IOP Conference Series: Earth and Environmental Science

PAPER • **OPEN ACCESS**

Improving efficiency and renewables utilization by hybrid heating plants for industrial buildings

To cite this article: M Noro *et al* 2022 *IOP Conf. Ser.: Earth Environ. Sci.* **1106** 012013

Improving efficiency and renewables utilization by hybrid heating plants for industrial buildings

M Noro[1,*], S Mancin[1] and F Cerboni[2]

[1]Department of Management and Engineering, University of Padova, 36100 Vicenza, Italy
[2]Officine Termotecniche Fraccaro s.r.l., 31033 Castelfranco Veneto, Italy

[*]Corresponding author email: marco.noro@unipd.it

Abstract. In this paper, a typical industrial building was modelled using a dynamic simulation software in three very different climatic zones in Italy. On the basis of the thermal loads, a hybrid condensing radiant tubes heating system was modelled. The radiant tubes system was coupled to an air heating system with terminals placed in the building fed by two heat sources: one deriving from the condensation of the exhausted of the radiant tubes, and the other by a heat pump with external air heat source. The energy performance of the hybrid heating system was evaluated by optimizing the nominal power of the heat pump, the bivalent temperature in alternative bivalent operation (the system gives priority to the heat pump, which switches off when the outside air temperature drops below the bivalent temperature and the radiant tubes turn on), and the peak power of the photovoltaic system on the roof of the building. This analysis was performed taking into account the variation in heat pump performance with the outside air temperature. The optimal configuration of the hybrid heating system (minimizing the annual amount of total non-renewable primary energy and maximizing the non-renewable primary energy ratio) was then compared to some more traditional heating systems for industrial buildings to evaluate the energy advantages of this innovative solution.

1. Introduction

Industrial buildings have different characteristics with respect to commercial and residential: some equipment could be present on the ceiling or walls (pipes and tubes, bridge cranes, etc.), heights are typically higher (could be more than 8 m), floor areas are very large with different kinds of occupation by workers, doors can be large and can be opened often. Moreover, comfort conditions requested are typically different, and thermal insulation of the walls and ceiling is usually scarce [1].

These conditions make traditional climatization plants not common in industrial buildings. Instead, high temperature radiant heating systems and air heater systems can be used because they are quite easy to install and with relatively low installation costs. Different air systems are available on the market: ground or wall-mounted air heaters fueled by natural gas or supplied by hot water, and mechanical ventilation plants [1]. More recently, high temperature radiant systems have been proposed, like radiant tubes equipped with small gas burners, or the more traditional types of panels heated by pressurized water or steam, or the electrical radiant panels [2] [3]. Such systems feature some positive characteristics: the heat flux can be directed towards the zone of interest, so comfort conditions can be reached with a lower air temperature [4] [5]. In the last decade, low temperature radiant heating floor systems have been installed in new industrial buildings with a higher level of thermal insulation, also due to the large diffusion of condensing boilers [6].

Recently, the indoor comfort conditions and energy performance of an innovative condensing radiant tubes plant have been studied by the authors [7]. The system has been dynamically simulated by coupling a heat exchanger to condense the exhausted from the tubes. Hot water produced alimented wall-mounted air heaters, which improved the thermal efficiency of the system. The primary energy saving was 7% with respect to a radiant floor coupled to a condensing boiler, but it could reach 30% when compared to a traditional air-heating system. As an additional advantage, better thermal comfort conditions could be allowed in the morning operation of the plant.

In the present study, a hybrid heating system is analyzed as a further development. An air-water heat pump is coupled to the condensing radiant tubes plant (condensing radiant tubes + heat pump system, CRT+HP). Heating is provided by both radiation (the radiant tubes) and convection (the wall mounted air heaters). The latter are fed by hot water (40 °C) by the condensation of the exhausted and by the heat pump. The scope of the study, based on simulations on Trnsys rel. 17 software, is to determine the values of external air bivalent temperature, the nominal thermal power of the heat pump, and the peak power of the photovoltaic plant installed on the roof in order to:

- minimize the $PE_{nren,tot}$ (annual total non-renewable primary energy consumed by the hybrid plant);
- maximize the $PES_{nren,tot}$ (annual total saving of non-renewable primary energy compared to traditional heating systems);
- satisfy the minimum value of the renewable quota (*QR*) according to Italian Legislative Decree 199/2021 (implementation of the Renewable Energy Source II Directive). *QR* has to be at least 60% referring to the considered services (only heating in this work). *QR* is defined as the ratio between annual quantities of the renewable primary energy used (delivered or produced on site, calculated using the conversion factors ($f_{p,ren}$) for natural gas, electricity from the grid, electricity from the photovoltaic system, thermal energy from the external environment as heat source of the heat pump) and of the total primary energy used (renewable + non-renewable), calculated using the conversion factors ($f_{p,tot} = f_{p,ren} + f_{p,nren}$) for each energy carrier delivered or produced on site.

The best solution is then compared to three benchmark heating systems:

- only condensing radiant tubes (CRT));
- air heater based system (Air);
- radiant floor coupled to condensing boiler (condensing radiant floor, CRF).

In order to consider both modern and old plants, the thermal efficiency of the generators for both Air and CRF is varied in suitable ranges.

2. Methods

Three steps are conceived for this study:

- calculation of the heating load in three different climates by modelling a typical industrial building (based on a real case) [7];
- determination of the best set of bivalent temperature in alternative bivalent operation, HP thermal power and PV peak power installed on the building roof. In alternative bivalent operation the system gives priority to the heat pump, which switches off when the outside air temperature drops below the bivalent temperature and the radiant tubes turn on. The hybrid condensing radiant tubes + heat pump system is modelled, and the energy performance for each climate are analyzed;
- modelling of the three benchmark heating systems and comparison of the energy performance with the CRT+HP hybrid system.

2.1. *Industrial building modelling*

The climate conditions of the simulated industrial building are reported in Table 1, while the size and characteristics of the opaque and transparent structures are not reported for the sake of brevity [7]. Other hypotheses consider an operation heating plant scheduling from 6.00 am to 6.00 pm, a presence of people and lighting scheduling (heating gain fixed at 5 W m^{-2}) from 8.00 am to 6.00 pm, and a presence of people of 48 persons, degree of activity of 2 met, and clothing of 1 clo. Air infiltration was supposed to be 0.5 volumes per hour. The daily heating needs determined by the dynamic simulations of the building for a heating period supposed to be from 15th September to 30th April are reported in Figure 1.

Table 1. General climatic data for the heating.

Type of building use (DPR 412/93)	E.8 Building for industrial activity		
Climatic zone	D	E	F
Resort (Province – State)	Roma (Roma – Italy)	Manta (Cuneo – Italy)	Agordo (Belluno – Italy)
Altitude a.s.l.	20	400	610
Latitude North	41° 54’	44° 36’	46° 17’
Longitude East	12° 29’	7° 29’	12° 00’
Degree Days	1415	2814	3376
Outdoor design air temperature	0 °C	-9.3 °C	-12 °C

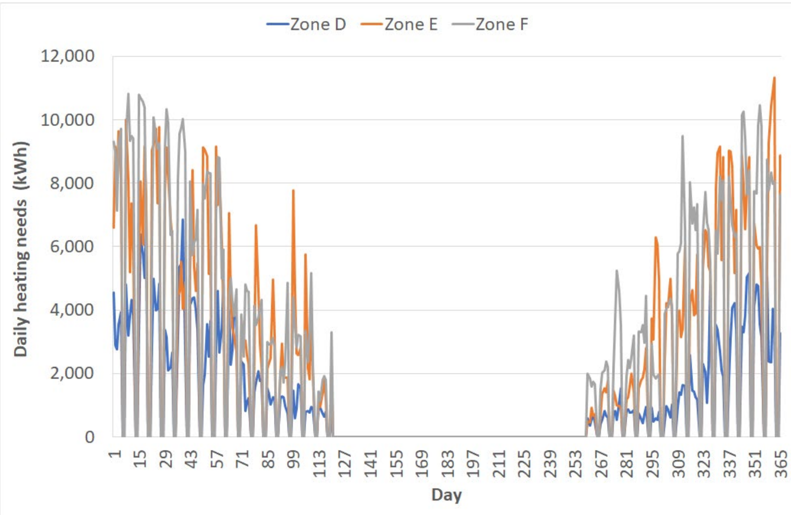


Figure 1. Thermal energy for daily heating needs for the three thermal zones (both sensible and due to infiltration of outdoor air).

2.2. *CRT+HP, CRT, Air, and CRF systems modelling*

In the hybrid configuration (CRT+HP), an air-water heat pump is coupled to condensing radiant tubes to increase the utilization of renewable energy. A suitable thermal energy storage (1000 L) decouples wall mounted air heaters from the hot water produced at 40 °C by the condensing heat exchanger and the heat pump (Figure 2a).

The combustion air flow rate is controlled by an exhausted tab that recirculates part of the exhausted to keep the excess air at the minimum value at part load operation (that is, when natural gas fuel is regulated by a proportional valve).

The dynamic operation of the system is simulated in Trnsys by coupling types 607 and 659. The former has been modified in order to simulate the behavior of the high temperature radiant tubes system. At the start of operation, the CRT burner is turned on at maximum power to obtain the maximum exhausted temperature. When the temperature of the indoor air increases near the set point, thermal power of the CRT burner is modulated by controlling the proportional valve of natural gas to have the fuel mass flow rate that is necessary to produce the heating load requested at that time step. Fuel modulation decreases the exhausted temperature and the exhausted tab is regulated to have the correct minimum air excess in the burner (Figure 2b) [7].

The heat pump, whose nominal data are reported in Table 2, is simulated by means of type 941.

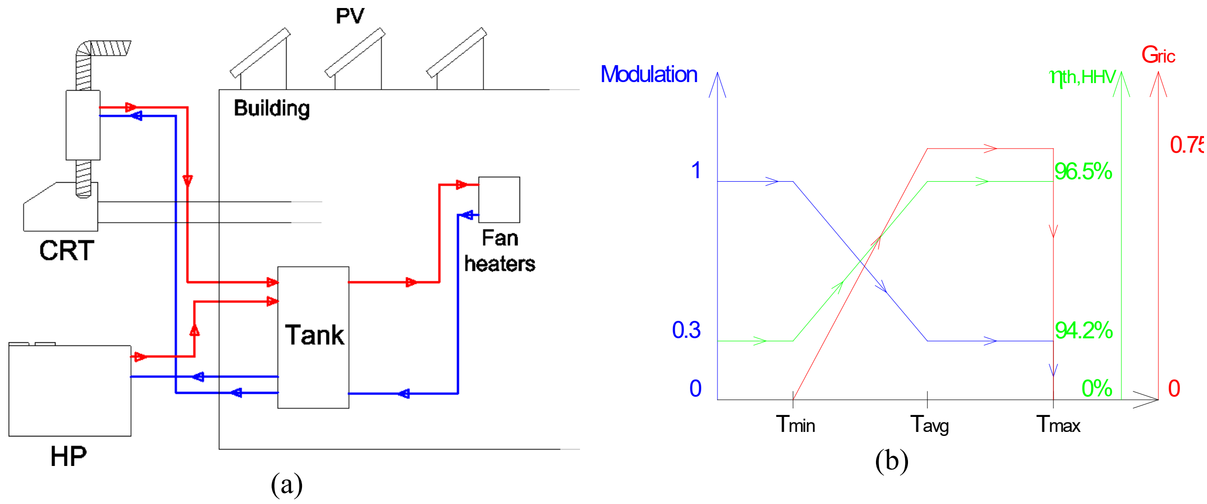


Figure 2. (a) Schematic of the CRT+HP plant; (b) Control logic of the proportional valve of natural gas (blue) and the exhausted tab (red). G_{ric} (recirculated exhausted mass flow rate) is expressed in terms of the fraction of the return flow of the radiant tubes. Thermal efficiency (on HHV) versus modulation is reported as well (green). In the simulations, the hypotheses are T_{min}=17 °C, T_{avg}=17.5 °C, T_{max}=18 °C.

Table 2. Nominal data of the air-water heat pump (mod. Clivet Spinchiller WSAN-XSC3 90.4) (D.B.=dry bulb temperature; W.B.=wet bulb temperature).

T_{ext} (°C)		$T_{out,cond}$ (°C)					
D.B.	W.B.	35			40		
		kW_{th}	kW_{el}	COP	kW_{th}	kW_{el}	COP
-7	-8	205.0	60.8	3.37	203.0	67.8	2.99
-5	-6	216.0	61.2	3.53	214.0	68.0	3.15
0	-1	245.0	62.4	3.93	243.0	68.9	3.53
2	1	260.0	62.8	4.14	256.0	69.4	3.69
7	**6**	**297.0**	**64.1**	**4.63**	**290.0**	**70.7**	**4.10**
12	11	344.0	65.7	5.24	336.0	72.1	4.66

The heat pump has priority operation, providing the thermal power to face the heating load according to the external air temperature T_{ext}. It operates in an alternative bivalent mode, i.e. its shutdown is when $T_{ext} < T_{biv}$, where the bivalent temperature T_{biv} has to be optimized. In each time step, the radiant tubes cover the heating load that is not satisfied by the heat pump. A minimum load factor of 30% for the radiant tubes is considered. Thermal storage can compensate for an eventual surplus or deficit in thermal energy. Finally, the photovoltaic field can cover (partially or in excess, depending on the peak power installed) the electric consumption of the heat pump. The values of some parameters used in the energy analysis are reported in Table 3.

Table 3. Main parameters for energy and economic analysis.

Symbol	Meaning	Value
$f_{p,nren,NG}$	Non-renewable primary energy conversion factor for natural gas	1.05
$f_{p,nren,el}$	Non-renewable primary energy conversion factor for electricity from the grid	1.95
$f_{p,ren,el}$	Renewable primary energy conversion factor for electricity from the grid	0.47
$f_{p,ren,PV}$	Renewable primary energy conversion factor for electricity from the PV field	1
$f_{p,ren,heat\_source\_HP}$	Renewable primary energy conversion factor for external air thermal energy	1
QR	Minimum renewable ratio for new buildings	60%
PV (kW_p)	(Reference) peak power of the PV field	200
PV (η_{nom})	(Reference) peak efficiency of the PV field	16.0%
PV ($m^2\ kW_p^{-1}$)	(Reference) specific area of the PV field	6.3

3. Results and discussion

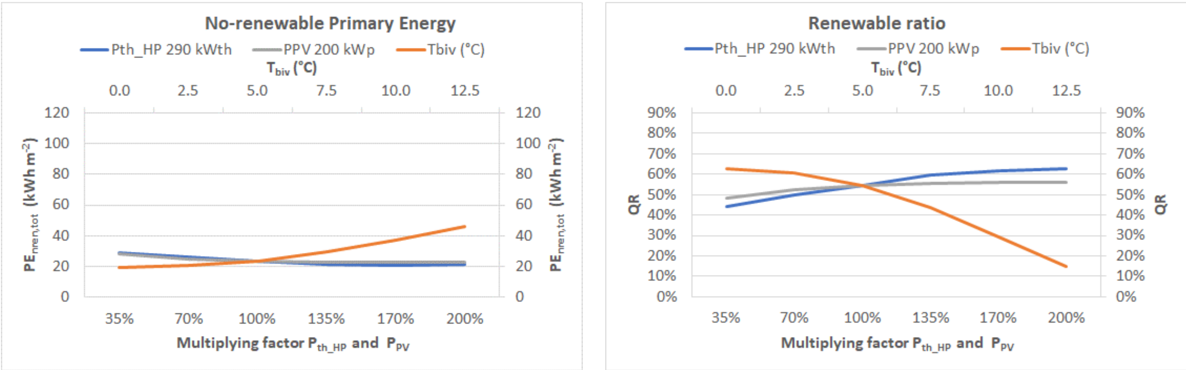
Firstly, the annual energy performance of the hybrid system in the three climatic zones (D, E, F) in terms of sensitivity analysis is reported. Section 3.1 reports the analysis of the effects of the values of external air bivalent temperature, the nominal power of the heat pump and peak power of the photovoltaic system on the main performance indices described above. The best values of these three variables compared to the reference ones (Table 3) optimize the energy performance indices.

Successively, the energy performances of the optimal configuration of the CRT+HP system are compared with the three benchmark heating systems (CRT, CRF, Air) (Section 3.2.). Finally, the area needed by the photovoltaic system is provided according to the installed peak power and the nominal efficiency of the modules (Section 3.3.).

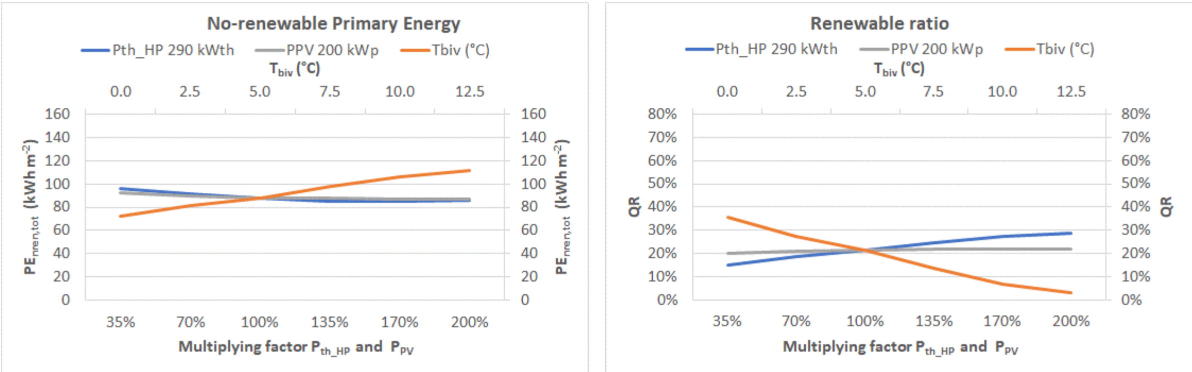
3.1. Non-renewable primary energy and renewable ratio

For each climatic zone, Figure 3 allows to highlight the best configuration of the plant in terms of bivalent temperature, multiplying factor of nominal output of the heat pump and multiplying factor of the peak power of the photovoltaic system. The figure is composed by two parts: the graphs on the left refer to non-renewable primary energy consumption, so the best configuration corresponds to the minimum of the curves; the graphs on the right refer to renewable ratio, so the best configuration corresponds to the maximum of the curves.

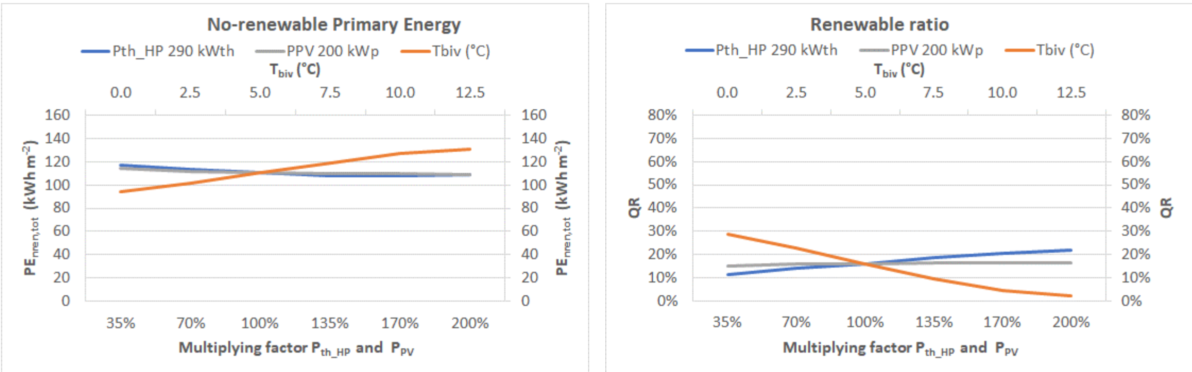
Figure 3 highlights that the configurations that minimize the consumption of non-renewable primary energy and allow for a remarkable renewable ratio are set up by (in climatic zone D / E / F, respectively): T_{biv} = 0 °C / 0 °C / 0 °C; nominal output of the heat pump (P_{th_HP}) = 493 kW_{th} / 392 kW_{th} / 392 kW_{th} (i.e., 170% / 135% / 135% of the nominal output of Table 2, equal to approximately 41% / 25% / 25% of the nominal installed power of the radiant tubes); peak power of the photovoltaic system (P_{PV}) = 340 kW_p / 270 kW_p / 270 kW_p (170% / 135% / 135% of the nominal peak power of Table 3).



Climatic zone D



Climatic zone E



Climatic zone F

Figure 3. $PE_{nren,tot}$ (left) and *QR* (right) of the hybrid CRT+HP system in function of the multiplication factor of the peak power of the photovoltaic system (PPV) and the nominal output of the heat pump (Pth_HP) (lower abscissa, left ordinate) and in function of the bivalent temperature (upper abscissa, right ordinate).

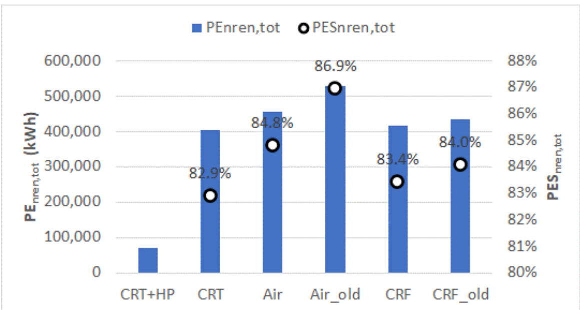
In the optimal configuration, the CRT+HP system shows a decrease in *PER* in colder climates (Table 4). This is due to the increased use of radiant tubes (i.e., natural gas) and the lower contribution of renewable energy by the heat pump. As a matter of fact, in colder climates the lower *COP* and lower electrical production by the photovoltaic field reduce the contribution of both thermal energy as a heat source at the evaporator and electrical energy powering the compressor. As a consequence, the renewable ratio *QR* decreases in colder climates, and the 60% value required by the Legislative Decree 199/2021 is exceeded only in climatic zone D. The photovoltaic production consumed by the heat pump is higher in colder climates (15% in zone D, 24% in zone F). The annual value of the *PER* is quite high in general, and extremely high in milder climates (Table 4).

Table 4. Annual values of the energy performance indices of the CRT+HP system in the optimal configuration for the three climatic zones (*PE*=primary energy).

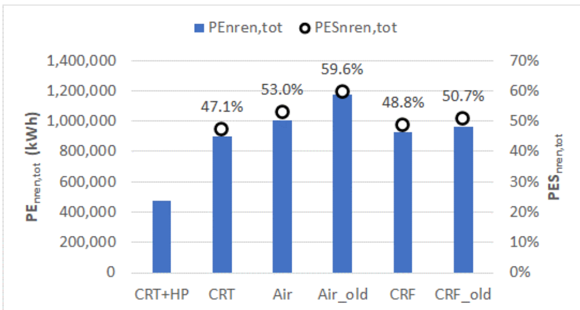
Symbol	Description	Unit	Zone D	Zone E	Zone F
$PE_{ren,el}$	Renewable quota of electricity from the grid	kWh	3,272	4,545	8,840
$PE_{nren,el}$	Non-renewable quota of electricity from the grid	kWh	13,575	18,857	36,675
$PE_{ren,PV}$	Renewable quota of electricity from the PV self-consumed	kWh	77,435	99,845	89,512
$PE_{ren,PV,exp}$	Renewable quota of electricity from the PV exported to the grid	kWh	431,252	367,027	284,480
$PE_{ren,heat\_source\_HP}$	Thermal energy as heat source of the HP	kWh	246,289	287,078	281,042
$PE_{ren,tot}$	Total renewable	kWh	326,996	391,468	379,393
$PE_{nren,NG}$	Non-renewable as natural gas	kWh	57,464	454,312	608,957
$PE_{nren,tot}$	Total non-renewable	kWh	71,039	473,168	645,632
PER	Primary energy ratio		5.35	1.69	1.44
QR	Renewable ratio		82.2%	45.3%	37.0%
$PE_{nren,tot}$	Specific total non-renewable	kWh m^{-2}	9.1	60.4	82.4

3.2. *Non-renewable primary energy savings*

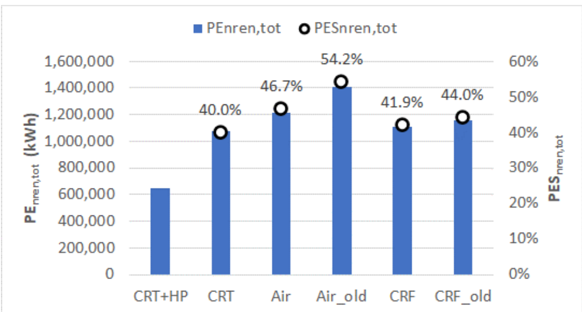
The hybrid system in the optimal configuration as deduced in the previous section allows extremely high non-renewable primary energy savings with respect to the benchmark plants (Figure 4).



Zone D



Zone E



Zone F

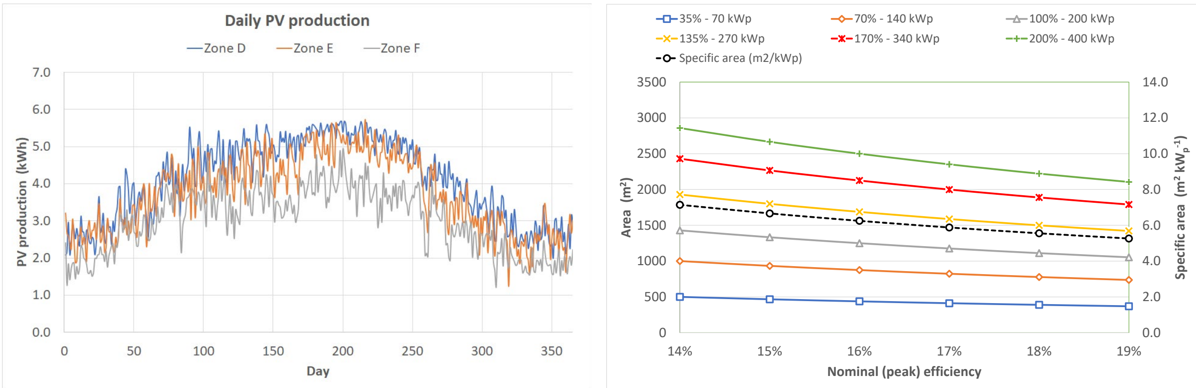
Figure 4. Total annual non-renewable primary energy consumption ($PE_{n,ren,tot}$) and savings of the hybrid CRT+HP system in optimal configuration ($PES_{nren,tot}$).

In particular, in milder climates (zone D), there is a greater input to the heat pump from renewable sources, both electric (from PV) and thermal to the evaporator (higher COP due to higher external temperatures). In fact, the hybrid configuration allows very high PES even with respect to CRT (40% to 82.9%), which is an already highly efficient solution.

3.3. Energy produced and area required by the photovoltaic system

Figure 5a reports the daily electricity production of the photovoltaic system in the three climatic zones. These data are obtained through the PV-GIS platform (https://re.jrc.ec.europa.eu/pvg_tools/en/tools.html#PVP) assuming an orientation for the modules towards south (0°), 35° tilt, monocrystalline silicon cells, system losses (inverter, electrical cable connections, dirt, etc.) equal to 14%.

Figure 5b shows the photovoltaic area required in specific and absolute terms as a function of peak efficiency and installed peak power. These data are useful to calculate in relation to the area available on the roof, equal to 7836 m^2. As a matter of fact, the PV required area for the optimal CRT+HP configuration is fully compatible with the available roof surface.



(a) (b)

Figure 5. (a) Daily production of electricity from the photovoltaic system in the three climatic zones; (b) the surface of photovoltaic required in specific (right ordinate) and absolute (left ordinate) terms as a function of the peak efficiency (abscissa) and of the peak power (parameter of the curves, expressed both in terms of kW$_p$ and multiplication factor with respect to the reference value of Table 2).

4. Conclusions

The paper focuses on the comparison of the energy performance of four heating systems for an industrial building located in three very different climatic zones, from mild to severe conditions. Dynamic simulations allowed to suitably choose the nominal power of the heat pump, the bivalent temperature of the external air, and the peak power of the photovoltaics plant to allow the best energy performance of the innovative hybrid condensing radiant tubes system. From the energy point of view, it is not advantageous to increase the size of the installed power of the heat pump above 40% of that of the radiant tubes in climatic zone D and 25% in zones E and F.

The non-renewable primary energy savings are very high: they can reach 87% with respect to a traditional air heater system in mild climates such as zone D (54% in zone F), and 84% with respect to a radiant floor coupled to a condensing boiler (44% in zone F).

As a further development of this work, the effects on the energy performance of a different control logic of the hybrid configuration (such as the bivalent parallel one) and of the absence of the PV plant could be analyzed. Furthermore, an economic analysis could be implemented to assess the economic viability of the hybrid system in comparison to the benchmark heating plants.

IOP Conf. Series: Earth and Environmental Science 1106 (2022) 012013 doi:10.1088/1755-1315/1106/1/012013

References

[1] Lazzarin R 2002 *Intervista sul riscaldamento degli ambienti nell'industria* (SGE, Padova)
[2] Brunello P, De Carli M, Magagnin P, Polito A and Zecchin R 2001 *Riscaldamento radiante a gas in ambienti industriali: fenomenologia, progettazione, verifica* (Proc. AiCARR Congr. Progettare l'involucro edilizio: correlazioni tra il sistema edificio e i sistemi impiantistici, Bologna)
[3] De Carli M and Polito A 2010 *Sistemi di climatizzazione per irraggiamento* (Proc. AiCARR Congr. Riduzione dei fabbisogni, recupero di efficienza e fonti rinnovabili per il risparmio energetico nel settore industriale, Padova)
[4] Brunello P, De Carli M, Polito A and Zecchin R 2002 *Comfort criteria and design aspects in high temperature radiant heating* (Proc. Indoor Air 2002, Monterey, California)
[5] D'Ambrosio Alfano F R 2010 *L'ambiente termico nell'industria* (Proc. AiCARR Congr. Riduzione dei fabbisogni, recupero di efficienza e fonti rinnovabili per il risparmio energetico nel settore industriale, Padova)
[6] Lazzarin R 1986 *Le caldaie a condensazione* (Editrice PEG, Milano)
[7] Noro M and Lazzarin R 2019 *Energy analysis of industrial climatization by an innovative radiant condensing system*, AIP Conference Proceedings 2191, 020121