e. Figure 7 part a)) it can be noticed that the traditional CHP system is less sensitive to PTHR variations than other options. So, PEC values are almost constant when PTHR ranges between 0.05 and 0.52. Beyond that point, the curve slope changes and PEC function tends to increase quite linearly. This is due to the fact that, as the heat demand shrinks, the CHP electric production is gradually reduced to match the constraint of heat balance, and part of electricity has to be purchased from the National Grid. Nevertheless, the PES curve has a growing trend and a maximum point is registered corresponding to PTHR equal to 0.52. As regards the CHP+2-stage HP layout, the PEC function is characterized by a growing trendline. That solution results more efficient than the aforementioned one owing to the use of renewable heat provided by the 2-stage HP. Additionally, its competitiveness is high for small building PTHR, while the same performance of traditional CHP, are achievable for PTHR higher than 0.52. Thus, the primary energy saving curve has an opposite trend compared to the traditional CHP layout, showing a maximum value equal to 29.62% for the lowest PTHR considered in the simulations.

In the end, the energy system involving the CO_2-HP and PV/T array shows a different behaviour when building PTHR changes. Referring to the layout characterized by $f_{PV/T}$ equal to 0.2, a minimum PEC value of 97.48 can be noticed. Specifically, that lay-out is more effective than CHP+2-stage HP for PTHR ranging between 0.22 and 0.3. It entails that this option is suitable only for a specific building typology. Moreover, when $f_{PV/T}$ increases, the PEC minimum values shift towards higher PTHR.

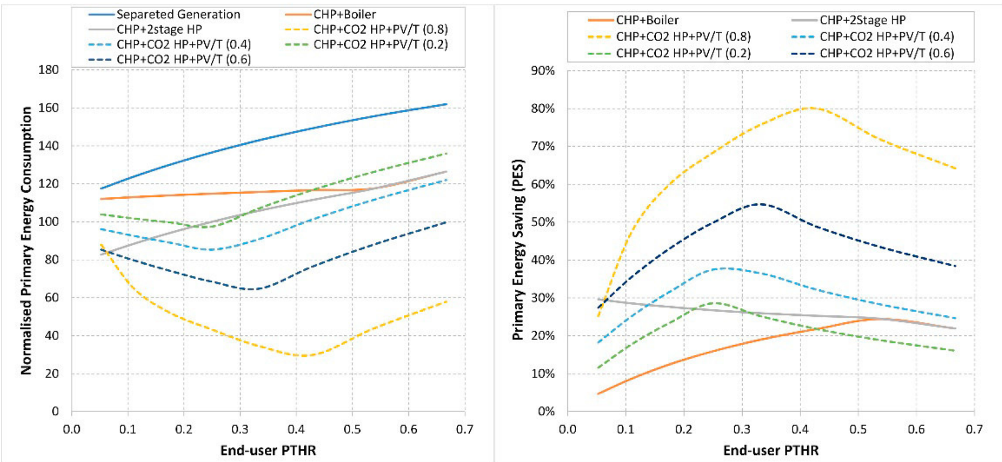

Fig. 7. Sensitivity analysis outcomes of simulated scenarios. a) PEC vs PTHR; b) PES vs. PTHR

Consequently, the optimized energy systems are feasible for buildings which re-quire more electricity. So, looking at Figure 7 part b), the minimum PEC values correspond to the maximised PES ones, accordingly. Yet, referring to the case study with $f_{PV/T}$ equal to 0.2, the maximum PES (i.e. 28.58%) is lower than the maximum one of CHP+2-stage HP anyhow, even if this latter occurs for a different PTHR.

Then, as mentioned in Section 2, the TESHP indicator variation has been investigated. All of the simulation results are plotted in Figure 8 where it can be noticed how TESHP associated to the 2-stage HP scenario, decreases linearly up to PTHR equal to 0.53. Conversely, in all other cases, TESHP increases linearly up to different PTHR thresholds depending on $f_{PV/T}$, and then, the curves slope changes. Therefore, beyond those limit PTHR values, the

CO_2-HP thermal energy fractions are almost constant be-cause the boiler does not operate. In those cases, only the CHP and HP are able to meet the building heat load.

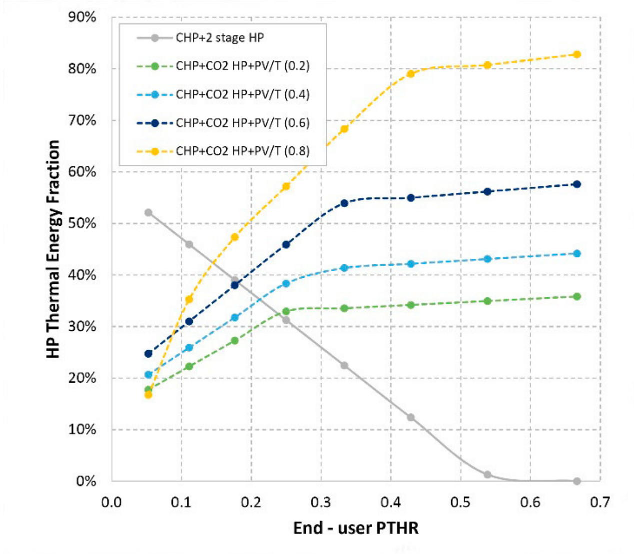

Fig. 8. TESHP as a function of PTHR

In order to provide a useful assessment tool to plant designers, the normalized low-grade heat production by PV/T array is presented in Figure 9. From data, it emerges that more thermal energy is required to drive the CO_2-HP once building PTHR and $f_{PV/T}$ in-crease. Moreover, the curves trendline are basically the same of those related to PES showing different maximum points. As a consequence, larger PV/T array sizes as well as higher available roof surfaces are required. By that chart, it is possible to calculate immediately the PV/T receiving surface by multiplying the site typical SRS value. Hence, when that indicator is calculated designers are able to make their choice complying with the building external constrains. In the end, the correlation between PES and f_{RES} for two different PTHR values is reported in in Figure 10.

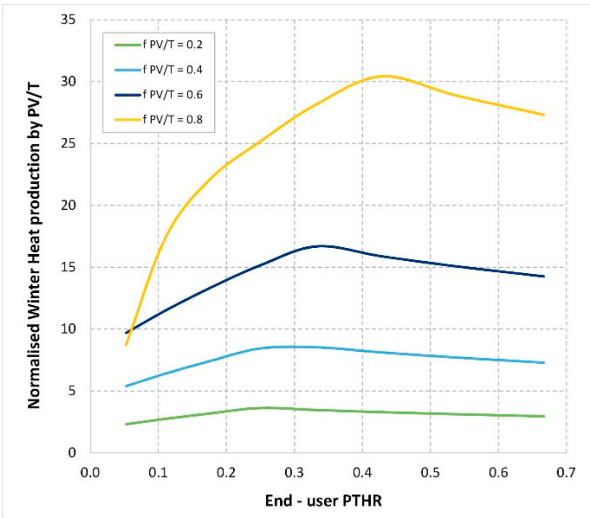

Fig. 9. Normalized heat production over the winter period by PV/T as a function of PTHR.

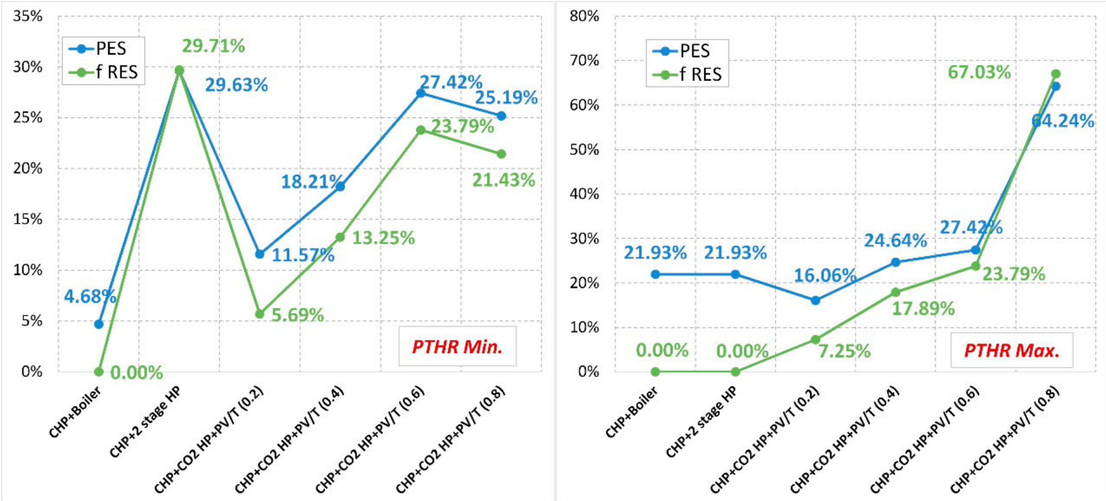

Fig. 10. Equivalent CHP primary energy saving indicator and renewable energy sources fraction vs. system layout options. a) Reference PTHR equal to 0.05; b) Reference PTHR equal to 0.67.

Specifically, Figure 10 part a), refers to PTHR equal to 0.05, while Figure 10 part b), refers to PTHR equal to 0.67. Looking at the first chart, it is possible to state that leverage ratio on PES deriving from renewables integration is almost null for CHP+2stage HP layout. In the other cases, the leverage ratio can be still registered and it decreases as fPV/T enhances. Yet, it is noteworthy that both PES and f_{RES} values, related to $f_{PV/T}$ equal to 0.8, are lower than the 0.6 ones. On the contrary, in the second chart (see Figure 10 part b)) the leverage ratio does not exist when $f_{PV/T}$ is 0.8.

Therefore, it is demonstrated that for such hybrid CHP systems a greater amount of renewable energy sources does not lead necessarily to higher PES and to proportional conversion efficiency enhancement.

4. Conclusions

In this work simulation results on innovative hybrid CHP systems for existing building are presented and they are compared to Separated Generation and to tradition-al CHP plants. Furthermore, a sensitivity analysis has been carried out on the main performance indicators with changes in building PTHR values. So, it is possible to identify the characteristic thresholds to assess the layouts competitiveness in terms of energy performance. The main findings can be outlined as follows:

- In the reference scenarios, when PTHR is equal to 0.25, the best layout option is the CHP+CO_2-HP+PV/T characterized by the lowest $f_{PV/T}$;
- When fPV/T increases up to 0.8 the equivalent primary energy saving can reach very high value such as 68.35%. Notwithstanding, the available roof surfaces has to be evaluated to make that technical option suitable.
- A leverage ratio to PES, due to the renewables integration, has been registered. It is generally not proportional to the renewable energy fractions allowing a more effective exploitation of carbon free sources;
- Sensitivity analysis shows how the energy efficiency of CHP+CO_2-HP+PV/T is strongly dependent on building typology, in terms of PTHR. All of sub-scenarios show different maximum PES values which shift towards higher PTHR as the $f_{PV/T}$ increases up to 0.8.
- When PTHR is equal to 0.05 the leverage ratio is approximately null for CHP+2- stage HP layout while CHP+CO_2-HP+PV/T at 0.8 does not provide additional benefit in terms of PES.

- When PTHR is equal to 0.68 the best option is always CHP+CO_2-HP+PV/T at 0.8 but a high renewable energy fraction, such as 67.03%, leads to a PES value of 64.24 only.

In conclusion, the authors believe that Hybrid CHP systems are the most promising technical solutions for buildings plant retrofitting in the short term. Nonetheless, it is well-known that an economic approach has to be applied so as to determine the actual cost effectiveness. Those issues will be addressed in the further development of this work.

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