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Application of multipurpose heat pumps in museums: a case study

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Abstract

The present work deals with the achievable benefits of using multipurpose heat pumps in museums, where heating and cooling are simultaneously required to ensure proper indoor conditions for artworks preservation. Air-handling units are usually installed to control temperature and relative humidity through both hot and cold coils that are usually fed by dedicated heat generators (e.g., heat pumps, boilers, and chillers). Using a multipurpose heat pump can reduce electrical input, as the same device can concurrently provide both heating and cooling power with a single energy input and recovering energy between the cold and the hot coils. In this perspective, the present work presents a representative real case study for Mediterranean climate. The building thermal load and the HVAC performances have been simulated in TRNSYS 17 and MATLAB with an hourly time step. The multipurpose heat pump provides an energy saving equal to 25% in cooling season compared to the use of a separate heat pump and a chiller. Indeed, the heating load is almost entirely met through the recovery of the condenser heat without significant additional energy input.

Keywords: Multi-purpose heat pump; energy savings; building dynamic simulation; heat recovery.

1. Introduction

1.1. Context

Energy reduction in the building sector is crucial to achieve the objectives set by the United Nations and European Union for the reduction of greenhouse gas emissions [1-2]. Currently, buildings in the European Union are responsible for about 40% of the total energy consumption for the services of heating and cooling [3].

In the last decades, the use of heat pumps (HP) for heating purposes has increased, thanks to their performance especially in the case of low supply temperatures and mild climates. Modern HPs also provide cooling service if a reversing valve is present resulting in an advantageous device that can be used in both winter and summer.

The market share of HP has been notably increasing in recent years: in 2020 the sold heat pumps in EU Countries were more than 1.5 million, about 50% more than the sold units in 2016 [4]. Air-to-water units account for ~13% of the total air-source market with 1.5 M units sold in the 2015–2019 period and a total installed capacity of ~24 GW at the end of 2019. HPs are also strategic devices for increasing the renewable share in nearly Zero Energy Buildings (nZEB), integrated hybrid systems, smart microgrids, and energy communities thanks to the energy shifts between heat to electricity: better exploitation and storage of renewable production (e.g., photovoltaic modules) is thus possible, also through advanced and optimally controlled demand response and power-to-heat strategies. Therefore, HP installation in new or existing buildings is often supported by national governments through several forms of incentives.

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An additional possible application of HP technology for energy efficiency purposes is the use of the so-called *multipurpose heat pumps (MP-HP)*, which are chillers where a total recovery of the heat at the condenser is possible. This type of generator, also called *total recovery chiller*, can be particularly useful in buildings where heating and cooling are simultaneously required. MP-HPs can be seen as both co-generators able to provide two different energy services by using a single energy input, or as a recovery solution as the removed "cold energy" is not dissipated into the environment, but it is re-injected at a higher temperature.

1.2. Literature review

The analysis of the state of the art on MP-HPs has shown a limited application of this technology on scientific research, even if the found results has hinted that this generator allows significant energy savings compared to traditional systems. The literature analysis results fragmented, also because this technology is presented with a variety of different names (such as multipurpose heat pump, multi-heat pump, total recovery chiller, multifunctional heat pump), making the literature research difficult.

Most of the papers on this topic presents experimental tests on MP-HP. Agrawal et al. [5] present the results of experimental test on a CO2 transcritical MP-HP for simultaneously production of heating and cooling services. Kang et al [6] carry out measurements on a MP-HP directly exchanging with indoor air, evaluating COP when varying compressor speed ratio. Liu et al [7] present the performance of a prototype MP-HP for both heating and domestic hot water services. At evaporator, this prototype can use external air, gray water, or both these sources with an either parallel or series configuration. The results show that the optimal performance is reached with the parallel configuration at evaporator, using both sources. Other works are aimed at enhancing the MP-HP performances with different methods. As an example, Boahen et al [8] tested a cascade MP-HP for the simultaneous delivering of heating, cooling and domestic hot water at different level of temperatures. In their series of papers, Byrne et al. [9-11] present the results of an in-house designed heat pump for multiple services. First, the performance was measured in steady-state conditions, using R407C as refrigerant [9]. In their second paper [10], the dynamic behavior of the heat pump was analyzed, focusing on the performance during transition among operational modes (e.g., from only cooling delivering to both cooling and heating delivering) and on the possibility of partially recovering heating to be used for defrosting. Finally [11], two refrigerants are compared (i.e., R407C and R290) to evaluate best energetic and exergetic performances. Cho et al [12] designed and tested a MP-HP, seeking the optimal refrigerant charge to enhance the total efficiency of the system, in different load and operation conditions. Chiu et al [13] show the results of a monitoring campaign on an air conditioning system where the heat recovery at the condenser is used for domestic hot water purposes.

A small amount of research papers focuses instead on the simulation of MP-HP performances when applied to case studies. Diaby et al. [14] compare two possible applications of a CO2 transcritical MP-HPs in a hotel: in the first case, the heat pump is used for heating, cooling and domestic hot water services; in the second one, the heat pump is used for simultaneous cooling and desalinization purposes. The latter application shows better performances due to the more suitable process temperatures. In [15], the authors expose the outputs of the application of MP-HPs in three climates and three different buildings: a low-energy residential building, a retail store and a small office building. The results hint that applying MP-HP in low-energy residential building allows higher energy savings, as this type of building has often simultaneous heating and cooling load, depending on the solar gains. Shen et al. [16] simulated the performance of MP-HPs in ten different US cities, using a restaurant as case study, for simultaneous production of either heating and domestic hot water, or cooling and domestic hot water. The comparison of electrical energy needs with this technology and a classical solution with heat pump/chiller and electric heater shows savings ranging between 47% and 64%.

1.3. Aim and presentation of the research

The present research aims at evaluating the achievable energy savings when a MP-HP is used as the thermal generator in an environment where heating and cooling services are simultaneously required. The MP-HP performance is compared to a classical configuration where two different generators are used, namely an electric heat pump and an electric chiller. After a presentation of the energy models of the generators (Section 2), we show a case study consisting of a museum room in Italy where temperature and relative humidity should be carefully controlled to avoid artwork degradation (Section 3). To maintain the indoor setpoint values, an air handling unit (AHU) is used, thus requiring both heating and cooling services, especially in the cooling period where the dehumidification demand is high. Two different configurations are compared: the so-called "separate configuration" with two separate hot and cold generators: e.g., the heat pump and the chiller, and an

MP-HP configuration where a unique multipurpose heat pump is used (see Fig. 1 and 2, respectively). The Results Section (Section 4) presents the comparison of the total electrical energy consumption of the two configurations, demonstrating the effectiveness of the multipurpose heat pump.

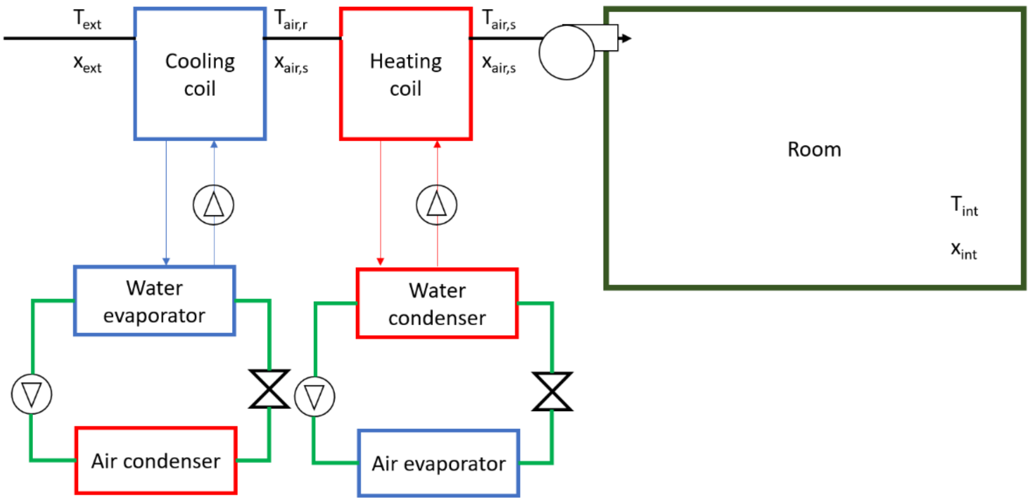

Fig. 1. The separate configuration, with a chiller and a heat pump, working separately for the AHU cooling and heating coil.

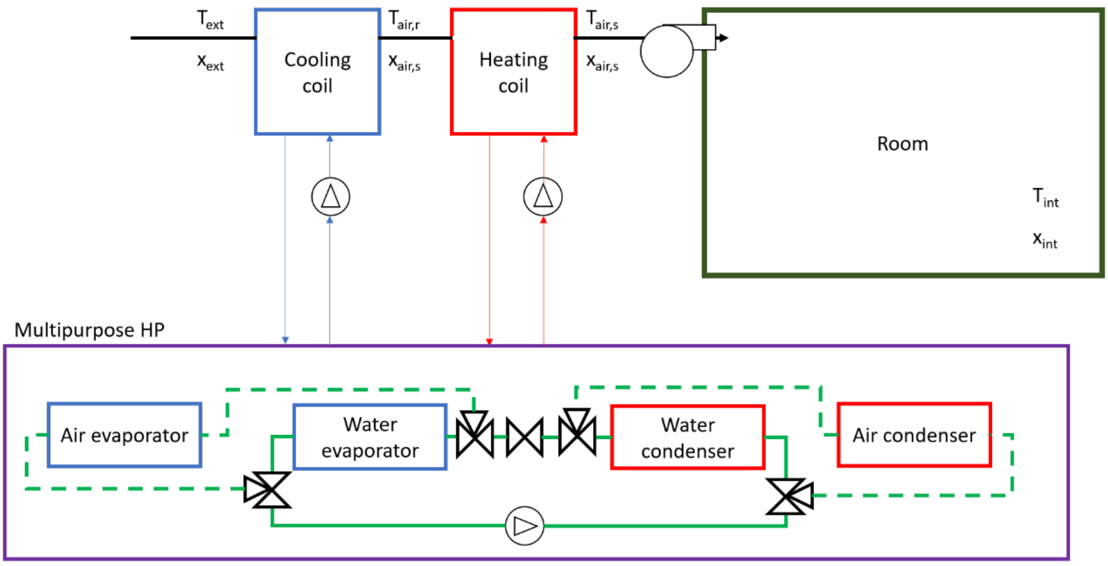

Fig. 2. MP-HP configuration where the generator provides both hot and cold water for the AHU cooling and heating coil..

2. The model

2.1. Multipurpose heat pump (MP-HP)

The considered MP-HP unit is a market-available device and the energy model is based on the manufacturer datasheets [17]. Depending on the dynamic load profile, external air temperature, and humidity, the AHU can only require heating power at the reheat coil ($\dot{Q}_{H,r}$), cooling power at the cooling coil ($\dot{Q}_{C,r}$), or both services at the same time ($\dot{Q}_{H,r}$ and $\dot{Q}_{C,r}$). According to the manufacturer's data [17], the considered multipurpose heat pump can work in three different operational modes (see also Fig. 3):

1. as a classical chiller, only providing cold water to the AHU cooling coil and using an outdoor-air heat exchanger as a condenser (Mode 1). In this case, the absorbed electrical energy at the compressor is evaluated as a function of the supply temperatures to the cooling coil ($T_{C,s}$) and partial load conditions (CR):
$$\frac{\dot{Q}_{C,r}}{\dot{E}_{el}} = EER_{C,MP-HP}\left(T_{C,s}, CR\right) \tag{1}$$

2. as a classical heat pump, only providing hot water to the AHU reheat coil and using an outdoor-air heat exchanger as an evaporator (Mode 2) In this case, the absorbed electrical energy at the compressor is evaluated as a function of the supply temperatures to the reheat coil ($T_{H,s}$) and partial load conditions (CR):
$$\frac{\dot{Q}_{H,r}}{\dot{E}_{el}} = COP_{H,MP-HP}\left(T_{H,s}, CR\right) \tag{2}$$

3. as a multipurpose heat pump; providing both cold and hot water to the AHU. In other words, the MP-HP operates as a chiller with a total recovery of the heat at the condenser (Mode 3). Air heat exchangers do not operate and possible discrepancies between hot/cold generations and thermal loads are managed using ad buffer water storages, according to the following control strategy [17]:
   - The MP-HP tries meeting the cooling load, evaluating the absorbed electrical energy at the compressor as a function of the supply temperatures to the hot and cold coils ($T_{H,s}$ and $T_{C,s}$, respectively) and partial load conditions (CR):
$$\dot{E}_{el} = \frac{\dot{Q}_{C,r}}{EER_{H\&C,MP-HP}\left(T_{H,s}, T_{C,s}, CR\right)} \tag{3a}$$
$$\dot{Q}_{H,MP-HP} = \dot{Q}_{C,r} + \dot{E}_{el} \tag{3b}$$
   - If $\dot{Q}_{H,MP-HP} \geq Q_{H,r}$, the multi-purpose heat pump follows the cooling load ($\dot{Q}_{C,MP-HP,eff} = Q_{C,r}$, $\dot{Q}_{H,MP-HP,eff} = \dot{Q}_{H,MP-HP}$), storing the possible heating surplus ($\dot{Q}_{H,MP-HP} - \dot{Q}_{H,r}$) in the hot thermal buffer. In this case, Eqs. 3a and 3b apply.
   - If $\dot{Q}_{H,MP-HP} < Q_{H,r}$, the multi-purpose heat pump follows the heating load by increasing its thermal output at the condensing section ($\dot{Q}_{H,MP-HP,eff} = Q_{H,r}$). The corresponding effective cooling production ($\dot{Q}_{C,MP-HP,eff}$) at the evaporator increases to a value higher than the cooling load ($\dot{Q}_{C,r}$), thus the cooling surplus ($\dot{Q}_{C,MP-HP,eff} - \dot{Q}_{C,r}$) is stored in the cold thermal buffer. In this case, Eqs. 3a and 3b are slightly modified as:
$$\dot{E}_{el} = \frac{\dot{Q}_{C,MP-HP,eff}}{EER_{H\&C,MP-HP}\left(T_{H,s}, T_{C,s}, CR\right)} = \frac{\dot{Q}_{H,r}}{\left(1 + EER_{H\&C,MP-HP}\left(T_{H,s}, T_{C,s}, CR\right)\right)} \tag{4a}$$
$$\dot{Q}_{H,MP-HP,eff} = \dot{Q}_{H,r} = \dot{Q}_{C,MP-HP,eff} + \dot{E}_{el} \tag{4b}$$

We arbitrarily chose the EER as the reference thermodynamic coefficient of performance of the MP – HP. Analogous formulae can be deployed by using condenser output and COP definition to model the MP-HP performances. Moreover, for the sake of simplification, the cold and hot thermal buffers are considered as ideal, without thermal losses or energy exchange constraints.

The values of $EER_{C,MP-HP}\left(T_{C,s}, CR\right)$, $COP_{H,MP-HP}\left(T_{H,s}, CR\right)$, and $EER_{H\&C,MP-HP}$ are obtained through the polynomial fitting of the nameplate data provided by the manufacturer [17] (see, for instance, Eqs. 5).
$$TR = \left(\frac{T_{H,s} + 273.15}{T_{C,s} + 273.15}\right) \tag{5a}$$
$$CR = \left(\frac{\dot{Q}_{C,r}}{\dot{Q}_{C,NOM,MP-HP}}\right) \tag{5b}$$

$$EER_{H\&C,MP-HP}(T_{H,s},T_{C,s},CR) = [\alpha_0 + \alpha_1 \times TR + \alpha_2 \times CR + \alpha_3 \times TR^2 + \alpha_4 \times TR \times CR] \times \left(\frac{T_{C,s} + 273.15}{T_{H,s} - T_{C,s}}\right) \tag{5c}$$

In Eqs. 5, the values of temperatures are in °C.

The nameplate data of the multipurpose heat pump working in Mode 1, Mode 2, and Mode 3 are reported in Table 1, Table 2, and Table 3, respectively.

Table 1. Values of cooling load, input electrical energy, and performance of a multipurpose heat pump operating in Mode 1 (data from [17]).

		$T_{ext} = 35\,°C$			$T_{ext} = 30\,°C$			$T_{ext} = 20\,°C$		
		$\dot{Q}_{C,MP-HP}$ [kW]	$\dot{E}_{el}$ [kW]	$EER_{C,MP-HP}$ [-]	$\dot{Q}_{C,MP-HP}$ [kW]	$\dot{E}_{el}$ [kW]	$EER_{C,MP-HP}$ [-]	$\dot{Q}_{C,MP-HP}$ [kW]	$\dot{E}_{el}$ [kW]	$EER_{C,MP-HP}$ [-]
CR=1	$T_{C,s} = 7\,°C$	43.0	14.0	3.07	46.4	12.9	3.61	52.5	10.9	4.80
	$T_{C,s} = 12\,°C$	49.8	14.7	3.39	53.8	13.7	3.92	59.8	11.5	5.21
	$T_{C,s} = 15\,°C$	54.2	15.1	3.58	57.2	14.0	4.09	63.6	11.9	5.35
CR=0.55	$T_{C,s} = 7\,°C$	23.7	6.3	3.75	25.5	5.8	4.41	28.9	4.9	5.87
	$T_{C,s} = 12\,°C$	27.4	6.6	4.15	29.6	6.2	4.79	32.9	5.2	6.36
	$T_{C,s} = 15\,°C$	29.8	6.8	4.38	31.5	6.3	4.99	35.0	5.4	6.54

Table 2. Values of heating load, input electrical energy, and performance of a multipurpose heat pump operating in Mode 2 (data from [17]).

		$T_{H,s} = 35\,°C$			$T_{H,s} = 45\,°C$			$T_{H,s} = 55\,°C$		
		$\dot{Q}_{H,MP-HP}$ [kW]	$\dot{E}_{el}$ [kW]	$COP_{H,MP-HP}$ [-]	$\dot{Q}_{H,MP-HP}$ [kW]	$\dot{E}_{el}$ [kW]	$COP_{H,MP-HP}$ [-]	$\dot{Q}_{H,MP-HP}$ [kW]	$\dot{E}_{el}$ [kW]	$COP_{H,MP-HP}$ [-]
CR=1	$T_{ext} = 0\,°C$	48.8	10.6	3.05	30.8	12.8	2.41	28.5	15.8	1.83
	$T_{ext} = 7\,°C$	55.7	11.0	4.45	46.0	13.2	3.48	42.3	16.0	2.65
	$T_{ext} = 15\,°C$	32.2	11.1	5.02	53.4	13.3	4.00	46.7	16.1	3.08
CR=0.55	$T_{ext} = 0\,°C$	15.4	4.8	3.39	23.0	5.8	2.67	14.3	7.0	2.03
	$T_{ext} = 7\,°C$	24.4	4.9	4.95	26.7	5.9	3.87	21.2	7.2	2.94
	$T_{ext} = 15\,°C$	27.8	5.0	5.58	15.4	6.0	4.45	24.8	7.2	3.43

Table 3. Values of cooling load, input electrical energy, and performance of a multipurpose heat pump operating in Mode 3 (data from [17]).

		$T_{H,s} = 35\,°C$			$T_{H,s} = 40\,°C$			$T_{H,s} = 55\,°C$		
		$\dot{Q}_{C,MP-HP}$ [kW]	$\dot{E}_{el}$ [kW]	$EER_{H\&C,MP-HP}$ [-]	$\dot{Q}_{C,MP-HP}$ [kW]	$\dot{E}_{el}$ [kW]	$EER_{H\&C,MP-HP}$ [-]	$\dot{Q}_{C,MP-HP}$ [kW]	$\dot{E}_{el}$ [kW]	$EER_{H\&C,MP-HP}$ [-]
CR=1	$T_{C,s} = 6\,°C$	49.6	11.3	4.37	45.2	13.4	3.38	36.3	15.9	2.28
	$T_{C,s} = 10\,°C$	54.8	11.9	4.61	46.3	17.6	2.64	41.5	16.5	2.52
	$T_{C,s} = 15\,°C$	61.1	12.6	4.87	56.8	14.6	3.89	48.4	17.1	2.82
CR=0.55	$T_{C,s} = 6\,°C$	28.3	5.10	5.34	24.9	6.01	4.14	19.9	7.17	2.78
	$T_{C,s} = 10\,°C$	30.2	5.35	5.64	25.4	7.90	3.22	22.8	7.41	3.08
	$T_{C,s} = 15\,°C$	33.6	5.65	5.95	31.2	6.56	4.76	26.6	7.71	3.45

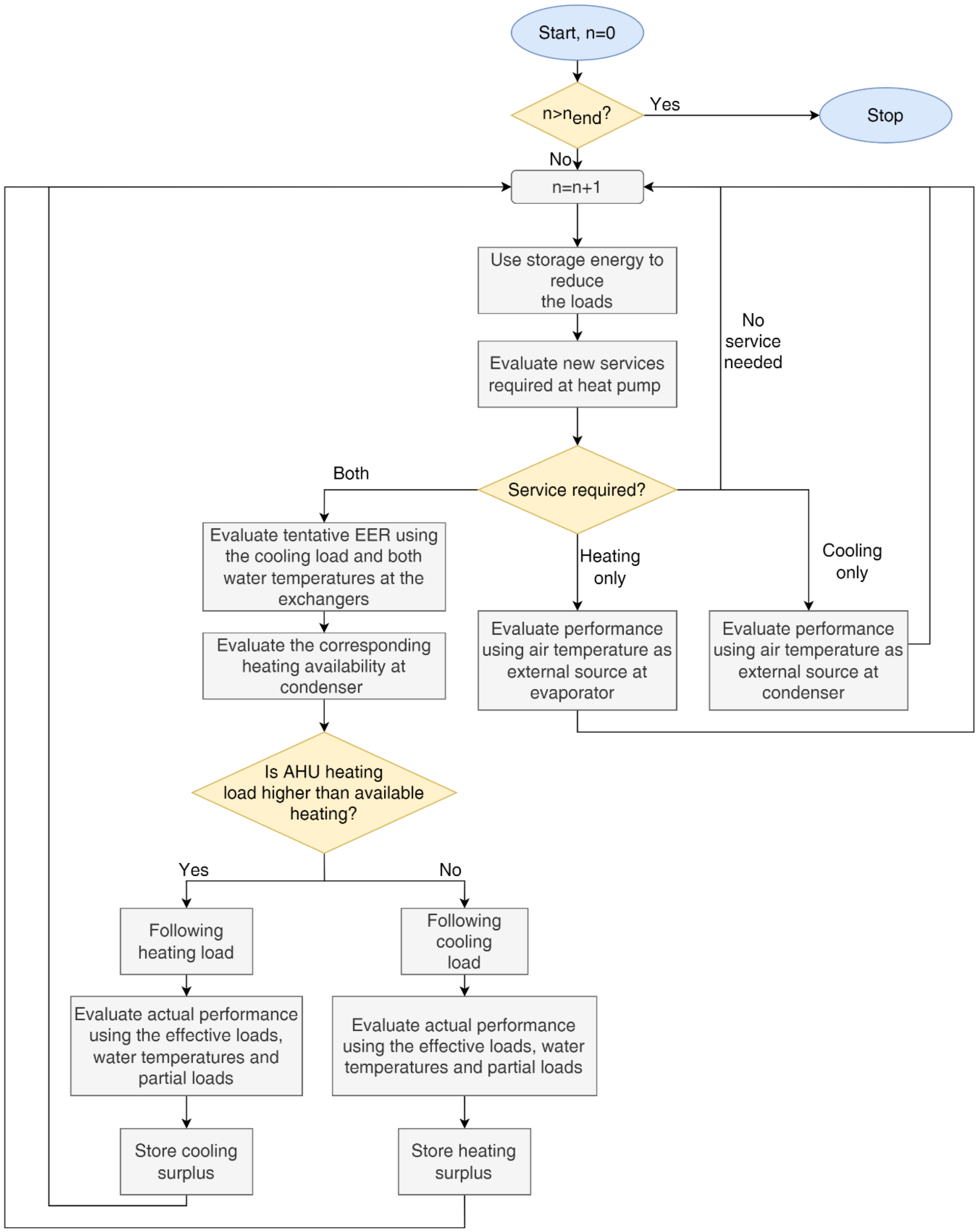

Fig. 3. MP-HP control strategy adopted in this study.

2.2. Separate heat pump and chiller configuration

For the separate configuration, the same regression coefficients obtained by fitting the data in Tables 1 and 2 are used. Using these values, the performances of the two generators in the separate configuration are evaluated as in Mode 1 ("Only cooling") and Mode 2 ("Only heating"). The performance coefficients are named $COP_{H,SC}$ and $EER_{C,SC}$.Application of the model to a museum showroom

To compare the efficiency of a multipurpose heat pump with the two separate generators, we selected a case study consisting of a room of a museum hosting temporary exhibitions in Pisa, Italy. The simulation period starts on July 1st up to August 31st, with a one-hour timestep. The reference outdoor climate (external temperature, relative humidity, horizontal solar radiation) refers to the TMY provided by the Italian Thermotechnical Committee [18].

The considered room has a floor area of 100 m^2 and a volume of 500 m^3; walls are made of bricks and masonry (U-value of external walls: 1.1 W/(m^2K)) and no glazed elements. For the maintenance of indoor conditions, an AHU is used, consisting of a cooling/dehumidifier coil, a reheat coil, a steam vaporizer, and a fan.

The room is kept at precise internal conditions to avoid artwork deterioration:

- The indoor temperature setpoint is equal to 25 °C, with a control dead band of ± 1K;
- The indoor relative humidity is equal to 50%, with a control dead band of ± 2%.

An hourly profile of visitors has been used as the source of both sensible and latent internal gains; the maximum peak is 100 visitors. The visitors can visit the museum every day from 9:00 a.m. to 7:00 p.m. However, to ensure the maintenance of the indoor air setpoints, the AHU can be activated 24/7.

Other details on the case study and visitors' presence profile can be found in [19-20]. For the simulation of the AHU, a dynamic model has been used [21]: this model simulates the behavior of the various components (two heating coils, a vaporizer, and a cooling coil) using ϵ-NTU equations, mass and heat balance. The model evaluates the temperature and humidity ratio exiting the single coils ($T_{air,r}$ and $x_{air,r}$, at the end of the cooling coil, and $T_{air,s}$ and $x_{air,s}$ at the end of heating coil), knowing the external parameters (T_{ext} and x_{ext}), ensuring the room energy requirements. The energy balance at the coils allows the evaluation of the supply temperatures $T_{H,s}$.and $T_{C,s}$, More information on this model can be found in [21].

The building-HVAC system has been simulated in TRNSYS 17 [22] and MATLAB [23] obtaining the hourly values of the performance coefficients and electrical energy input as presented in Section 2. The two configurations in previous Figs. 1 and 2 are then compared in terms of seasonal energy input.

3. Energy performance results

Through the dynamic simulation of the building-AHU system, hourly values of supply temperatures $T_{H,s}$.and $T_{C,s}$ at the cooling and heating coils are calculated. Those temperatures are the required temperatures at the evaporator and condenser of the devices, the same in both "separate" and "combined" configurations as they depend on the same thermal loads and heat transfer performances of the two coils. Through the thermal loads, the supply temperatures and (in case of a single energy load) the external temperature, the performance of the heat pump is evaluated.

On average, the required supply temperature at the heating coil is 39.5 °C, and the one at the cooling coil is 7.7 °C. The average external temperature is 22.5 °C. Table 4 shows the results of the comparison of the two generator configurations of the case study, using the previously presented indicators. Also the value of Total Efficiency Ratio (TER), defined as the ratio between the total provided energy and the total electrical energy input, is shown.

The results show that the simultaneous operation of the MP-HP for both services frequently occurs: more than 90% of the heating load is delivered through this operation mode (Mode 3). In this case, considering the greater relevance of the cooling load, the hot thermal storage is charged. Mode 2 ("Only heating") is rarely used: it only applies in those timesteps when only the heating load occurs. On the contrary, the MP-HP frequently works in Mode 1 ("Only cooling") using the hot water buffer to meet the heating load and recover the heat stored in the previous Mode-3 operation.

Fig.4 shows the operation of the MP-HP for a typical day in July. During the night, the cooling load is low, so the MP-HP follows the heating profile. As an example, at "Hour 1" the MP-HP provides the AHU heating requirements, but the cooling output results in an overproduction compared to the actual load and the surplus energy is stored in the cold water storage. At "Hour 2", the stored energy in the cold water storage is sufficient to cover the AHU cooling load, so the MP-HP works in Mode 2 ("Only heating" mode). During the opening hours of the museum, the high cooling load drives the AHU operations that switch between Mode 1 and Mode 3, depending on the charging/discharging status of the hot water storage. As an example, at "Hour 16", the heating output at MP-HP is over 14 kW, even if the actual requirement is around 6 kW. The surplus is stored in the hot water buffer and used to meet the heating load at "Hour 17", where the generator works in Mode 1 ("Only cooling").

Table 4. Comparison of indicators in combined vs. separate configuration.

	MP-HP case	Separate case
Total cooling load required at AHU [MWh]	13.9	13.9
Total heating load required at AHU [MWh]	8.8	8.8
Total electrical energy input [MWh]	3.2	4.3
Cooling load provided by the generator in Mode 1 (“Only cooling”) [MWh]	7.3	13.9
Share of cooling load provided in Mode 1 (“Only cooling”) [%]	53	100
Seasonal coefficient of performance in Mode 1 (“Only cooling”), $SEER_{C,MP-HP}$ or $SEER_{C,SC}$	4.63	5.00
Heating load provided by the generator in Mode 2 (“Only heating”) [MWh]	0.7	8.8
Share of heating load provided in Mode 2 (“Only heating”) [%]	8	100
Seasonal coefficient of performance in Mode 2 (“Only heating”) (Mode 2), $SCOP_{H,MP-HP}$ or $SCOP_{H,SC}$	5.20	5.70
Cooling load provided by the generator in Mode 3 (“Both heating and cooling”) [MWh]	6.6	0
Share of cooling load provided in Mode 3 (“Both heating and cooling”) [%]	47	0
Heating load provided by the generator in Mode 3 (“Both heating and cooling”) [MWh]	8.1	0
Share of heating load provided in Mode 3 (“Both heating and cooling”) [%]	92	0
Seasonal coefficient of performance in Mode 3 (“Both heating and cooling”), $SEER_{H\&C,MP-HP}$	4.11	-
Seasonal total efficiency ratio, TER_{MP-HP}or TER_{SC}	7.09	5.27

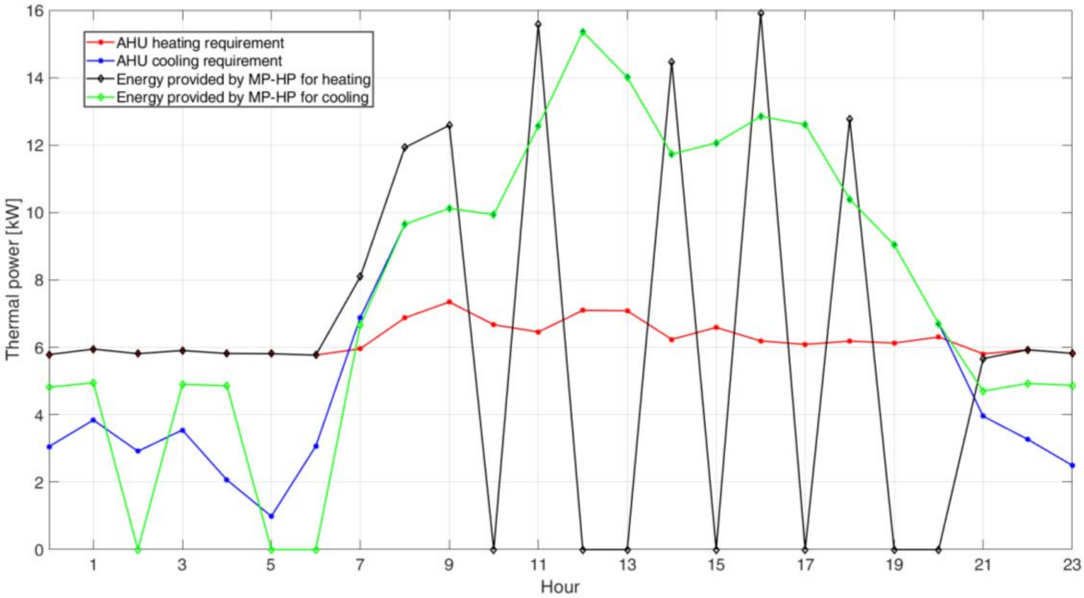

Fig. 4. Modes of operation of MP-HP in a day of July: energy delivered by the heat pump compared to the energy requirements at AHU. The position of the line representing delivered energy and required energy indicates the surplus of heating/cooling stored in dedicated buffers and later used.

Table 4 shows that the average MP-HP coefficient of performance is lower than in the case of separate configuration, namely, $SEER_{H\&C,MP-HP} < SEER_{C,MP-HP}$. Indeed, the average temperature difference between the supply water temperature (7.7 °C) and the outdoor air temperature (22.5 °C) is lower than the temperature difference between the two supply temperatures in Mode 3 (7.7 °C and 39.5 °C). However, the latter comparison is affected by our choice of using EER as the coefficient of performance for the MP-HP and it does not consider the simultaneous delivery of both heating and cooling loads. The TER indexes in Table 4 provide a better comparison of the two configurations, accounting for both hot and cold services. As previously mentioned, this indicator is defined as:

$$TER_{MP-HP} = \frac{\left(\sum \dot{Q}_{H,MP-HP,eff} + \sum \dot{Q}_{C,MP-HP,eff}\right)}{\sum \dot{E}_{el}} \quad (6a)$$

$$TER_{SC} = \frac{\left(\sum \dot{Q}_{H,r} + \sum \dot{Q}_{C,r}\right)}{\sum \dot{E}_{el}} \quad (6b)$$

Thus, the comparison of this index in combined and separate configuration hints the better exploitation of electrical energy in the MP-HP use. In this case study, using an MP-HP allows a decrease of electrical energy input equal to 25%. In Fig. 5, the daily electrical energy inputs for the "separate" and "combined" configurations are compared over a typical week (from 1st August to 7th August). For each day, the electrical energy consumptions in the three operational modes are independently visible. The figure shows that the heating load is almost always delivered as a total recovery of heat at the condenser when providing also cooling service. The daily reduction of electrical energy ranges between 20% and 30%.

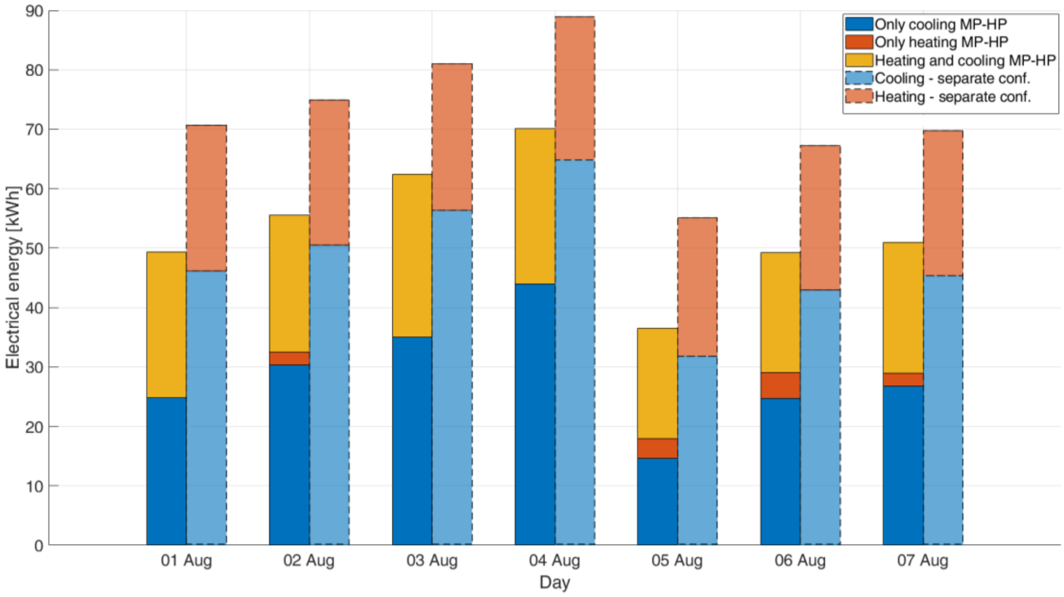

Fig. 5. Comparison of daily electrical energy input for combinate and separate configurations for a typical week.

4. Conclusions

In this paper, we have shown the potential of using a multi-purpose heat pump in a building where heating and cooling loads are simultaneously required. The analysis has compared the energy requirements of a "separate" configuration, using an independent air-source chiller and a heat pump, with a "combined" configuration using a MP-HP to feed the same AHU.

For the analysis, a case study has been identified: a room of a museum in the Mediterranean area where indoor temperature and relative humidity are kept constant using the AHU. Through an hourly dynamic simulation, the electrical energy consumptions required to operate the cooling and reheat coils have been calculated for both "separate" and "combined" configurations. The results show a reduction of electrical energy input of about 25% in the case of a "combined" configuration and MP-HP use. Due to the greater relevance of the cooling load in the presented case study, the MP-HP mainly operates in "Both heating and cooling" mode (Mode 3) and "Cooling only" mode (Mode 1). The system uses the surplus of the heating production in Mode 3 to charge the hot storage and then uses this energy in Mode 1 avoiding the need for another heating generator.

As a matter of fact, together with possible energy savings, the paper has also investigated the importance of the two "energy buffers" in MP-HP systems: indeed, depending on hot and cold load profiles, energy recovery would not be feasible where the two instantaneous load profiles were not properly synchronized. Thus, further development of the research will include the modeling of other MP-HPs devices (also using more efficient refrigerants as R744), a more accurate model of the thermal buffers in the MP-HP contexts, including the effects of their optimal sizing and control required to assess the actual potentiality of those systems. In addition, the efficiency of this technology in a whole-year simulation, also in different climates, and various types of buildings and services will also be investigated.

Nomenclature and acronyms

Acronyms	
AHU	Air handling unit
HP	Heat pump
MP-HP	Multi-purpose heat pump
nZEB	Nearly zero energy building
Nomenclature	
$COP_{H,MP-HP}$	Coefficient of performance of the multi-purpose heat pump in “Only heating” mode
$COP_{H,SC}$	Coefficient of performance of classical heat pump in separate configuration
CR	Capacity ratio
$\dot{E}_{el}$	Electrical energy needs at compressor
$EER_{H\&C,MP-HP}$	Coefficient of performance of multi-purpose heat pump in “Both heating and cooling” mode
$EER_{C,MP-HP}$	Coefficient of performance of the multi-purpose heat pump in “Only cooling” mode
$EER_{C,SC}$	Coefficient of performance of the classical chiller in separate configuration
$\dot{Q}_{C,MP-HP}$	Thermal output available at evaporator of multi-purpose heat pump
$\dot{Q}_{C,MP-HP,eff}$	Effective thermal output delivered at evaporator of multi-purpose heat pump
$\dot{Q}_{C,NOM,MP-HP}$	Nominal cooling heat of the multi-purpose heat pump
$\dot{Q}_{C,r}$	Cooling load required at the cooling coil of the air handling unit
$\dot{Q}_{H,MP-HP}$	Thermal output available at condenser of multi-purpose heat pump
$\dot{Q}_{H,MP-HP,eff}$	Effective thermal output delivered at condenser of multi-purpose heat pump
$\dot{Q}_{H,r}$	Heating load required at the heating coil of the air handling unit
$SCOP_{H,MP-HP}$	Average coefficient of performance of multi-purpose heat pump in “Only heating” mode
$SCOP_{H,SC}$	Average coefficient of performance of classical heat pump in separate configuration
$SEER_{C,MP-HP}$	Average coefficient of performance of multi-purpose heat pump in “Only cooling” mode
$SEER_{C,SC}$	Average coefficient of performance of classical chiller in separate configuration
$T_{air,r}$	Temperature of the air after the cooling and dehumidification process in the AHU
$T_{air,s}$	Temperature of the supply air entering the room
$T_{C,s}$	Supply temperature at cooling coil
T_{ext}	External temperature
$T_{H,s}$	Supply temperature at heating coil
T_{int}	Temperature of the thermal zone (Museum’s rooms)
TER_{MP-HP}	Total efficiency ratio of multi-purpose heat pump
TER_{SC}	Total efficiency ratio of separate configuration
TR	Supply temperatures ratio
$x_{air,r}$	Humidity ratio of the air after the cooling and dehumidification process in the AHU
$x_{air,s}$	Humidity ratio of the supply air entering the room
x_{ext}	Humidity ratio of the external air
x_{int}	Humidity ratio of the internal air
$\alpha_1 - \alpha_5$	Coefficients of the polynomial fitting of nameplate data of performances of multi-purpose heat pump

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