Innovative Hybrid energy systems for heading towards NZEB qualification for existing buildings

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***Abstract*—This paper deals with the potential role of new hybrid energy systems application along with the heating share concept. It analyses the possibility to develop new plant refurbishment strategy so as to promote the deployment of small scale smart energy systems. Up to now, many new technologies have been implemented can be used for achieving the NZEB objectives. The paper clears up how is possible to share the heat for a small group of dwellings arranged in a single lot. Through the use of a new plant layout for high temperature heat production, it was possible to investigate and compare the results with the typical separated generation systems. Therefore, the new plant design allows the four dwellings to share a cold heat sink able to feed 4 trans-critical CO2 heat pumps. In this way, the four dwellings have been interconnected each other by that hydraulic loop while the electricity is generated by PV arrays and CHP. Outcomes of this comparative analysis has been reported and discussed.**

Keywords—CO2 Heat pump; PV; Heat sharing. Energy Efficiency.

I. Introduction

The envelope retrofitting actions to existing building stocks enhance their energy performance. To do so, the European Union promoted in the last years several directives dealing with the necessity to reduce the buildings energy demand [1].

In this framework, existing buildings energy efficiency represents a great challenge to cope with. [2] This is mainly due to the fact that it is not easy to select the best measure matching with restrictive regulations and architectural constraints as well. Indeed, it may lead to the selection of "non-invasive" but less performing building elements. In addition, a search is ongoing to find innovative technological and plant engineering solutions, based on the study of highly efficient materials [3] and innovative energy generation systems [4-7]. Several studies demonstrated the long pay-back period related to those interventions, occurring up to 25-30 years later [8,9]. Thus, the renewable energy sources integration in such buildings is either very often not permitted or strongly limited for landscape issues even if the plants installation is feasible from a technical point of view. Having said, 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.

This paper deals with the potential role of new hybrid energy systems application along with the heating share concept and district heating [10,11] providing both electricity and heat which are compatible with the aforementioned limitations. Moreover, the work analyses the possibility to develop new plant refurbishment strategy so as to promote the deployment of small scale smart energy systems for heading towards the NZEB qualification [12-14].

The hybrid energy system is considered an encouraging approach for future buildings, in order to achieve a reduction in CO2 emissions, savings in terms of primary energy and a suitable building oriented towards a future NZEB [15-17]. In detail, the paper clear up how through the use of an innovative hybrid energy system it is possible to share the heat for a small group of dwellings arranged in a single lot.

II. Methods

When we talk about space heating and domestic hot water, the choice of the device is essential for obtaining good energy and economic performance. For a single-family home, the most common heating device is the conditioning boiler even if the use of solar systems, cogenerators (CHP) and heat pumps are the best solutions to improve efficiency [18].

The new plant layout options for high temperature heat production (i.e. for water supply temperature equal to 65 °C-70 °C), along with the electricity generation, were investigated

This research has been carried out within the "Renovation of existing buildings in NZEB vision (nearly Zero Energy Buildings)" Project of National Interest (Progetto di Ricerca di Interesse Nazionale - PRIN) funded by the Italian Ministry of Education, Universities and Research (MIUR).

and compared to the typical separated generation system. Specifically, a group of four dwellings have been considered as case study and the power plant consists of a combination of an air source heat pump (35kWt), a micro CHP (6 kWe - 10 kWt), four trans-critical CO2 electric heat pumps (CO2-HPs of 12kWt) and PV arrays (7 kWp). The analyzed housing complex consists of 4 dwellings of about 170 m^2, built on two floors and arranged close to each other. The distribution system is placed in a central position respect to the buildings, to minimize dispersion and promote the plants performance. Moreover, two dwellings are equipped with a photovoltaic system placed on the roof surface of the building.

In detail, the traditional heat pump is dedicated to produce low grade heat, i.e. at 35°C, by means of a water loop representing the shared cold heat sink for the CO2-HPs. In this way the four dwellings have been interconnected each other by that hydraulic loop as in a small-scale district heating plant. Therefore, CO2-HPs are thermally driven by that shared heat sink and the electricity is generated by PV arrays and CHP. Finally, the CHP is able to provide continuously Domestic Hot Water (DHW) in a centralized way. Yang, Ma, Li, and Hua, verified and validated a trans-critical CO_2 heat pump model that shows that decreasing inlet temperature and increasing mass flow rate of cooling water cannot only increase the system performance but also reduce the optimal heat rejection pressure, at which the maximum COP can be obtained [19]. The research focused mainly on the design of a smart energy system based on the use of transcritical CO_2 heat pumps.

This paper first makes a review of the scientific literature within the field. Smart Energy Systems take an integrated holistic focus on the inclusion of more sectors (electricity, heating, cooling, industry, buildings and transportation) and allows for the identification of more achievable and affordable solutions to the transformation into future renewable and sustainable energy solutions [20].

All the hybrid systems components were simulated by a dedicated MATLAB energy model and were analyzed on the basis of four main indicators such as Primary Energy Consumption (PEC), Primary Energy Saving (PES), renewable energy fraction (fRES) and renewable heat delivered to the end-user. In the end, since the building Power To Heat Ratio (PTHR) is a meaningful parameter which plays a key role in defining the most effective sizing process, a sensitivity analysis was carried out with varying that value in a wide range (0.1-0.8). The mathematical models produced (traditional heat pump, trans-critical CO_2 electric heat pump, CHP and PV) are used to simulate the performance of the innovative plant solution and the results are compared to verify the accuracy of the simulation model. Finally, a sensitivity analysis was carried out which allowed to estimate the final values with percentage variations. In detail, were chosen a variations of 15%, the results were compared and discussed.

III. Mathematical Modelling

In accordance with the foregoing, the hybrid system was simulated with the mathematical MATLAB Simulink model. The schematic diagram of the proposed innovative hybrid energy system is shown in "Fig.1" and consists in four trans-critical CO2 electric heat pump (CO2-HP) connected an air source heat pump to thermally drive shared heat sink, a micro CHP to provide continuously domestic hot water, and PV arrays to generate electricity.

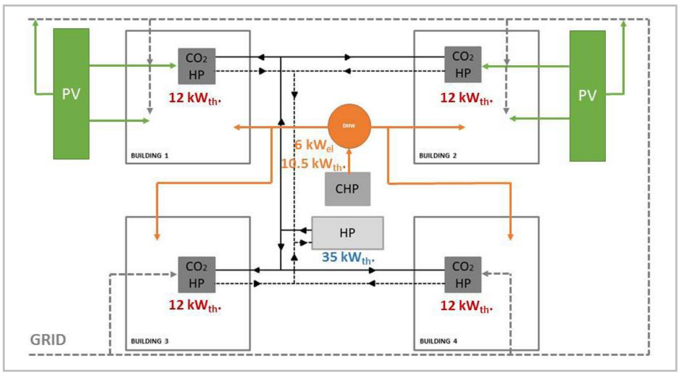

Fig. 1. Hybrid energy system layout

Natural refrigerants are the green alternative to Freon, with a very low environmental impact. With minimum values of ODP (Ozone Depletion Potential) and GWP (Global Warming Potential) they are respectful of the atmospheric ozone layer and contribute to global warming below the limits established by the Kyoto protocol.

The specific characteristics of carbon dioxide, in addition to good heat transmission properties, reside in a high volumetric cooling capacity, which allows the use of small displacement compressors. Thanks to the high efficiency of the compressor e excellent CO2 transport properties The COP of a real CO2 system could be significantly higher [21].

The peculiarity of carbon dioxide compared to other refrigerants consists in an accurate system designed specifically to cope a characteristic state diagram (P/T). Since CO2 is not toxic, it is not flammable, it is not subject to any patent and there are no use limitations all over the world, its costs of production and distribution is contained compared to other refrigerant gases [22,23]. Over the years, several experimental studies have been carried out on transcritical CO2 systems, and since they cannot be assimilated to conventional cycles, they must be studied carefully. Although such experiments are useful and provide valuable data, they are often expensive and time-consuming. For this reason, it was necessary to use cheaper approaches to study the practical applications of the transcritical cycle, such as the use of numerical simulations. Modeling of a transcritical carbon dioxide heat pump system is conducted based on thermodynamic analysis and based on the transport characteristics of the refrigerant and secondary fluid.

In detail, there are two factors that require the utmost attention when using CO2 as a refrigerant, the low critical temperature and the high working pressure [23,24], in particular carbon dioxide reaches its critical point at a temperature of 304, 13 K (31 ° C) and at a pressure of 7.375 * 10 ^ 6 (73.75 Bar). The system model consists mainly of five modules, a compressor, a gas cooler, an internal heat exchanger, an evaporator and an expansion valve. The developed algorithm simulates the thermodynamic properties of CO2 within the heat pump, in transcritical conditions.

The design pressure reaches 170 bar inside the gas cooler and 70 bar to the evaporator, with a compression ratio calculated as p2/p1 equal to 2.428. The temperature of the CO2 inside the cooler gas passes from 120 ° C to 63.6 ° C reaching a temperature of 28.67 at the evaporator. These values are shown in the Pressure-Enthalpy diagram “Fig.2” and detailed in table I.

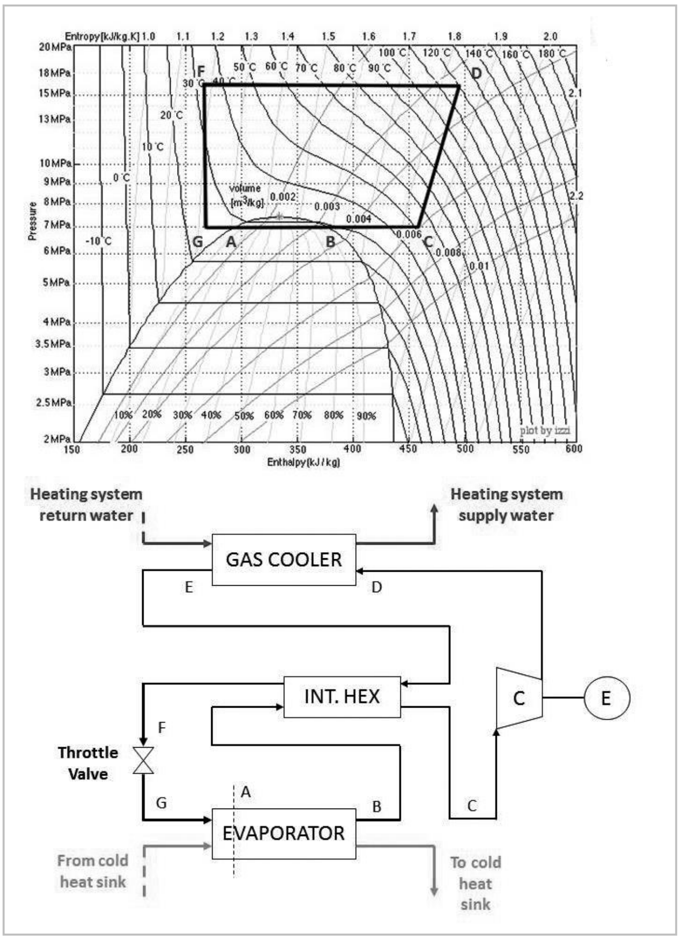

Fig. 2. P-h diagram Carbon Diovìxide Refrigerant [R744]

TABLE I. TRANSCRITICAL CO_2 HEAT PUMP PARAMETERS

Component	CO2 parameter		Water parameter	
Gas cooler	T=120 [°C]	P= 17 [MPa]	55 °C Inlet	65 °C Outlet
Internal heat exchanger	T=33.67[°C] T=28.67[°C]	P= 17 [MPa] P= 7 [MPa]	-	-
Expander	T=28.67[°C]	P= 7 [MPa]	40 °C Inlet	35 °C Outlet
Compressor	T =52[°C]	P= 7 [MPa] P= 17 [MPa]	-	-

The efficiency of the heat pumps is measured by the coefficient of performance (COP) given by ratio between energy yield (heat transferred to the environment to be heated) and the electricity consumed. The COP of the CO2-HPs systems is influenced by various operating variables, such as the water outlet temperature or the outside temperature, and it is around COP 4.

The new plant design allows the four dwellings to share a cold heat sink (at 35-40 °C) able to feed the four trans-critical CO2-HPs where the low grade heat is produced by a traditional HP with a COP of 4.5. Therefore CO2-HPs are thermally driven by the shared heat sink and the electricity is generated by PV arrays and CHP. In detail, the two dwellings facing south are equipped with a photovoltaic system for peak power of 7 kW. Finally, the CHP is able to centrally supply continuous DHW thanks to the use of an hot thermal storage. For this first system analyzed, the following balance equations were considered:

Electric Balance :

$$E_{el,Build} + E_{el,HP} = E_{el,CHP} + E_{el,PV} + E_{el,Grid} + E_{el,Excess} \quad (1)$$

Thermal Balance:

$$E_{H,Build} + E_{DHW} = E_{H,HPCO2} + E_{DHW,CHP} \quad (2)$$

In the NZEB perspective all of the hybrid systems components were analyzed on the basis of four main indicators such as Primary Energy Consumption (PEC), Primary Energy Saving (PES), renewable energy fraction (fRES) and renewable heat delivered to the end-user. In the end, since the building Power To Heat Ratio (PTHR) is a meaningful parameter which plays a key role in defining the most effective sizing process, a sensitivity analysis was carried out with varying that value in a wide range (0.1-0.8). The Primary Energy Saving is given by the difference between the Primary Energy consumed by the reference system and the energy consumed by the hybrid system. These values have been calculated as follows:

$$PEC = E_{fuel,CHP} + E_{fuel,Grid} \quad (3)$$

$$fRES = \frac{E_{pv} + E_{Hp}}{E_{H,Build.} + E_{el,Hp} + E_{DHW}} \quad (4)$$

$$PTHR = \frac{E_{el,Build.}}{E_{H,Build.} + E_{DHW,Build.}} \quad (5)$$

The research continued with the study of a traditional system that uses the boiler for the production of heat and domestic hot water. Also in this case, the equations taken into consideration are shown below.

Electrical Balance:

$$E_{el,Build} = E_{el,Grid} \quad (6)$$

Thermal Balance:

$$E_{H,Build} = E_{H,Boiler} + E_{H,BoilerDHW} \quad (7)$$

Once the reference values were obtained, the performance indicator were calculated and compared with the hybrid system. Finally, in the last part of the research, a sensitivity analysis was calculated comparing the nominal case with two hypothesized cases. Sensitivity analysis was calculated as the ratio between thermal energy and electrical energy.

IV. Results

A parametric study is conducted to determine the systematic response of the transcritical CO2 cycle subject to different operating conditions and how the entire hybrid system is influenced accordingly, compared to a NZEB perspective of buildings. The results are discussed and compared with the findings previously reported in the literature. Finally, a brief discussion on the values obtained from the different performance indicators was considered. The entire hybrid system has been evaluated according to its final efficiency, to then be compared to a traditional system that use a boiler for heating and DHW production. Moreover this system does not foresee any renewable energy supplement as there are no PV panels, and the entire electricity is bought from the grid. Efficiency results were compared with the innovative hybrid system and discussed. In the first analysis, considering the case of the hybrid system, the total thermal energy produced was evaluated by the sum of four CO2 heat pumps, a CHP and a traditional HP energy. The results have been reported in percentages in "Fig.3".

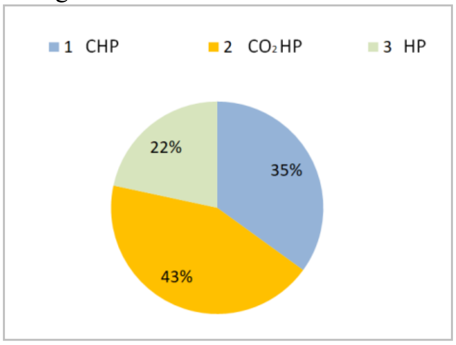

Fig. 3. Total termal energy

As can be seen from the graph, the energy percentage of the 4 HPs obtains the largest slice with a value of 43%, then follows the CHP with a percentage of 35%, and finally the traditional heat pump with the 22 %. In this case, the total efficiency of the system was calculated as 0.8466, considering the electricity purchased in part from the national grid and partly sold, thanks to the use of PV panels. In "Fig.4" the amount of energy bought during the year is shown in light blue, while the energy produced is shown in dark blue.

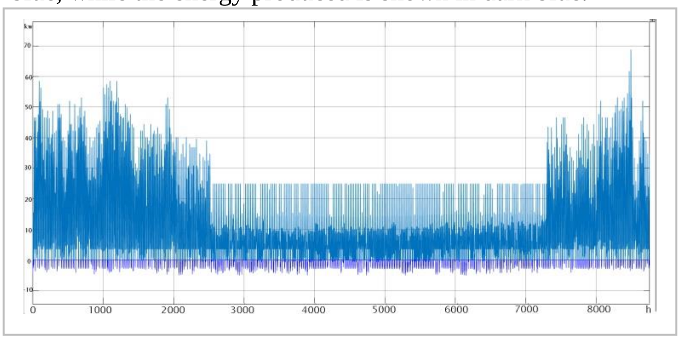

Fig. 4. Electrical demand and electricity excess

Moreover, "Fig. 5" shows a comparison between the electric load of the four buildings and the electric production of PV panels, located on two of them.

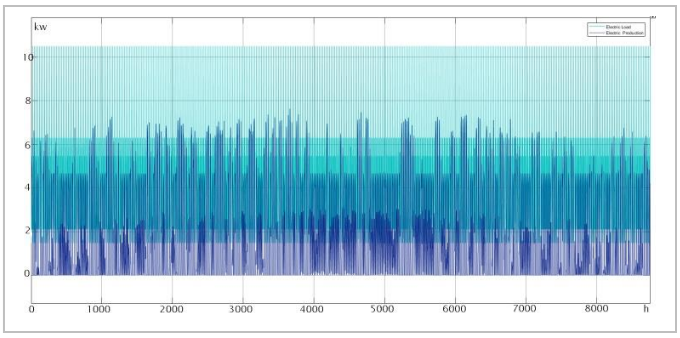

Fig. 5. Electric load Vs PV electricity produciton

It was therefore possible to synthesize the entire energy produced by the hybrid system in a histogram "Fig. 6" and the traditional energy system in "Fig.7" in which we find the electrical demand, heat and DHW demand, jointly with PV and electricity excess.

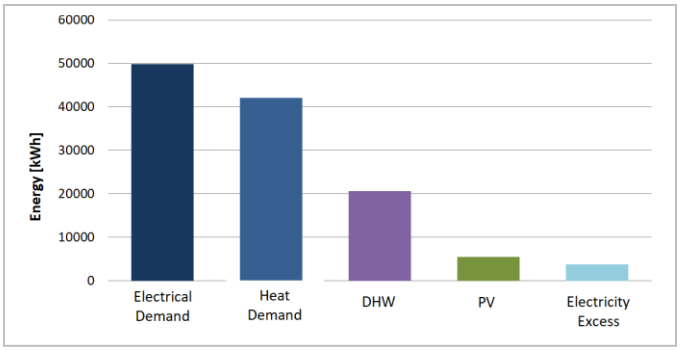

Fig. 6. Total energy produced in the hybrid energy system

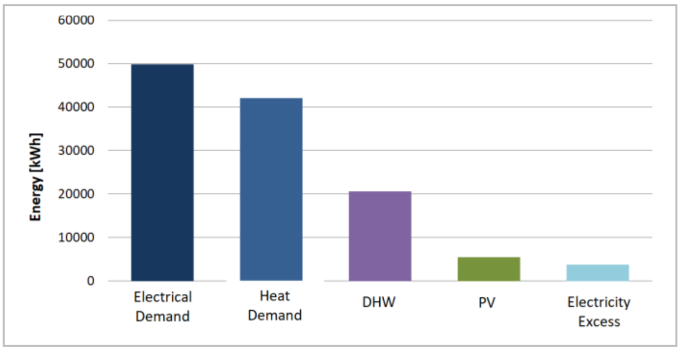

Fig. 7. Total energy produced in the traditional energy system

The overall efficiency of the system was also assessed considering the performance indicators described above.

As previously mentioned, the simultaneous study of a traditional system has made it possible to compare the results and clearly identify the energy saved by choosing to adopt an innovative energy system. The same work carried out and visible from the above graphs, was then produced for the second case equipped with boilers with 0.6477 system efficiency. All comparative and mentioned results are reported in tables II and III.

TABLE II. COMPARISON BETWEEN HYBRID AND TRADITIONAL SYSTEMS

	HYBRID SYSTEM	**TRADITIONAL SYSTEM**
HEATING EFFICIENCY	2.3105	0.7289
DHW EFFICIENCY	0.5190	0.7996
RES FRACTION ON ELECTRICITY	0.1027	-
RENEWABLE HEAT FRACTION	0.4209	-

TABLE III. HEAT TRANSCRITICAL P HYBRID AND TRADITIONAL SYSTEMS PERFORMANCE INDICATORS

PERFORMANCE INDICATOR	**HYBRID SYSTEM**	**TRADITIONAL SYSTEM**
PEC [KWH]	137517.27	168001.050
PES [KWH]	30483.78	
FRES	0.2742	-
SYSTEM EFFICIENCY	0.8466	0.5845

What we can see from the reported data is that the thermal efficiency as well as the overall efficiency is higher in the hybrid system. For the approach taken into consideration, the net ZEB target is more difficult to obtain for fossil fuel energy supply systems. The use of electricity is favored over fossil fuels (e.g. heat pumps against fossil fuel boilers); furthermore, the renewable energy ratio is not zero, as it includes off-site electricity generated from renewable sources [25].The last phase of the study focused on a sensitivity analysis assuming initially an increase in building electrical loads of 15%, and then a 15% decrease. These results are shown and described in table IV.

TABLE IV. PTHR VALUES INCREASING AND DECREASING BUILDING ELECTRIC LOADS OF 15%

	ELECTRICAL LOAD [KWH]	**PTHR**
HYBRID SYSTEM	35463.036	0.565301
+15%	40782.4914	0.650096
-15%	30143.58	0.480506

The performance indicator evaluated with a variation of 15% are shown in figure 8.

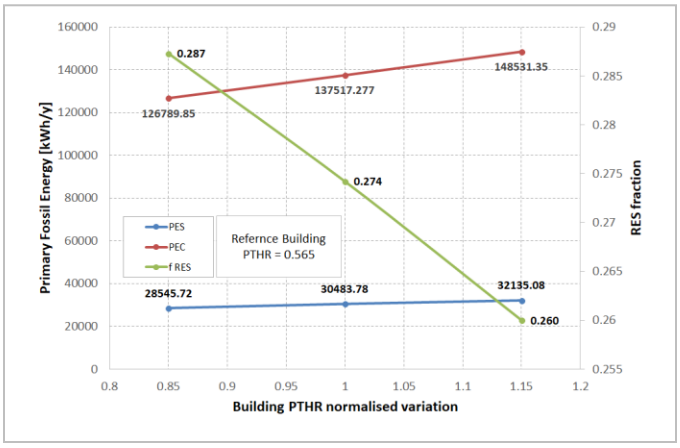

Fig. 8. Performance indicators

Some considerations of the chart:

- The renewable fraction decreases with the increase in PTHR; the total energy required by the system has increased, not modifying the renewable production.
- The PES instead increases with the PTHR because it decreases the excess electricity sold to the network.
- The PEC increases because there is a higher demand for electricity from the network

V. CONCLUSIONS

CO_2 is recognized as the most economically advantageous alternative for industrial plants, refrigerated warehouses and freezing facilities, even considering the costs of the equipment adjustment. In some cases, however, this reluctance has prompted implant designers to take in consideration of other types of natural refrigerants. Already in the thirties it was used in the refrigeration systems of ships and for the last century conditioning of buildings, considering that in both applications a refrigerant was required "sure"; at its disadvantage they play its thermodynamic properties, or its critical temperature and its critical pressure.

CO_2 is already widely used in many applications both in small plants and in large facilities for hypermarkets. The carbon dioxide refrigeration plants installed in the world are now very numerous, but they go spreading also for small plants and will surely have more success in the future, especially for its negligible environmental pollution and its energy efficiency.

In addition, CO_2 is preferred in those applications where losses cannot be avoided and in applications with greater energy efficiency, which can be achieved precisely through the use of this fluid and its characteristic cycle. In this article, definition of NZEB is reviewed as well as development trend. Several promising and mature energy-efficient measures for NZEB, such as Transcritical CO_2 heat pump, CHP, PV renewable source, are briefly introduced. In addition, evaluation indicator and relevant research methodology are reviewed. Some conclusions are drawn as follows:

1) comparing the hybrid system with the traditional one, a primary energy saving of -18% can be accomplished. Therefore, by substituting the most common technologies with the new commercial ones, and by the adoption of the heat sharing philosophy an overall conversion efficiency equal to 84.66% has been registered.

2) even though the CHP application for DHW production shows a lower efficiency due to the CHP heat recovery efficiency, the electrical output contributes positively to reduce the fossil primary energy consumption of the whole system.

3) By the use of PV and CHP a lower electricity purchase is attainable; notwithstanding, a large electricity excess is sold to the Grid by the Net metering option.

Whether electrical storage devices were applied, a better renewable energy exploitation will be obtained, increasing the dwellings energy classification.

4) The COP of the CO_2-HPs is strongly influenced by several operating parameters, such as the water supply temperature, the end-user temperature drop as well as the cold heat sink temperature. Additionally the CO2 supercritical conditions impose specific outlet temperature from the gas cooler in order to produce hot water compatible with high temperature emission systems. In that way, CO2-HPs are able to operate with COP = 4.

5) From sensitivity analysis it emerges that as the building PTHR increases the fRES decreases almost linearly. Nevertheless, the Hysys primary fossil energy consumption is higher than the reference scenario one, but the energy saving, compared with the traditional system, slight increases of 5.4% more.

6) The CO2-HPs adoption for boostering the air-source HPs heat production along with the hybridization concept are the viable solution for heading towards the NZEB qualification.

The next step of the research will be to perfect the energy hybrid system by making the most of the potential that the CO2 refrigerant can provide. We are projected into a future where environmental regulations limit the use of harmful refrigerants, so it will be nearly possible that transcritical CO2 heat pumps will become increasingly used.

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