FREESCOO facade 3.0, a compact DEC thermally driven air-conditioning system for apartments

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Abstract

FREESCOO is an innovative Desiccant Evaporative Cooling air conditioning system designed for ventilation, cooling, dehumidification and heating of buildings in residential and tertiary sectors. This paper presents the third generation of the façade version, which will be tested on field in Milan (Italy) within the Merezzate+ project supported by Climate-KIC. The adsorption bed used by the system is a finned heat exchanger packed with silica gel grains, which allows simultaneous dehumidification and cooling of the process air. The direct evaporative cooling process, operated downstream to the dehumidification, is realized using a rotary plate humidifier. The regeneration of the adsorption bed is done through low-grade heat around 60 °C and the only electrical consumption is for the fans and water recirculation. The unit has been designed in order to be integrated in the loggia of small apartments of roughly 47 m^2. The result is a Seasonal Energy Efficiency Ratio around 10.7. From the primary energy savings perspective with respect to a conventional air conditioning, they can be up to 36% if the electricity generation is not renewable heavy or the district heating has a renewable energy quota.

Desiccant Evaporative Cooling, air-conditioning, adsorption, thermal driven

1. Introduction

Building air conditioning represents a large contribution on the overall building sector energy consumption, in particular in Mediterranean countries (European Environment Agency 2016, European Environment Agency 2016b).

Historically, Desiccant Evaporative Cooling (DEC) systems based on an open thermodynamic cycle (Daou et al., 2006) were studied coupled with available solar thermal energy, thus the name “solar cooling”. The DEC name derives from the two processes at the basis of the thermodynamic cycle. The first one is the air dehumidification process without reaching the dew point temperature, but by means of moisture sorption. The second type of process is the direct and/or indirect evaporative cooling. Thermodynamic cycles of this type can be implemented in refrigeration units based on desiccant wheels or solid or liquid beds.

These refrigeration units require as inputs: water for the evaporative cooling, electricity to run the air fans and thermal energy for the sorption material regeneration. The regeneration energy is used to release the trapped water vapor, allowing the restart of the sorption cycle. The required temperature for the regeneration process changes wildly with the specific material chosen. In the case of DEC systems for solar cooling, one of the most used sorption materials is Silica-Gel, which can be regenerated even with relatively low-grade heat (60°C).

This work presents the analysis of an innovative air-conditioning system based on a DEC cycle. Specifically, in the case study here presented is coupled with a 4th generation district heating system (Lake et al.,2017 e Lund et al. 2014), but it could work also by being coupled with a solar thermal field. The system is compact, so suitable for being installed on a building façade. The nominal cooling power is around 2.2 kW. Therefore, it can be used

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for the air conditioning of small apartments, like the 47 m^2 two rooms apartment here considered as case study. One of the key aspects of this concept is the design of the adsorption beds, which allow to increase the amount of sorption material, while reducing the regeneration temperature (Finocchiaro et al., 2016). The main features of the system are: use of water as refrigerant; use of a cooled adsorption bed; use of high efficiency evaporative cooling; use of low grade heat (60°C); overall high electrical efficiency (EER>9); being compact and plug & play.

The work here presented is linked to the project “Merezzate+: a living lab for the integration of clean energy and sustainable mobility” financed by EIT Climate-KIC. The project aims at developing a new city model, based on the concept of “smart urban environment”. The proposed approach focuses on the city as a district, dealing with sustainability issues from a social, environmental and economic point of view in a comprehensive way taking actions on energy, mobility and circular economy, which are among the most impactful sectors on climate change. The approach will be demonstrated in the new district “REDO Smart District” in Cascina Merezzate Street (Milan, Italy). This site will become a “living lab” for the development, the feasibility and the implementation of an inclusive district that will be based on circular economy and low CO_2 emissions. The project will include the construction of 800 apartments, 600 of which provided by the project partner InvestiRE SGR.

In aforementioned project, among the proposed solutions for clean heating and cooling, three FREESCOO façade 3.0 prototype units are designed, prototyped and monitored on field. FREESCOO façade is synergistic with the adoption of a low temperature 4th generation district heating system, which allows the integration of renewable energy sources like solar thermal fields thanks to the low temperature required.

The manuscript is composed by two main sections, at first the analysis of the cooling energy required by the case study apartment is presented and then the coupling of the apartment with an ad hoc dynamic TRNSYS model of the FREESCOO façade 3.0 is discussed.

2. Apartment energy needs assessment

In this section the input and output results from the dynamic simulation using TRNSYS 18 are reported.

2.1 Climate analysis

The weather file used for the simulation is a Typical Meteorological Year Type 2 and is based on the available Meteonorm data for Milano Linate (id 160800). In Figure 1 and 2 the temperature and absolute humidity frequency and cumulated frequency are shown for the period between May and September. The figures show that for 30% of the considered period the external temperature is above 22 °C and the external humidity is above 12 g/kg. The weather analysis highlights the need for cooling and dehumidification.

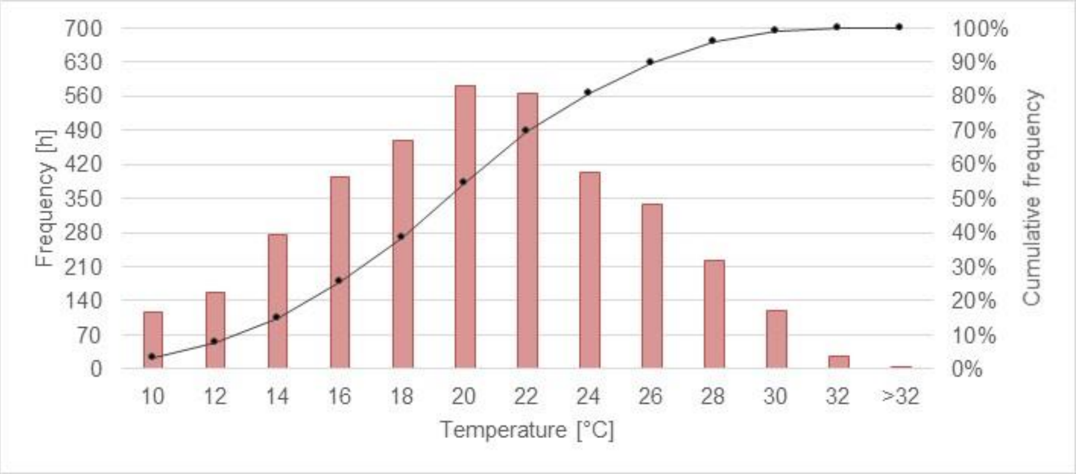

Fig. 1: External dry bulb temperature, monthly frequency (bars) and cumulative frequency (line) for the period May-September

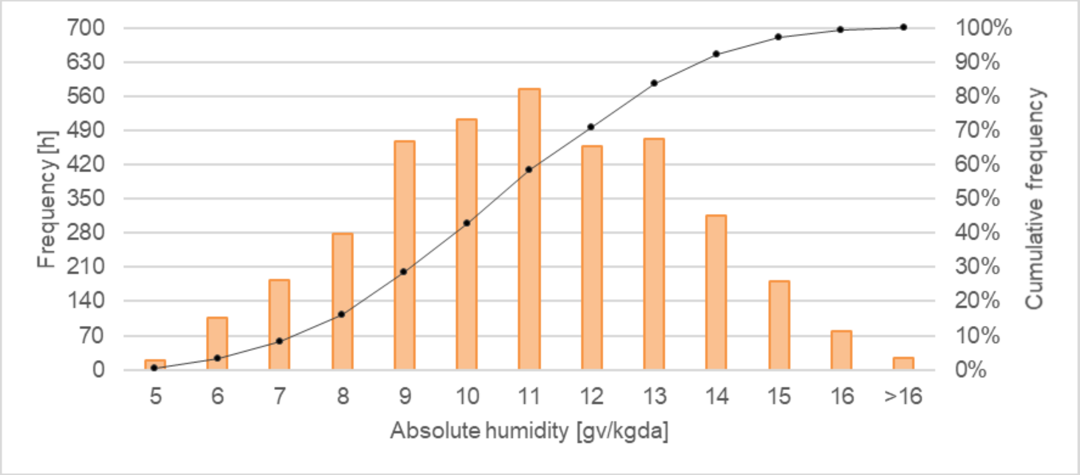

Fig. 2: Absolute humidity, monthly frequency (bars) and cumulated frequency (line) for the period May-September

2.2 Apartment simulation model

The case study apartment is a two rooms apartment at the fourth floor of the apartment building labeled E06. The apartment has only one façade towards the external environment with a Southeast orientation. The apartment adjoins two other apartments on the Southwest and Northeast sides and with the common area on the North-West side, where the stairs and elevators are located.

The apartment was modeled using the dynamic simulation software TRNSYS 18. Figure 3 shows the modelled thermal zones and their boundary conditions. The apartment has a total area of 46.9 m^2, which is divided in living room (23.4 m^2) and bedroom (23.5 m^2). Furthermore, a balcony (loggia) is present and considered as a solar shading by the model. The boundaries with the other apartments are assumed adiabatic, since the air temperature can be assumed similar.

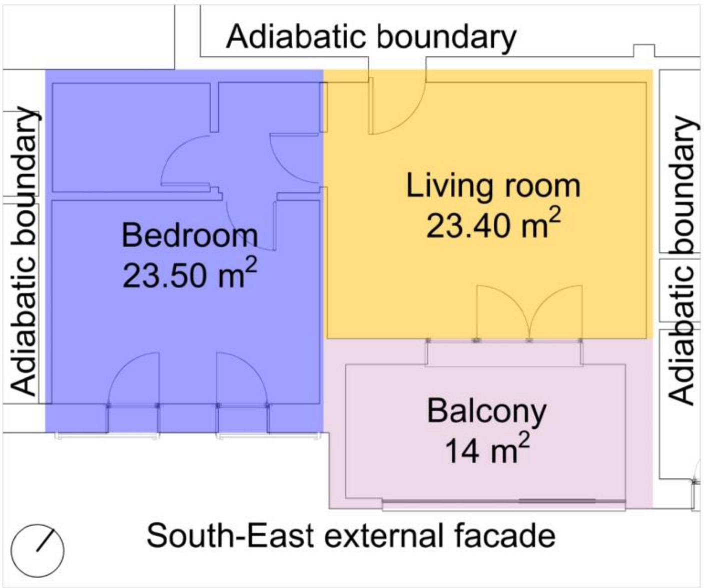

Fig. 3: Thermal zones scheme and boundary conditions

The apartment building E07 in the surrounding of E06 was also modeled to account for the shading on the apartment under analysis.

The U-Value (U) of the building envelope components are reported in Table 1. They derive from the “REDO Smart District Milano” actual project.

Tab. 1: Thermal transmittance (U) of the building envelope components

Layer	U (W/m^2/K)
External wall	0.215
Common area wall	0.623
Apartments dividing wall	0.254
Apartment dividing wall	0.470
Ceiling between apartments	0.443
Common area floor	0.307
Window 80x125+110	1.360
Window 250x235	1.360

60 W/person were considered for the internal gains due to people present in the apartment (33% convective and 60% radiative heat transfer) and 40 W/person of latent heat gain. Two occupation profiles were identified, one for the living room and one for the bedroom according to (Dott et al., 2013).

The internal gains due to appliances were also considered with a peak rate of 4.39 W/m^2 according to (Dott et al., 2013), 2/3 of the appliances gains were considered in the living room and 1/3 in the bedroom. Therefore, the final peak heat gains are respectively 5.87 W/m^2 for the living room and 2.92 W/m^2 for the bedroom. The profile trend between the two thermal zones is similar, therefore only the living room time series is shown in Figure 4.

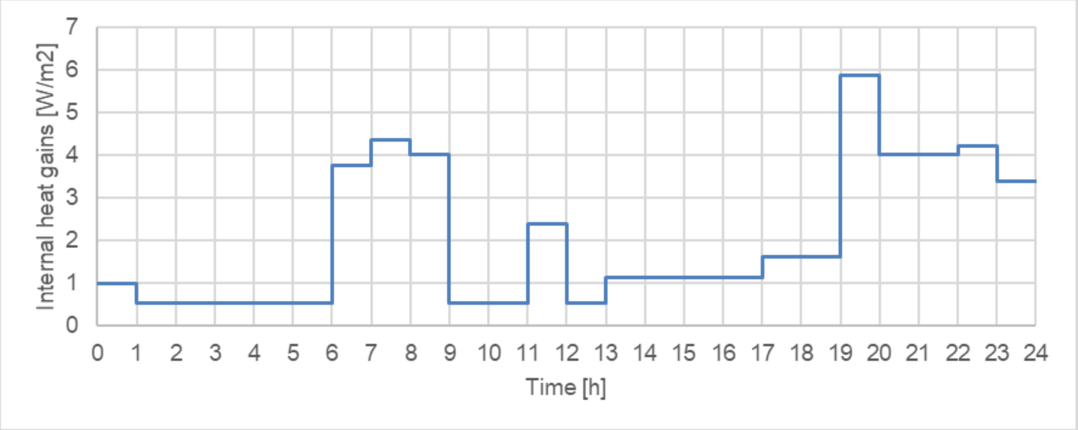

Fig. 4: Living room internal gain profile

The model also accounts for air infiltration and natural ventilation. The air infiltration is set constantly at 0.05 vol/h (volume air change per hour), while the natural ventilation is set at 0.25 vol/h at the external temperature and humidity condition.

To assess the energy needs of the apartment and idealized heating and cooling system was setup. It is able to track the temperature and humidity set-points in the apartment.

The Italian heating season is defined by DPR 26/08/1993 n. 412, depending on the climate area. Milan is located in the Climatic zone E, meaning that the heating season starts on the 15th of October and ends on the 15th of April. The remaining part of the year is considered as cooling season.

For the heating season, the temperature set-point is 20 °C from 7 a.m. to 9 p.m. and a setback temperature of 16 °C in the remaining hours. For the cooling season, the temperature set-point is kept constant at 26 °C for the whole day, while the relative humidity set-point is 50%.

2.3 Results

The overall sensible heating demand resulting from the simulation of the apartment is 570 kWh (12.15 kWh/m^2), the monthly distribution is shown in Figure 5 in orange color (Qsens,heat_25). The overall sensible cooling demand is 845 kWh (18 kWh/m^2) shown in color blue in Figure 5 (Qsens,cool_25), while the latent cooling demand due to dehumidification is 273 kWh (5.83 kWh/m^2) shown in color grey in Figure 5 (Qdehum_25). In Figure 6 and 7 are reported the heating and cooling demands frequency (bars) and cumulated frequency (lines).

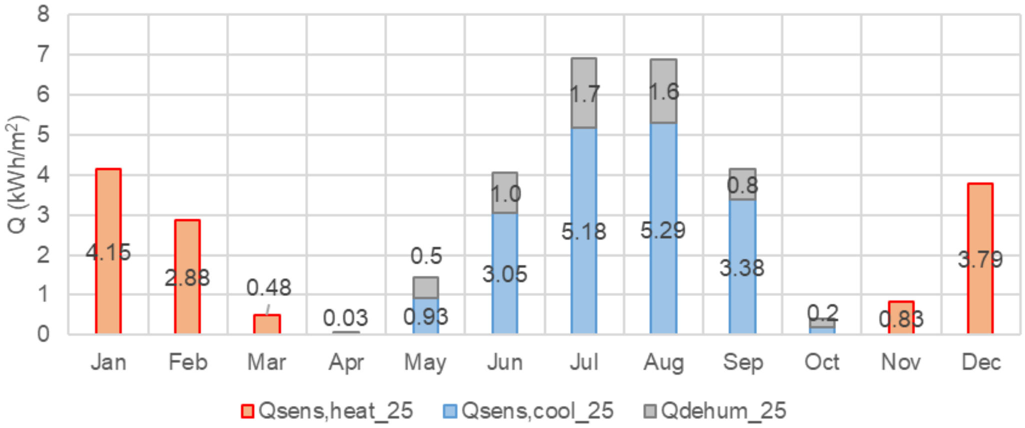

Fig. 5: Apartment monthly energy needs

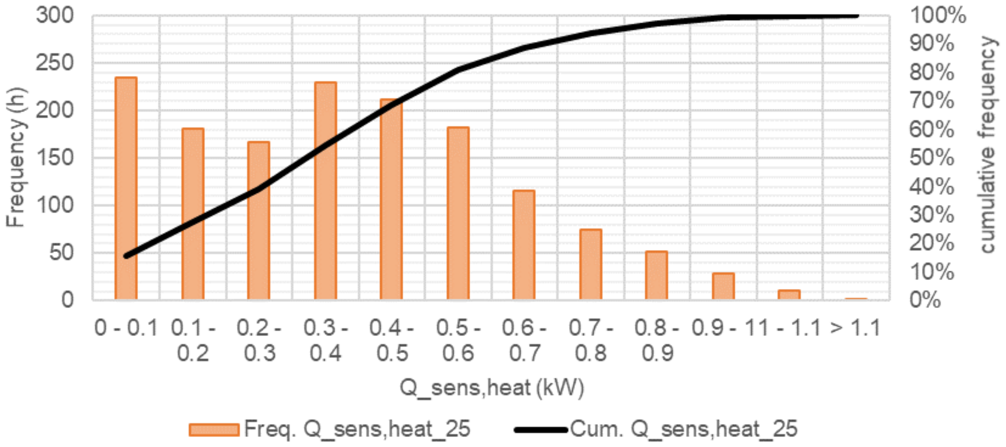

Fig. 6: Sensible heating load (Q_sens,heat_25) frequency (bars) and cumulative frequency (line)

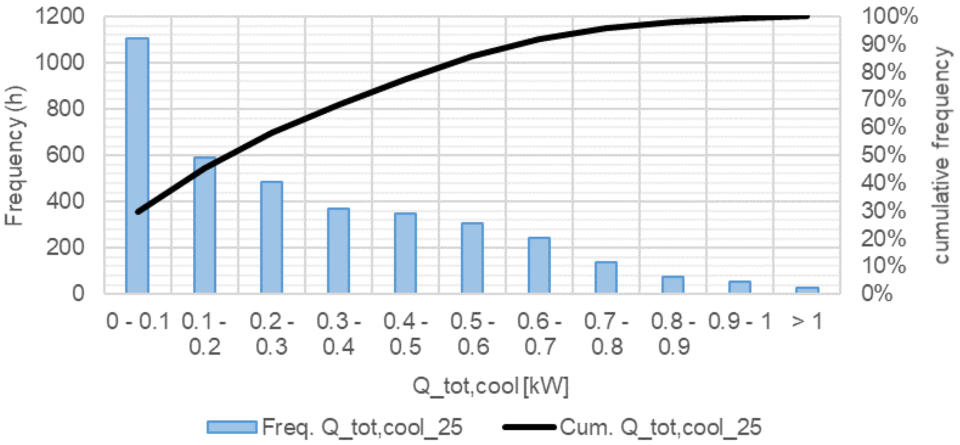

Fig. 7: Overall cooling load (Q_tot,cool_25), sensible and latent, frequency (bar) and cumulative frequency (line)

3. Overall system description and TRNSYS model

From the technological point of view, the new concept FREESCOO façade 3.0 improves on the older version (Finocchiaro et al., 2016b e Beccali et al. 2018), because it can also work in closed-loop mode, recirculating all the process air, similarly to a conventional split air conditioning system. This allows the transfer of all the cooling power produced to the internal environment, reducing or neglecting the energy necessary for the fresh air treatment. Indeed, the fresh airflow rate can be adjusted and it is not coupled with the operation of the thermodynamic cycle, while in traditional DEC systems due to the open cycle approach, this is not the case.

The system is ductable and characterized by a limited footprint, allowing it to be installed also on small balconies. In Figure 8, a visual rendering of the installation is shown.

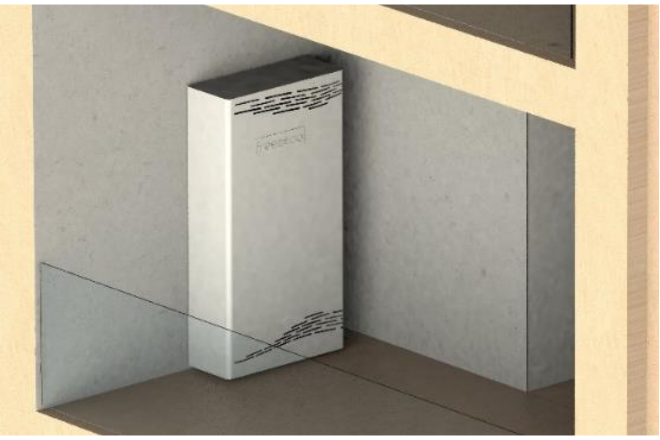

Fig. 8: 3D rendering of the FREESCOO façade 3.0 for vertical wall installation in the Merezzate+ case study

About the processes inside the machine, Figure 8 and the following sentences describe it.

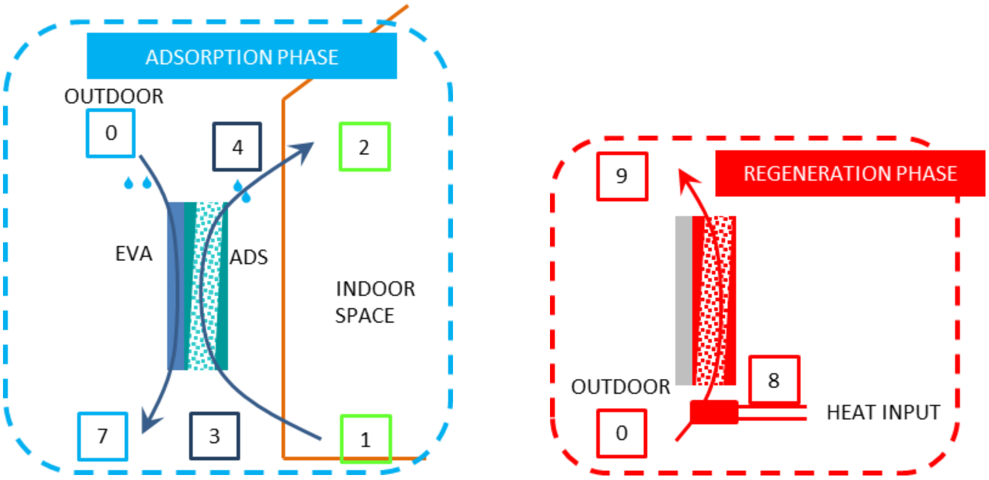

Fig. 9: Freescoo 3.0 summer cycle

The process air passes in the cooled adsorption bed for its dehumidification and direct evaporative cooling process (points 3-4 in Fig.8). Thanks to the exchange of heat with the outside air, cooled as well by a direct evaporative cooling process, the adsorption heat can be rejected to the external ambient (points 0-7 in Fig.9).

The coupling of dehumidification and cooling steps allows increasing the energy performance of the whole process in comparison to standard desiccant rotor based DEC cycles.

When the adsorbent material is saturated with moisture, this must be "reactivated" by means of an heat input. For the regeneration of the adsorption material, the cycle is now open to the ambient. A flow rate of ambient air (point 0 in the right box of Fig.8) is drawn through a heating coil (point 8) and then through the adsorption beds for its regeneration.

Two adsorbent beds are included in the Freescoo unit to ensure continuous operation of the system. While the first one is working to dehumidify the air, the other one is regenerated using heat from the heat distribution system. A network of air dumpers provides the automatic commutation between the two adsorption beds to guarantee a continuous process.

In case of need of ventilation, an adequate air change can be guaranteed opening an air damper that permits to take part of the air form the ambient, which follows the dehumidification process and then enters the conditioned room. This additional small flow rate (50-70 m^3/h) exfiltrates through windows and doors of the building.

The nominal heating power of the system is 2 kW, while the nominal cooling power is 2.2 kW, the airflow rate range is between 0 and 700 m^3/h. The maximum thermal power need is 2.7 kW for regeneration purposes and 2 kW for heating, while the maximum electric power consumption is around 200 W. The ventilation flow rate can also be adjusted between 0 and 150 m^3/h.

In order to assess the seasonal performance of FREESCOO, a dynamic simulation model of the concept was realized through TRNSYS by coupling it with the apartment model. The overall system model is composed by the following blocks:

- Weather data reader and solar geometry calculator;
- District heating network;
- Apartment model;
- FREESCOO façade 3.0 (adsorption cooled beds and indirect evaporative cooler, fans, water circulators);
- PID control of cooling power via air flow rate regulation.

For the models of the adsorption cooled beds and the direct evaporative cooling process, semi-empirical based models have been derived starting from experimental data taken from prototypes tested in lab. In Table 2, the main parameters that characterize the simulations are shown. In particular, the model used to simulate the adsorption bed is based on iso-thermal lines typical for regular density silica gel and other empirical parameters taking into account the thermal and moisture exchange effectiveness.

Tab. 2: TRNSYS simulation parameters and hypothesis

Description	Value
Weather file	Milano Linate .tm2
Time step	0.25 h
Cooling season	1st May to 30th September
FREESCOO on/off	24 h/g
Apartment cooling set-point	26 °C
Fresh air flow rate	120 m^3/h
Volume of handled air	1 vol/h
Cooling power modulation	variable air flow rate

4. Results

4.1 Energy performance

In the next section, the simulation results are reported for two weeks starting in mid-July. In Figure 10 is shown that the apartment internal temperatures always stay in between the upper and lower boundaries of the cooling set-point temperature. Furthermore, the modulation factor of the FREESCOO refrigeration unit, which is proportional to the airflow rate, stays in between the minimum value to allow for the ventilation flow rate and at maximum around 70%. This means that the machine has still 30% cooling power to spare concerning the peak demand of the apartment.

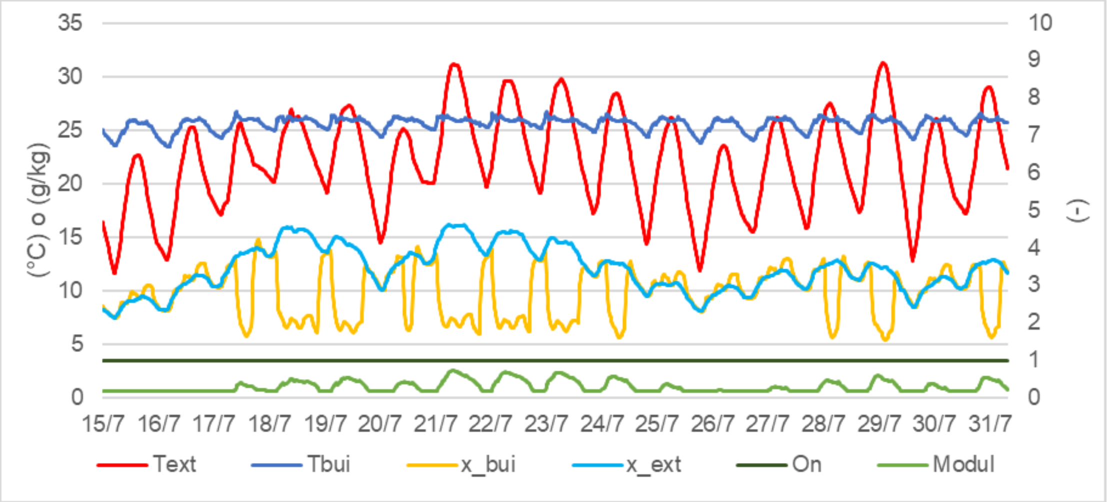

Fig. 10: Results shown for the period between mid-July and the end of July (x-axis), external air temperature ('Text', red, left y-axis), internal air temperature ('Tbui', blue, left y-axis), external and internal absolute humidity ('x_ext', light blue, yellow, left y-axis), modulation factor ('Modul', green, right y-axis), On-Off of the device ('On', dark green, right y-axis).

In Figure 10, it is also shown that the refrigeration unit is also able to keep the absolute humidity below the maximum value via dehumidification.

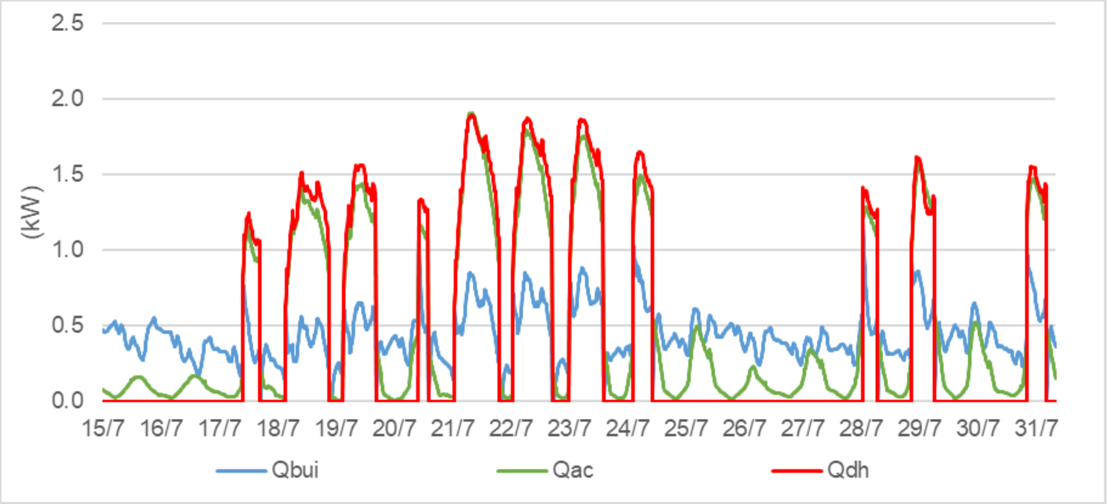

Fig. 11: time horizon between mid-July to the end of July (x-axis), cooling power provided to the apartment ('Qbui', light blue, left y-axis), overall cooling power required for air conditioning ('Qac', green, left y-axis), heating power provided by the district heating ('Qdh', red, left y-axis)

For the same two weeks in July the cooling power provided by the refrigeration unit and the heating power required are shown in Figure 11. One remark can be made on the cooling power required for air conditioning, which is similar to the required heating power by the machine, and only slightly lower, meaning that the thermal COP of the refrigeration unit is around 1. Furthermore, in some cases, FREESCOO is able to provide cooling power even without any direct heat consumption. This kind of performance is obtained thanks to the indirect evaporative cooling, which allows the reduction of the apartment air temperature by exchanging heat with the external air while in presence of water evaporation. This operation mode is activated every time the wet bulb temperature of the external air is below 20 °C.

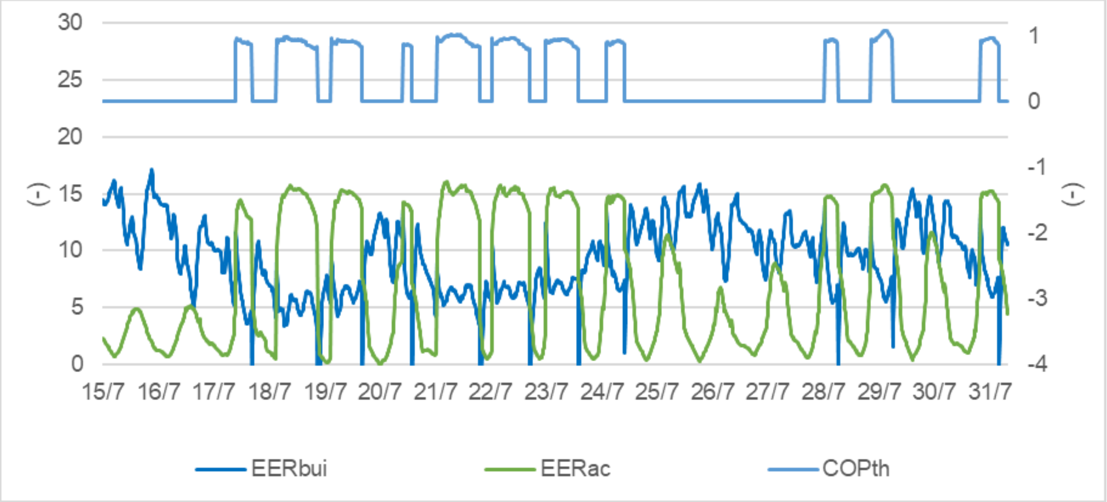

Fig. 12: time horizon between mid-July to the end of July (x-axis), electrical EER referred to the provided cooling power ('EERbui', blue, right y-axis), electrical EER referred to the air conditioning cooling power ('EERac', green, right y-axis), thermal COP ('COPth', light blue, right y-axis).

Fig. 12 shows the global electric performance of the unit due to the air handling process of outside air (EER ac) and the performance related only to the cooling power delivered to the building (EER bui) which can benefit also from the free cooling and the indirect cooling process. The monthly energy performance of the system is reported in Figure 13. As an example, in July (Fig.13) the monthly electrical EER is around 11.2, while the thermal COP is 1.3. In May the thermal COP increases considerably, this is due because in May the machine operates mostly in indirect evaporative cooling, requiring little to no heat from the district heating system.

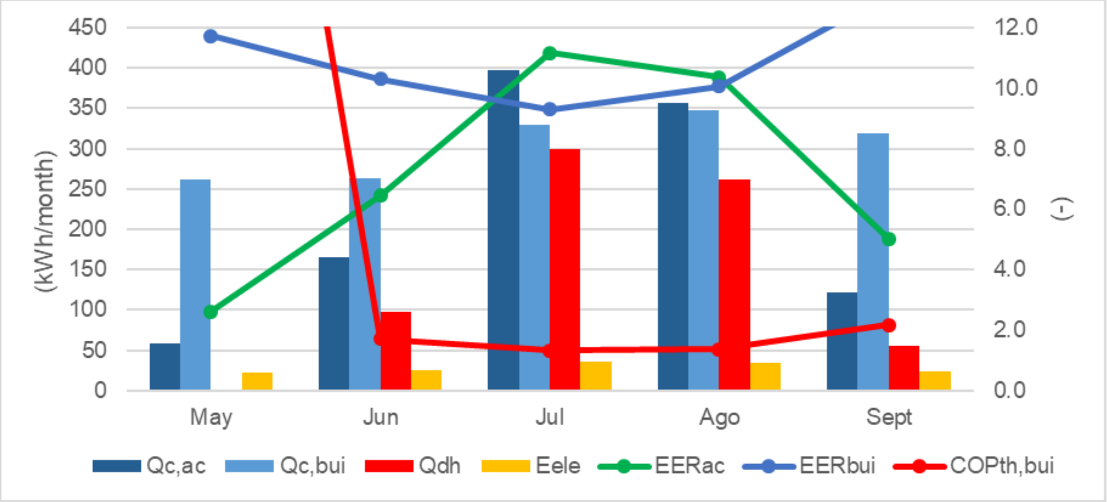

Fig. 13: Monthly energy performance of FREESCOO façade 3.0

Tab. 3: Seasonal performance summary FREESCOO façade 3.0

Qc,ac	kWh	1099
Qc,bui	kWh	1521
Qdh	kWh	715
Eele	kWh	142
EERac	-	7.7
EERbui	-	10.7
COPth,bui	-	2.13
water consumption	l	2136

4.2 Operational costs

In order to quantify the economic and energy savings of the proposed concept, Table 4 summarizes the calculations relative to the primary energy savings due to nonrenewable energy sources and economic savings. The new concept was compared with a traditional air conditioning system, based on a vapor compression cycle, and having a SEER (Seasonal Energy Efficiency Ratio) equal to 3, same fresh air change rate and a ventilation consumption equal to 75% with respect to the FREESCOO system. In Table 4, three specific cases are reported. In reference Case 1, the primary energy conversion factors for nonrenewable energy were ($f_{P,nren}$) 1.07 for district heating and 1.95 for electricity. In reference Case 2, the electricity factor was chosen as 2.5 according to the typical number used for the EU. In reference Case 3 the hypothesis of introducing a 30% renewable quota to the district heating generation for example produced by solar thermal leading to a primary energy conversion factor of 0.75.In terms of money savings, for all cases the use of freescoo permits to save 44% of the total costs due to the operation of the conventional air conditioning system. The results show that the convenience in terms of primary energy savings is strongly related to the renewable quota of the heat used to drive the freescoo unit and the specific characteristics of the grid.

Tab. 4: Operational energy and economic savings

Cooling energy provided	kWh	1521		
Electricity used	kWh	142		
District heating heat used	kWh	715		

		case 1	**case 2**	**case 3**
Primary energy factor district heating	kWh/kWh	1.07	1.07	0.75
Primary energy factor electricity	kWh/kWh	1.95	2.5	1.95
District heating renewable quota		0%	0%	30%
Thermal energy cost	€/kWh	0.076		
Electricity price	€/kWh	0.25		
Energy savings section				
Traditional air conditioning system				
SEER		3		
Total electrical consumption	kWh	649		
Total Primary energy consumption	kWh	1 266	1 623	1 266
FREESCOO façade 3.0				
District heating Primary Energy	kWh	765	765	536
Electricity Primary energy	kWh	277	356	277
Total Primary energy consumption	kWh	1043	1121	814
Primary energy savings	kWh	223	502	452
Primary energy savings	%	**18%**	**31%**	**36%**
Economic savings section				
Traditonal air conditioning system				
Heating and cooling cost	€	127	127	127
Ventilation cost	€	36	36	36
Total cost	€	162	162	162
FREESCOO façade 3.0				
District heating cost	€	55	55	55
Electricity cost	€	36	36	36
Total cost	€	90	90	90
Savings	€	72	72	72
		44%	**44%**	**44%**

5. Conclusions

In the project Merezzate+ sponsored by Climate-KIC, an innovative high-efficiency air conditioning system, named FREESCO façade 3.0 is being developed, realized, installed, monitored and optimized. FREESCOO façade 3.0 is based on a DEC (Desiccant Evaporative Cooling) thermodynamic cycle. The system uses mainly low-grade heat to work (60°C), with a smaller contribution of electricity for ventilation and water for the humidification process. One of the crucial aspects of the system are the new adsorbent beds developed, which allow the packaging of a large amount of adsorption material, while also reducing the regeneration temperature. The other main features of the system are use of water as a refrigerant; use of high efficiency evaporative cooling; high electrical Energy Efficiency Ratio (EER > 10); lastly, it is compact and plug & play. In this manuscript, the advantages of this new concept were proven in a simulation case study located in Milan. The system will be coupled with a 4th generation low-temperature district heating system, which allows the introduction of renewable energies, such as solar thermal fields. The results of the simulation prove that the design of the refrigeration unit being developed agrees with the energy needs of the case study apartment. From the primary energy savings perspective for a conventional air conditioning system, they can be up to 36% if the electricity generation is not renewable heavy or the district heating has a renewable energy quota. From the economic perspective, the new concept allows up to 44% economic savings with compared to a traditional system.

6. Acknowledgments

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