A Methodological Approach to Assess the Climatic Potential of Natural Ventilation Through Façades

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Abstract

Due to the rapid development of super insulated and airtight buildings, the energy requirement for mechanical ventilation is becoming more and more dominant in today's highly efficient buildings. In this scenario, natural ventilation has the potential to reduce energy use for buildings while maintaining ventilation rates that are consistent with acceptable indoor air quality. The increase in air temperature and frequency of extreme weather events (e.g. heavy rains, heat and cold waves) due to climate change will alter future outdoor boundary conditions and consequently the potential for natural ventilation in buildings. Therefore, to respond to the fluctuations in outdoor boundary conditions, the building envelope should become more and more dynamically responsive. In that sense, the façade plays an important role by regulating indoor comfort based on outdoor environmental conditions. This paper presents a methodological approach to investigate the potential of natural ventilation through the façade in office buildings in present and future climate conditions. It reviews technologies and strategies that maximise the use of natural ventilation in office buildings located in six selected different European climates. Numerical analyses were conducted, considering outdoor air temperature and humidity. Integrated façades with hybrid systems and strategies is one of the key solutions for increasing the potential of natural ventilation. The results showed that a hybrid solution with low-pressure drop heat recovery had the greatest potential to maximise the possibilities of low energy façade integrated ventilation.

Keywords

Natural ventilation, building façade, climate change

1 INTRODUCTION

Buildings currently contribute to 40% of global primary energy consumption and 30% of CO_2 emissions (World Energy Council (WEC) (2013)). The European Commission has set a low carbon economy road map that states that greenhouse gas emissions shall be cut to 80% below 1990 levels by 2050, and 20% by 2020. One of the strategies to achieve this goal is to develop high-performance building skins that are responsive and dynamically regulate the heat flows, light distribution, air and vapour transport (Perino, 2008). As the thermal insulation of a building is improved, energy demand is reduced and heat loss due to ventilation becomes an increasingly important entry in the energy balance of the building. In fact, thermodynamic treatment of ventilation air still requires a significant amount of energy which makes exploiting natural ventilation, here with the meaning of ventilation air without thermodynamic treatment, an important strategy to consider. Over the years, natural ventilation has developed from being merely considered as a mostly uncontrolled phenomenon based on air infiltration through cracks and airing through windows, to a demand-controlled fresh air supply system that also provides a cooling function. Therefore, a hybrid ventilation system that couples both natural- and mechanical ventilation can represent a robust and sustainable solution (Heiselberg, 2002). Office buildings are an interesting case for the implementation of natural and hybrid ventilation solutions because of the strict regulation for indoor climate conditions and regular occupancy schedules. The larger size of office buildings is also often an asset as it creates conditions with substantial thermal and pressure differences on each side of the façade and which can be utilized (Walker, 2006).

Building facades play an important role in architecture both from an aesthetics' perspective and as the interface between the indoor- and the outdoor environment which makes them a key element in natural ventilation and indoor climate strategies. Facades should, to a certain degree, respond to changing external environmental conditions to ensure a stellar performance in terms of energy and indoor comfort. This means that incorporating climate change predictions is more and more an emerging area of interest in the façade's development (Barclaya, 2012). Since climate change is expected to affect the global trends of the variables which influence natural ventilation potential in buildings (such as outdoor air temperature, wind, irradiation), this study aims at investigating the extent to which strategies for natural ventilation in buildings can effectively account for changing weather patterns and their resulting ability to reduce energy use for ventilation in present and future climatic conditions.

This paper also presents a numerical investigation of the impact of the present and future climatic conditions on the façade's ability to integrate natural ventilation by calculating the Climatic Potential of Natural Ventilation (CPNV) index and looking at the sensitivity of the CPNV at different European latitudes. The climate analysis conducted in this work is used to estimate the variability of the CPNV due to temperature and relative humidity changes (i.e. preheating/precooling, humidifying/dehumidifying) of the ventilation air coupled with active and passive treatments through solar availability and heat recovery systems. The CPNV index is therefore modified, and the Extended Climatic Potential of Natural ventilation (ΔCPNV) is assessed to understand how a small change in the thermodynamic conditions of the air, implemented through an action carried out at the façade level, can increase the potential use of natural airflow for building climatization.

Because the main output of this paper is to develop a methodology to carry out the above-mentioned analysis, the results are limited to selected locations and south-facing facades.

The objectives of this paper are therefore:

- To present a novel methodological approach to investigate the potential of natural ventilation through the façade in office buildings;
- To apply such a methodology that considers present and future climate conditions in a few selected locations;
- To assess the extent to which the potential of natural ventilation through the façade is affected by modified patterns in climate change scenarios;
- To identify what are the most promising functionalities that an integrated building envelope system should incorporate to maximise the exploitation of natural ventilation through minimal air treatment at façade level.

2 METHODOLOGY

The paper presents a methodological approach to assess the CPNV through façades in past, present and future climate conditions. It is based on earlier work by Causone (Causone, 2016) (see section 2.1) and it consists of processing past climatic data (historical scenario) (i.e. historical periods depending on the data collection for each location), present (Scenario 2020) and future (Scenario 2050). *Energyplus* (U.S. Department of Energy's Building Technologies Office, National Renewable Energy Laboratory, 2019) weather data files (*.epw*) were used as climatic data input for the past scenario and as the basis for creating the weather data files for the present and future climate scenarios using the Climate Change World Weather (CCWW) file generator version 1.8 (v1.8) (Sustainable Energy Research Group - University of Southampton, 2019). The CCWW v1.8 uses the HadCM3 scenario data of experiment ensemble available from the Intergovernmental Panel on Climate Change (IPCC) Data Distribution Centre related to the Third Assessment Report of IPCC (Belcher, 2005), (IPCC Data Distribution Centre, n.d.). Hourly *.epw* weather data for the present-day climate is adjusted with the monthly climate change prediction values of the HadCM3 scenario datasets. The generated weather data files were used in the analysis conducted in *Energyplus*, while data was processed and visualized using Python programming language and Excel.

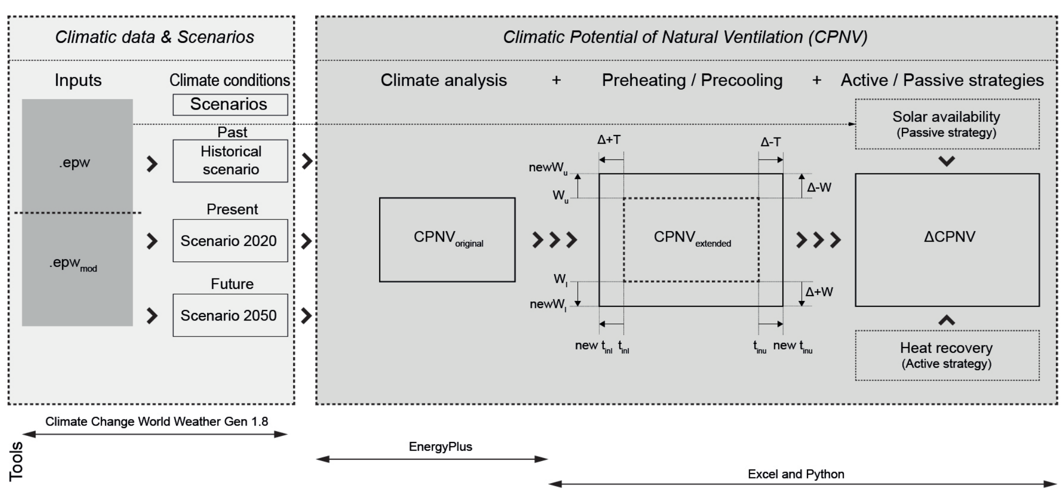

FIG. 1 Workflow of the process for the calculation of climatic potential of natural ventilation in each case study city

Fig. 1 summarizes the workflow elaborated for the calculation of CPNV in each location. The analysis of the solar availability, i.e. global solar irradiance on vertical and horizontal planes, (W/m^2), and heat recovery systems were performed to determine the active and passive strategies to adopt when the use of natural ventilation was not possible.

2.1 CLIMATE ZONES AND CITIES SELECTION

The climate analysis was conducted for six selected European cities incrementally separated by of 5-degrees of latitude and located in different climate zones according to the Köppen-Geiger climate classification (Kottek, Grieser, Beck, Rudolf, & Rubel, 2006) (Fig. 2).

The selected cities were spread out over the following zones:

- *Nordic zone*: Oslo (59.9° N, 10.7° E) classified as warm-summer humid continental climate [Dfb] and Copenhagen (55.6 ° N, 12.5° E) with temperate oceanic climate (Cfb).
- *Continental zone*: Brussels (50.8° N, 4.3° E) where the climate is warm and temperate (Cfb) and Milan (45.4° N, 9.1° E) with humid subtropical climate (Cfa).
- *Mediterranean zone*: Madrid (40.4° N, 3.7° W) and Valletta (35.4° N, 14.3° E) classified as Mediterranean hot-summer humid continental climate (Csa).

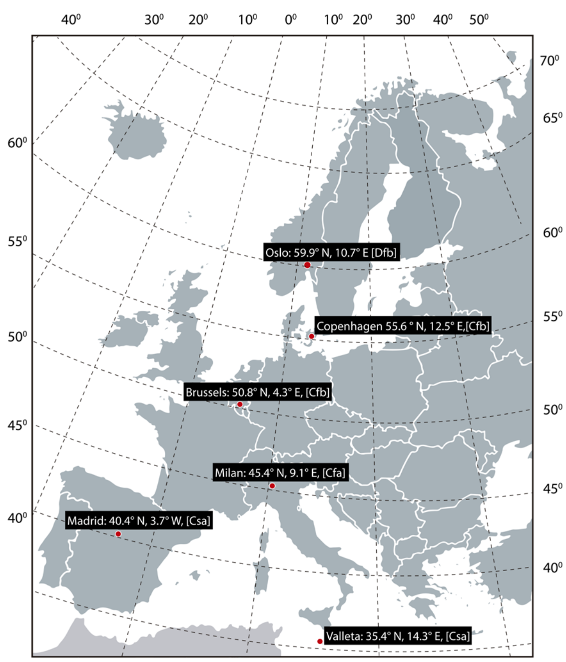

FIG. 2 Map of Europe with the six selected European cities evenly distributed (5-degrees of latitude) according to the Köppen-Geiger climate classification.

After selecting the cities based on general climatic characteristics, the yearly outdoor temperature variation is plotted against the upper and lower temperature boundary conditions for thermal comfort (Fig 3 a) determined by the adaptive (ASHRAE, 2013). According to (Givoni, 1969) (Berglund, 1998) (Fountain, 1999) (Wyon, 2006) (ASHRAE, 2009), 30–70% relative humidity (RH) was assumed as a range to guarantee comfortable conditions for both thermal and indoor air quality (IAQ). Additional selection criteria were also considered such as: (i) the diversity of the meteorological conditions during the year (e.g. different percentage of sky coverage, level of precipitation) for the cities in the same climate zone according to Köppen-Geiger climate classification (e.g. Copenhagen and Brussels or Madrid and Valletta), which might result in a variability in the climatic potential of using natural ventilation; and (ii) the mean monthly global solar irradiance available on the different orientations (Fig. 3). Although there are other factors than the latitude which influence the local climate, the cities were chosen to provide a basic overview of the climatic variations in terms of potentials of solar energy exploitation, and which influences the dynamic interaction between buildings and the outdoor environment.

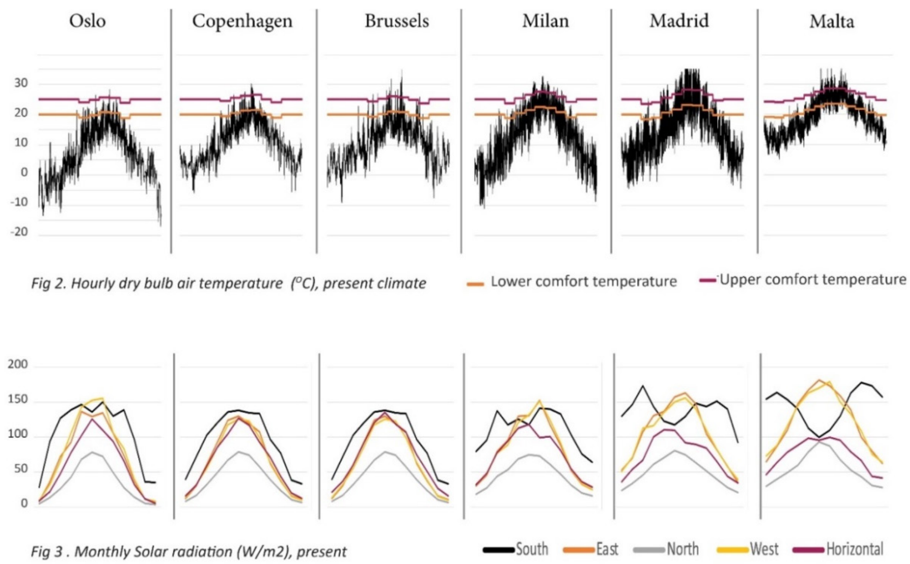

FIG. 3 (above) Hourly dry bulb air temperature and (below) average monthly solar irradiance on vertical (South, East, North and West) and horizontal planes at the historical climatic data. Data has been processed from the original .epw file

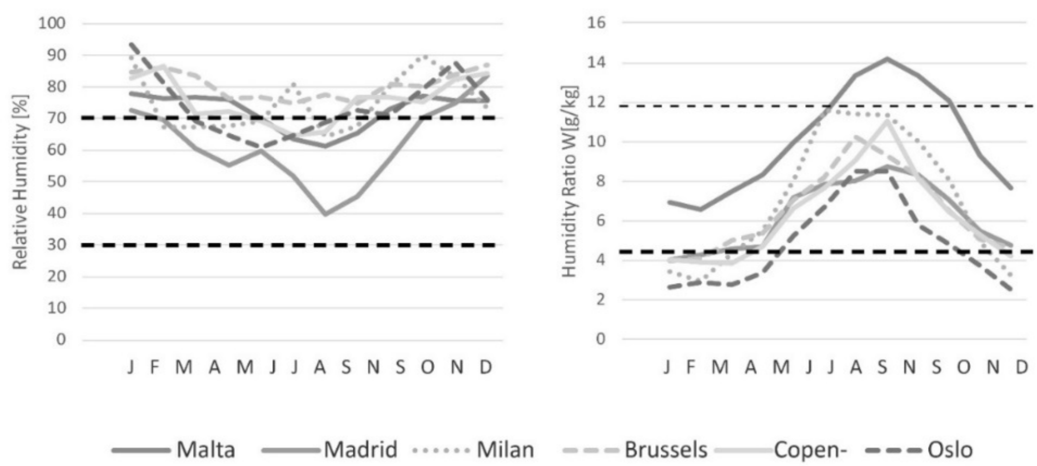

FIG. 4 (left) Monthly relative humidity and (right) average humidity ratio W (g/kg) for the selected cities in present climate conditions

Fig. 4 (left) shows that considering only RH, most climates provide conditions that are outside the comfort zone. In fact, humidity level of the outdoor air in cold climates is too high to be used as a direct fresh air supply. Therefore, Causone (Causone, 2016) proposes absolute humidity ratio (W) (g/kg) as adaptive humidity constraints linked to the adaptive comfort temperature limits in relation to the assessment of the potential of natural ventilation, since the RH of the outdoor air is of little significance when the possibility to ventilate the building directly with outdoor air is evaluated. The W ratio illustrates the opposite situation to RH boundaries (Fig. 4 right).

2.2 CLIMATE ANALYSIS

The methodology that was used to assess the extent to which a climate provides favourable (thermodynamic) conditions for natural ventilation is based on the method developed by Causone (Causone, 2016). This methodology evaluates the suitability of using natural ventilation in a given climatic context by calculating the Climatic Potential of Natural Ventilation (CPNV). The CPNV is defined as the number of hours in a year when natural ventilation can be used

$$(\sum_{i=1}^{n} h_{NV,i})$$

without incurring any heating or cooling load for the indoor space, divided by the total number of hours in a year (h_{yr}). This method is based on a climate analysis and is intended for conceptual designs where quick calculations are necessary, and a first approximation of the natural ventilation potential is required. It relies only on climate weather data and includes adaptive comfort models reported in the literature as well as the adaptive humidity constraints linked to the adaptive comfort temperature limits (Causone, 2016). It is therefore important to underline that the method only considers the suitability in terms of the temperature and relative humidity levels of the incoming air and does not analyse nor account for the natural mechanisms that assure the airflow. The word “natural ventilation” needs thus to be read as “without change in the thermodynamic conditions of the air” and in not related to natural-induced airflow movement. In this study, the CPNV is calculated during working hours ($CPNV_{work}$) in an office building occupied from Monday to Friday between 8:00 a.m. to 6:00 p.m. (). The $CPNV_{work}$ is defined as the following equation:

$$CPNV_{work} = \frac{\sum_{i=1}^{n} h_{NV,i}}{h_{yr-work}}$$

Ranges defining the upper (u) and lower (l) thresholds for temperature and humidity ratio were set to determine the use of natural ventilation in the selected locations in different periods of the year, since, according to the previous literature (Givoni, 1969) (Berglund, 1998) (Fountain, 1999) (Wyon, 2006) (ASHRAE, 2009), the air temperature range which is considered comfortable in an indoor space may change during the year according to seasons. This happens when the outdoor temperature (T_{out}) and outdoor humidity ratio (W_{out}) are within the comfort range established for their fluctuations (Fig. 5), as follows:

$T_{in,l} \leq T_{out} \leq T_{in,u}$ and $W_{in,l} \leq W_{out} \leq W_{in,u}$

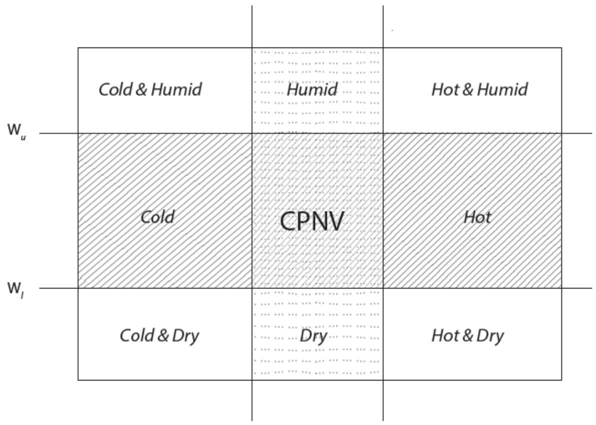

FIG. 5 Illustration of boundary conditions for CPNV, based on (Causone, 2016)

2.2.1 Extended Climatic Potential of Natural ventilation (ΔCPNV)

The CPNV is an index developed without any specific reference to the façade. However, in this work, the index was modified to understand how small of a change in the thermodynamic conditions of the air, implemented through an action carried out at the façade level, was necessary to increase the potential use of natural airflow for building climatization. The next step was then to estimate the difference (ΔCPNV) between the initial CPNV ($CPNV_{original}$) and the extended CPNV ($CPNV_{extended}$) achieved by expanding the boundaries ($T_{in,l}$, $T_{in,u}$, $W_{in,l}$, $W_{in,u}$) as a result of treating the temperature and humidity of the ventilation air (i.e. preheating/precooling, humidifying/dehumidifying) at the façade level (Fig. 6 left). The calculation of the ΔCPNV highlighted, for example, that the outdoor air should be preheated if it fell below the lower comfort temperature threshold or preheated and humidified if it fell below both the temperature and the specific humidity comfort conditions. This did not mean that the comfort range was increased because of a lower or a higher inlet temperature or humidity ratio, but rather that the periods of time in which natural ventilation is used could be extended with small treatments on the ventilation air.

$$\Delta CPNV = CPNV_{extended} - CPNV_{original}$$

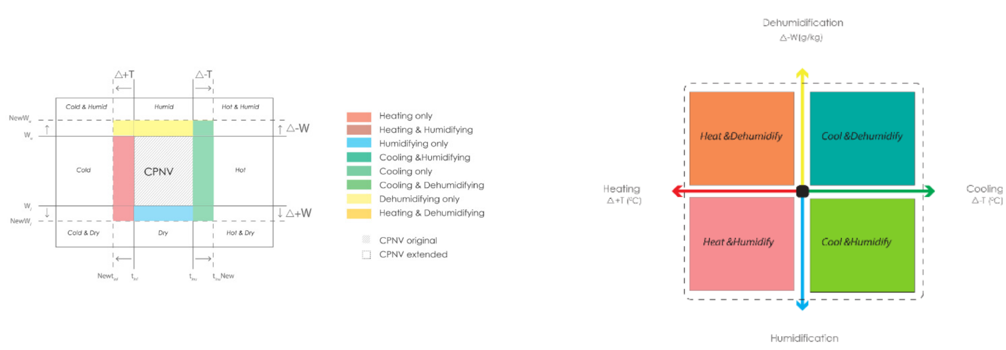

FIG. 6 (left) Visualization of different measures to maximize the CPNV (right) Concept of matrix graph for the results' visualization

This calculation was performed with a purposely developed script programmed in Python. The choice of the programming language was a functional one and allowed creating a tool (e.g. a digital dashboard with a user-friendly interface to calculate and optimize the climatic potential of natural ventilation according to a given climate. See section 5) which could later be shared through open access to a wider community. However, the automated procedures proposed in this methodology could have been implemented in any programming language.

Fig. 6 (left) shows that an increase of the CPNV can achieved by expanding the CPNV area and shifting at least one of the four boundaries of the CPNV domain. When deciding to move one or more of the boundary edges making up the original CPNV area, a corresponding action on the inlet air can be identified (Fig. 6 left). In Fig. 6 (right) the original area of the CPNV ($CPNV_{original}$) is represented as a point and the treatments of temperature and humidity of inlet air are shown on the x-axis and y-axis. The changes in humidity following the positive or negative y-axis mean that dehumidification or humidification of the incoming air is carried out, respectively.

A change in the temperature indicates the addition (preheating) or reduction (precooling) of heat to the inlet air along the positive and the negative x-axis, respectively. In the quarters the combination of both a change in the temperature and the humidity are visualized (Fig. 6 right). The figure was simplified from a 3D matrix graph to a two-dimensional graph with the negative values on the x-axis (-ΔT) representing preheating and positive values representing precooling (+ΔT), while the y-axis shows the change in ΔCPNV. The effect of humidity is shown parametrically on the same graph (see section 3. Results and discussion).

2.2.2 Solar availability and heat recovery

When calculating ΔCPNV, no information is given on how the air is thermodynamically treated.

This means that it can be done either naturally or mechanically. In this part of the study, some passive strategies enabled through active façade technologies, such as solar thermal energy availability and heat recovery, are assessed in connection to the ΔCPNV. The time during which sunlight is available was compared against the time when preheating or precooling is required and evaluated to assess whether the direct solar heat gain would be enough to preheat or precool the inlet air to the required temperature. The heat recovery was selected as a hybrid/natural ventilation strategy to assess to what extent it could expand the natural ventilation potential, by assuming the possibility to pre-heat/pre-cool the incoming airflow by recovering heat from the exhaust flow.

Different efficiency factors of the heat recovery unit were tested for both heating and cooling, within the range 60-90%, which is a realistic range for different types of heat recovery systems currently available. The supply temperature after the heat recovery with an efficiency (η) and the outdoor temperature (T_{out}) was calculated as follows:

$$\eta = \frac{T_{supply} - T_{out}}{T_{exhaust} - T_{out}}$$

3 RESULTS AND DISCUSSION

3.1 CPNV IN THE PAST, PRESENT AND FUTURE CLIMATE CONDITIONS

The annual percentage of time when outdoor conditions were within the comfort zone varied from one climate zone to another. This affected the domain of the $CPNV_{original}$.

The conducted climate analysis demonstrated that, at high latitudes (i.e. above 55° N) characterized by a cold climate, the $CPNV_{original}$ had the lowest potential in the historical scenario with a value of 5% in Oslo and Copenhagen, but that it increased by about 2% in both cities in the future weather scenario. Oppositely, in the Continental and Mediterranean zones which included the cities of Milan, Madrid and Valletta, the $CPNV_{original}$ in 2020 reached 16%, 15% and 17% respectively but in 2050, these numbers were reduced to 13% in Milan and Madrid and 14% in Valletta. Brussels represented the exception within its climatic zone, being the only city where the $CPNV_{original}$ was equal to 4% in the present climate and increased 7% in 2050, a behaviour otherwise only seen in the Nordic zone (Table 1).

TABLE 1 $CPNV_{original}$ in selected cities in the past, present, and future climate conditions

CLIMATE ZONES	CITY	CLIMATE CONDITIONS / SCENARIO		
		Past / Historical scenario	**Present / Scenario 2020**	**Future / Scenario 2050**
Nordic zone	Oslo	5%	7%	7%
	Copenhagen	5%	5%	7%
Continental zone	Brussels	4%	5%	7%
	Milan	16%	15%	13%
Mediterranean zone	Madrid	15%	14%	13%
	Valletta	17%	15%	14%

3.2 ΔCPNV BY PREHEATING AND PRECOOLING OF THE SUPPLY AIR

One of the possible actions that can be carried out at façade level to support its use as a ventilation inlet for the building is to pre-heat or pre-cool the airflow so that its thermodynamic conditions are within the CPNV area. Contrary to conventional ventilation systems, which can pre-heat or pre-cool air within a relatively large range, façade-integrated ventilation technologies face many technical challenges. For this reason, the analysis of the pre-heating and pre-cooling potential is limited to a range of ±10 C°. This arbitrary limit has been set considering that larger increases/decreases in the temperature would probably become uninteresting in a façade integration perspective. This analysis shows how façade-integrated solutions, which can be either small active devices or passive solutions for pre-heating/cooling, can extend the CNPV both in present and future climate conditions.

3.2.1 Nordic zone

The analysis conducted with the historical climate scenario in Oslo showed that by only preheating the inlet air by up to an additional 10 ˚C, the ΔCPNV increased by 30%. This means that it was possible to use natural ventilation 30% more of the time during the year (Fig. 7). By combining preheating and either humidifying or dehumidifying, the ΔCPNV increased even more in all scenarios. For the 2020 and 2050 scenarios, the ΔCPNV could be increased by 28% and 27% respectively. A combination of humidification and preheating allowed the most substantial increase in potential, and humidifying with 4g/kg could provide a ΔCPNV up to 35%, 33%, 32% for historical, 2020 and 2050 scenarios, respectively.

Precooling did not contribute substantially to the ΔCPNV in the historical climate and present scenario conditions in the Nordic zone. In fact, precooling gave less than a 1% change in the ΔCPNV because Oslo is predominantly a cold climate. However, in the future climate scenario, the precooling treatment could increase the ΔCPNV by around 2% ΔCPNV considering a precooling that lowers the inlet temperature by 4°C and humidifying rate of 3g/kg.

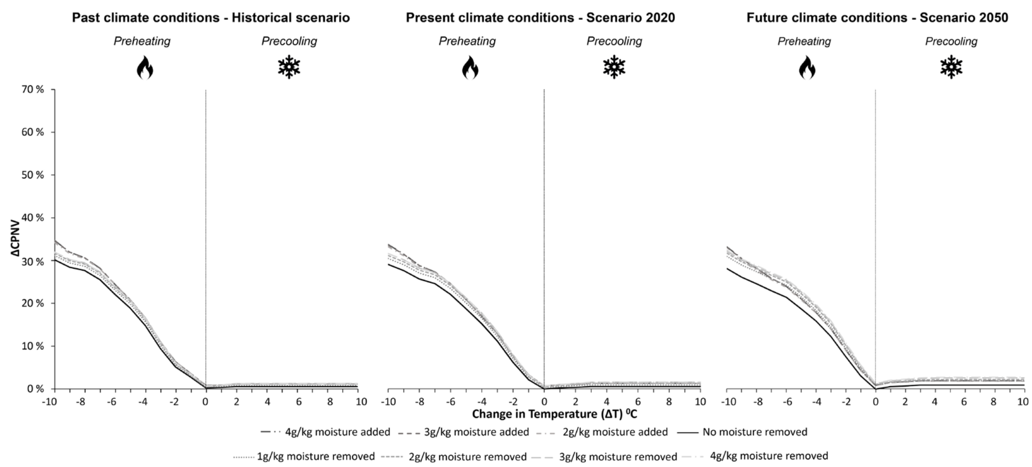

FIG. 7 Graph of ΔCPNV, for preheating and precooling in Oslo in the historical, 2020 and 2050 scenarios

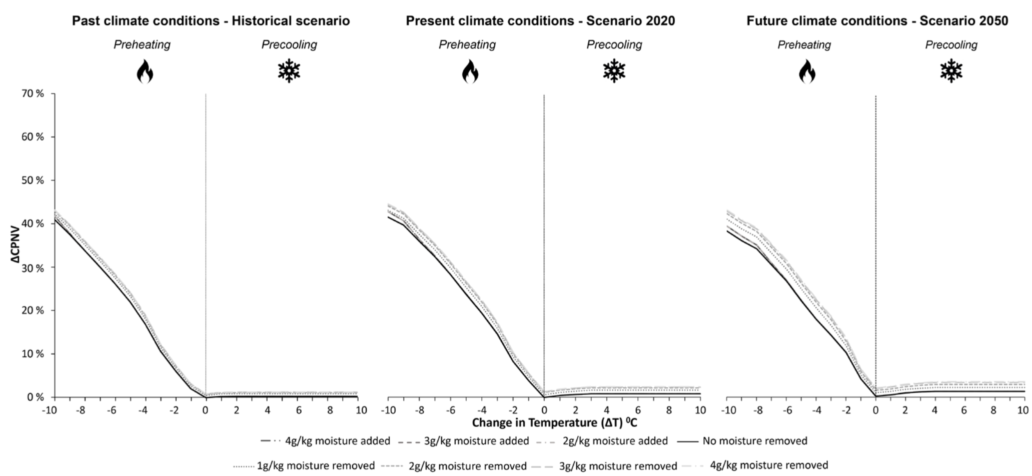

FIG. 8 Graph of ΔCPNV, for preheating and precooling in Copenhagen in the historical, 2020 and 2050 scenarios

The outcomes in Copenhagen showed that preheating with ΔT of 10 ˚C increased the ΔCPNV to 40% in the historical scenario and 41% in the 2020 scenario, while in the 2050 scenario, the ΔCPNV was just below 38%. A change in the humidity content of the inlet air did not contribute to improving the ΔCPNV in the past or present climate scenario but did provide benefits in the future climate conditions scenario for 2050, in which both preheating and precooling had a positive impact. Precooling of the inlet air was not relevant for the historical scenario but was increasingly beneficial in the scenarios for 2020 and 2050. Coupling precooling with 4 g/kg of dehumidification allowed a maximum 3% of ΔCPNV to be achieved in 2050 (Fig. 8).

3.2.2 Continental zone

Brussels and Milan have high levels of relative humidity throughout the year, which makes dehumidification a key aspect in improving the ΔCPNV for both preheating and precooling treatments.

In Brussels, preheating the inlet air alone could increase the ΔCPNV to 43% in the historical scenario, 44% in the 2020 scenario, and 45% for the 2050 scenario. However, the combination of preheating and dehumidification could lead to a ΔCPNV above 50% in 2050. The effect of dehumidification was such as that, even without increasing or reducing the inlet air temperature, the ΔCPNV could be increased to 3% regardless of the climate scenario. The combination of precooling with dehumidification was also shown to be progressively interesting and ranged from 7% in the historical scenario to 10% in the scenario 2050, while precooling alone only yielded a ΔCPNV of 2% (Fig. 9).

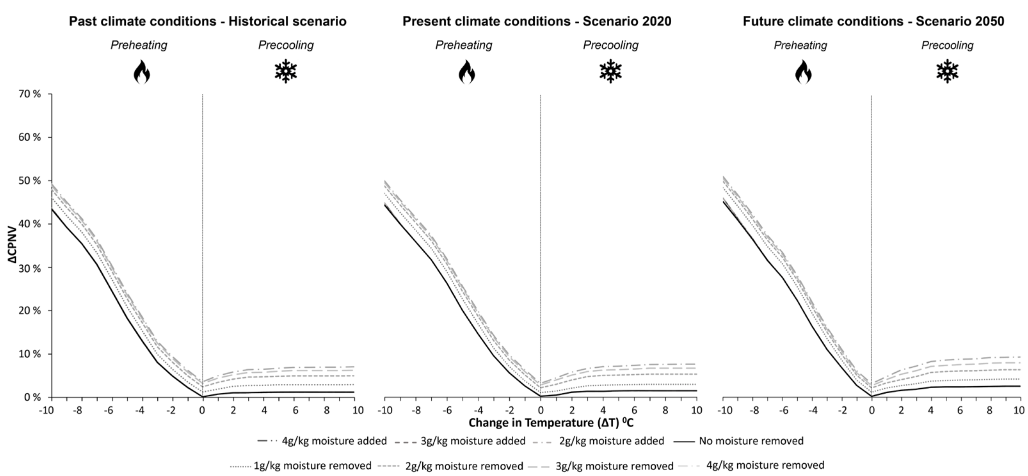

FIG. 9 Graph of ΔCPNV, for preheating and precooling in Brussels in the historical, 2020 and 2050 scenarios

In the historical scenario of Milan (Fig. 10), the ΔCPNV reached 27% by only preheating the inlet air, while it rose to 39% when coupled with dehumidification.

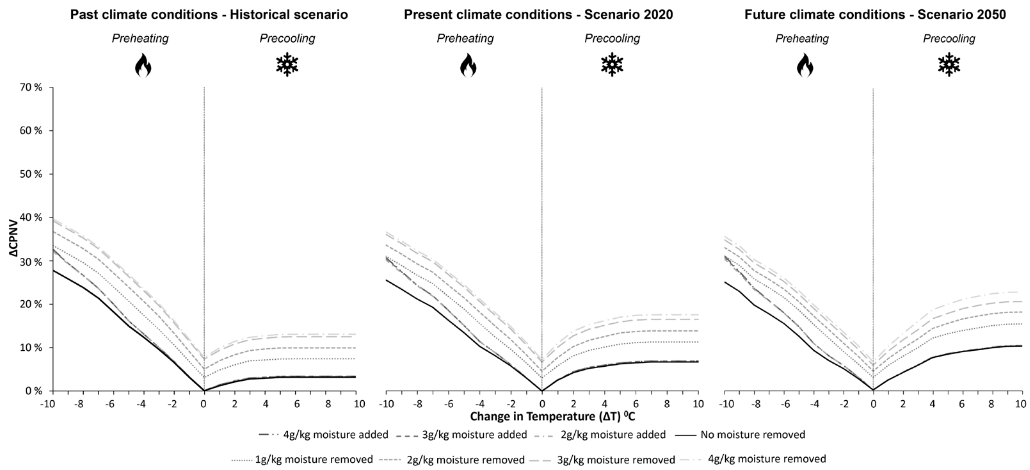

FIG. 10 Graph of ΔCPNV, for preheating and precooling in Milan in the historical, 2020 and 2050 scenarios

The ΔCPNV for preheating alone was slightly lower in 2020 and 2050, with an estimated value of 25%. Preheating combined with humidifying/dehumidifying was consistently more beneficial despite the ΔCPNV progressively reducing from 2020 to 2050. The combined treatment of preheating and humidifying became meaningful only when heating up the inlet air by 10˚C and by adding moisture content of 2 g/kg. Precooling alone raised the ΔCPNV to 3% in the historical scenario to 10% in the scenario 2050. Combining precooling and humidification or dehumidification was also increasingly interesting with a ΔCPNV of 12% for the past scenario and a ΔCPNV of 15% in 2020. The highest value of ΔCPNV was 21%, reached in the 2050 scenario by coupling precooling with a rate of dehumidification of 4 g/kg.

3.2.3 Mediterranean zone

In Madrid, for the past climatic scenario conditions, the ΔCPNV was 38% with the preheating treatment alone, but only reached 36% and 34% in the 2020 and 2050 scenarios, respectively. Generally, the humidification treatment improved the potential of natural ventilation in Madrid due to a relatively dry climate. In fact, the humidification of the inlet air by 2g/kg coupled with preheating of 10 ˚C contributed to an additional to 8% compared to the preheating treatment alone. The precooling treatment displayed higher potential when coupled with humidification by contributing to an additional 3% compared to precooling alone in the 2050 scenario. Finally, regardless of the scenario, the dehumidification did not seem to provide a substantial contribution in Madrid (Fig. 11).

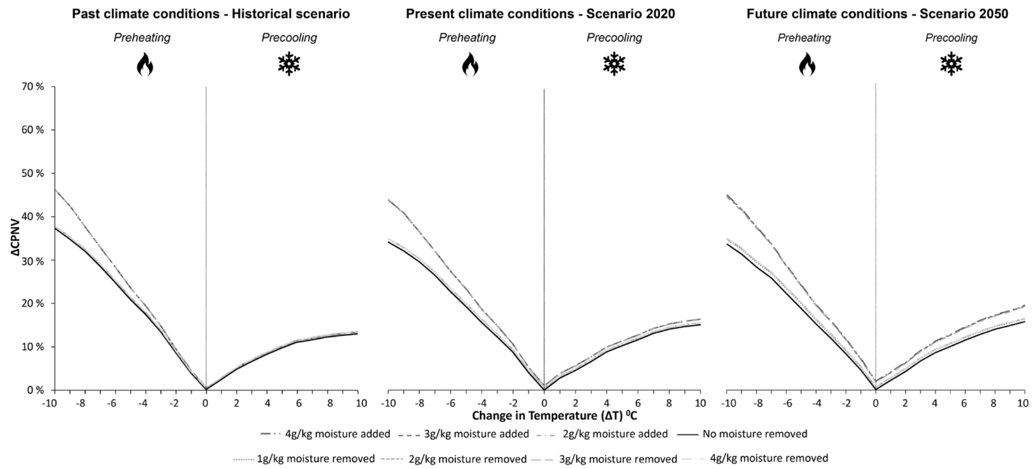

FIG. 11 Graph of ΔCPNV, for preheating and precooling in Madrid in the historical, 2020 and 2050 scenarios

The climate in Valletta was the mildest amongst all the analysed climates. Therefore, it exhibited the highest potential for natural ventilation for both preheating and precooling seasons. By preheating the inlet air by an additional 10 ˚C, the ΔCPNV was almost as high as 50% in the historical scenario, while in scenario 2020 and in scenario 2050 the value dropped to 47% and 41% respectively.
If the inlet air was preheated and dehumidified by removing 4 g/kg moisture, the ΔCPNV could be increased to reach 69% in the historical climate scenario and despite some reductions seen in the 2020 and 2050 scenarios, the value was still always above 60%.

In the historical scenario, the ΔCPNV using precooling alone was only about 3%, and remained relatively constant for the 2020 and 2050 scenarios. Dehumidifying without preheating or precooling could increase the ΔCPNV up to 15% in all scenarios, and when combined to precooling, in the 2050 scenario, the ΔCPNV could be as high as 30%. The dehumidification process was then also important in Valetta as well, despite the lower relative humidity (Fig. 12).

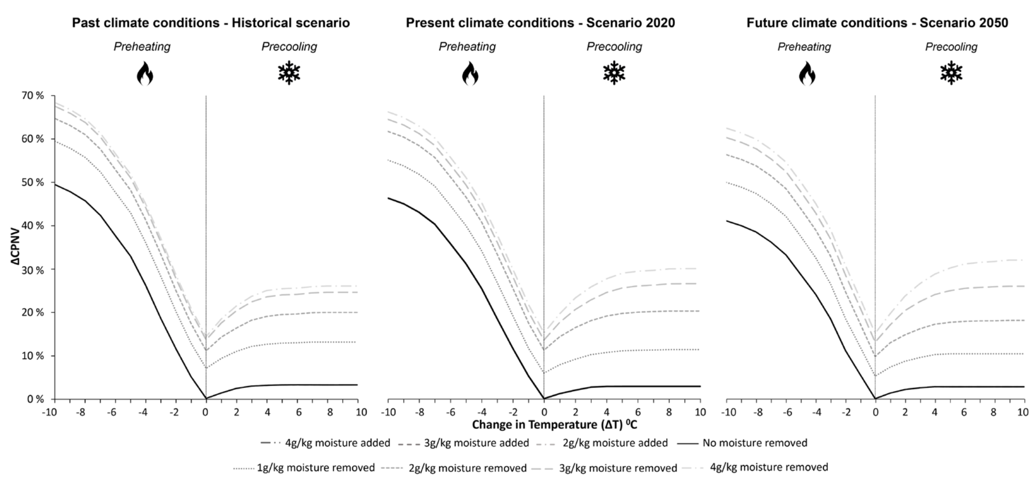

FIG. 12 Graph of ΔCPNV, for preheating and precooling in Valletta in the historical, 2020 and 2050 scenarios

3.2.4 Discussion on the ΔCPNV by preheating and precooling inlet air

The results indicated that the potential for natural ventilation in Europe increased significantly (30-50%) when the inlet air was preheated (Fig. 13).

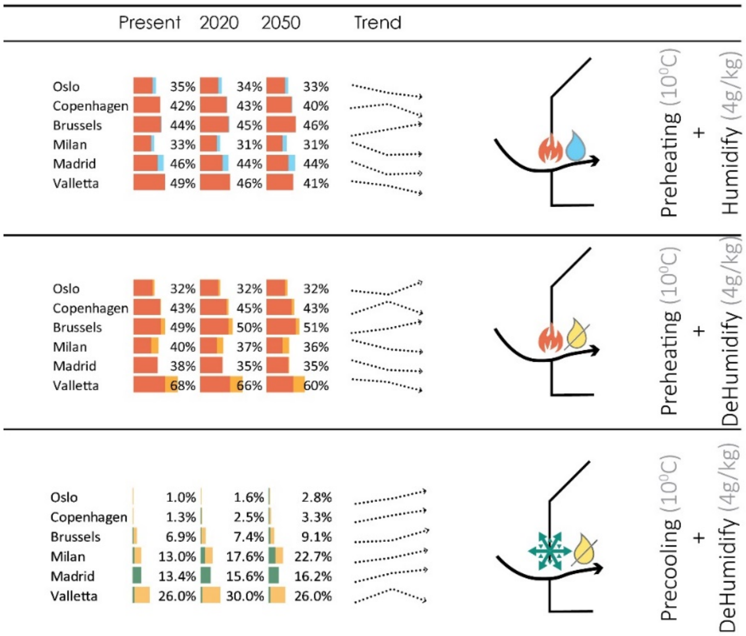

FIG. 13 Summary of ΔCPNV and treatments on the inlet air for all scenarios in the analysed cities

However, in future climatic conditions this potential was estimated to slightly decrease by 2-3% in all the analysed climates, except in Brussels. Precooling the air became more important in the future climate conditions of Europe and particularly at lower latitudes. Humidity was not as important as temperature when preheating at higher latitudes. However, dehumidification still played an important role when using precooling in all climates and especially at lower latitudes. Finally, the combined effect of changing the temperature and the humidity of the ventilation air supply provided relevant effects in terms of potential use of natural ventilation in all of the analysed cities.

3.3 SOLAR AVAILABILITY

Solar availability plays a crucial role in passive preheating of the ventilation supply air through the façade. The meaningfulness of solar availability resides in the possibility to convert solar power via integrated systems or use it as a passive thermal energy source. However, to maximise the direct use of solar energy at façade level without adding too many components such as batteries, it is important that the availability of solar energy matches as much as possible the energy requirements of the building. The analyses conducted in this study was useful to understand how solar energy could be used to provide energy for small air treatment systems directly integrated in the façade, as well as to understand if the timing between solar energy availability and energy demand for pre-heating and pre-cooling could be improved in a way that solar energy is best utilised and used in its most efficient form (as thermal energy or converted to electricity). In this part of the study a sub-layer is added to the investigation of the ΔCPNV and considers how solar availability in terms of available sunlight hours and solar radiation intensity can be coupled to partially solar powered preheating systems of the inlet air. The investigation assumes that the different preheating systems can require a minimum value of solar irradiance of 0 to 400 W/m^2 to function on solar power, which makes them dependant on the two components that define solar availability, namely the time of the day when solar energy is available (in consideration to when it is required i.e. timing) and the amount of solar energy available.

3.3.1 Nordic zone

In Oslo and in Copenhagen preheating the incoming air using solar energy allowed the ΔCPNV to reach 10% in the historical climate scenario when the system required a solar irradiance greater than 400 W/m^2 on the south oriented facade. In Oslo, the ΔCPNV decreased to 7% in the 2020 scenario and 6% in the 2050 scenario. While in Copenhagen, it maintained the values of the historical scenario all the way through to the 2050 scenario.

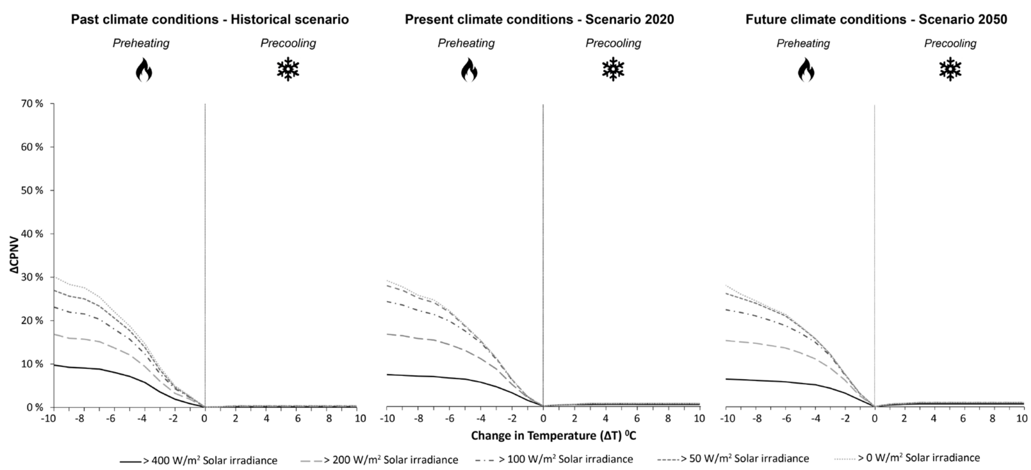

FIG. 14 Variation of the ΔCPNV when the preheating of the air is dependent on a minimum amount of solar irradiance on south facade at the time of preheating and precooling requirements in Oslo for historical, 2020 and 2050 scenarios

In Oslo, during the preheating season in the historical climatic scenario, a system requiring a solar irradiance of 50 W/m^2 or more could provide a ΔCPNV 25% when the air was preheated by an additional 10°C. This figure slightly increased by a small amount (around 2-3%) in the scenarios 2020 and 2050 (Fig. 14). During the warm season, the precooling needs almost always occurred when there was a solar irradiance of more than 400 W/m^2 on the south façade, in both cities of Nordic zone.

During the preheating season in Copenhagen, for preheating systems which needed a solar irradiance value of 100 W/m^2 or more could provide a ΔCPNV above 35% in the past climate scenario and up to 30% in 2050 (Fig. 15).

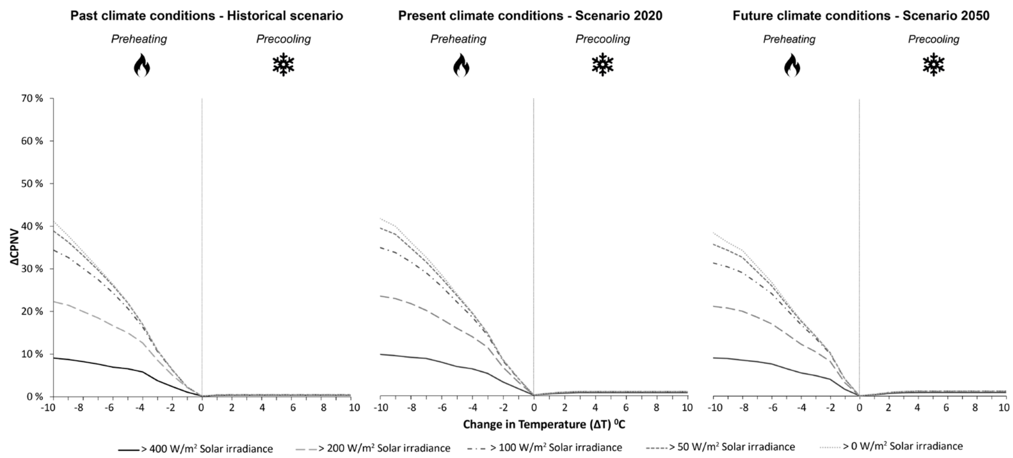

FIG. 15 Variation of the ΔCPNV when the preheating of the air is dependent on a minimum amount of solar irradiance on south facade at the time of preheating and precooling requirements in Copenhagen for historical, 2020 and 2050 scenarios

3.3.2 Continental zone

In Brussels, a ΔCPNV of around 10% was achievable by preheating with a value of solar irradiance of 400 W/m^2 or more but decreased to only 6% in the 2050 future scenario. Similarly all of the ΔCPNVs decreased for all the cases in which preheating was dependent on given amounts of available solar energy present and in future climate condition scenarios in Brussels (Fig. 16).

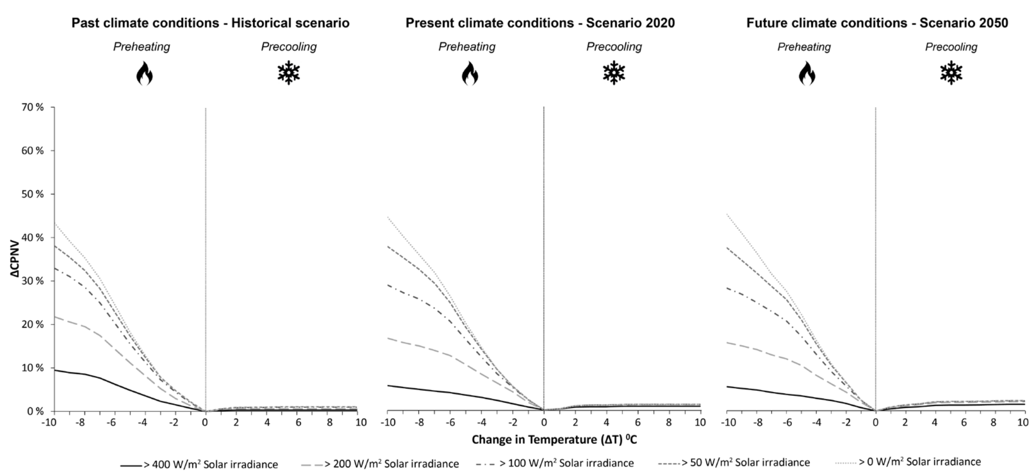

FIG. 16 Variation of the ΔCPNV when the preheating of the air is dependent on a minimum amount of solar irradiance on south facade at the time of preheating and precooling requirements in Brussels for historical, 2020 and 2050 scenarios

In Milan, a ΔCPNVs of 6% could be achieved through preheating inlet air with systems requiring a solar irradiance value of 400 W/m^2 or more on the south oriented façade but this figure decreased to 4% in 2050. For cases requiring 50 W/m^2 or more irradiance available, the ΔCPNV reached 20% during preheating in the historical scenario but showed a decrease to about 3% in the 2050 future scenario. During the precooling season, when an irradiance od 400 W/m^2 or more was available on the facade, a ΔCPNV of 8% was achieved. Furthermore, there was a substantial change in terms of solar availability for precooling from 1.8% in historical climate scenario to 6.9% in the 2050 scenario in Milan. In 2050, the ΔCPNV was higher during precooling than preheating when an irradiance of 400 W/m^2 or more was available (Fig. 17).

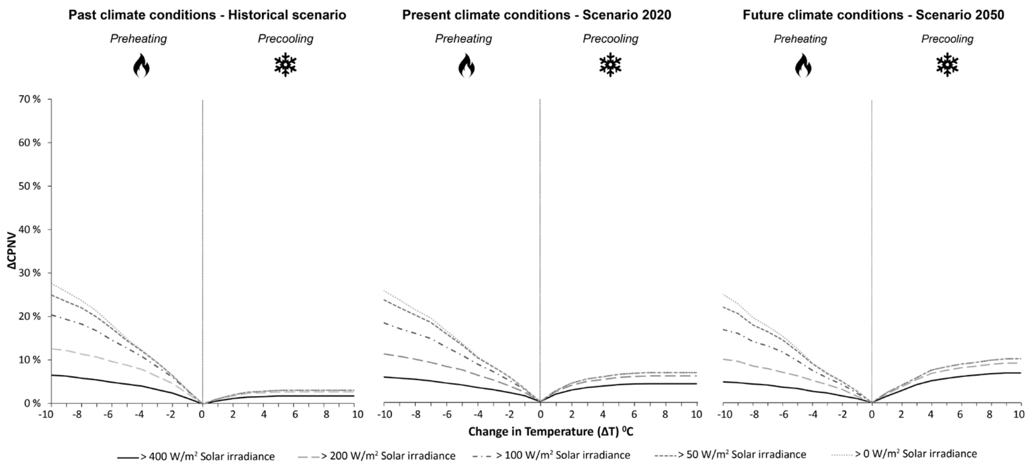

FIG. 17 Variation of the ΔCPNV when the preheating of the air is dependent on a minimum amount of solar irradiance on south facade at the time of preheating and precooling requirements in Milan for historical, 2020 and 2050 scenarios

3.3.3 Mediterranean zone

In Madrid the ΔCPNVs was in the 10% range when 400 W/m^2 or more were available during the preheating season in all three climatic condition scenarios. During the precooling season, the future climate scenarios showed a slight increase of the ΔCPNV when solar irradiance available was equal or greater than 400 W/m^2 (Fig. 18).

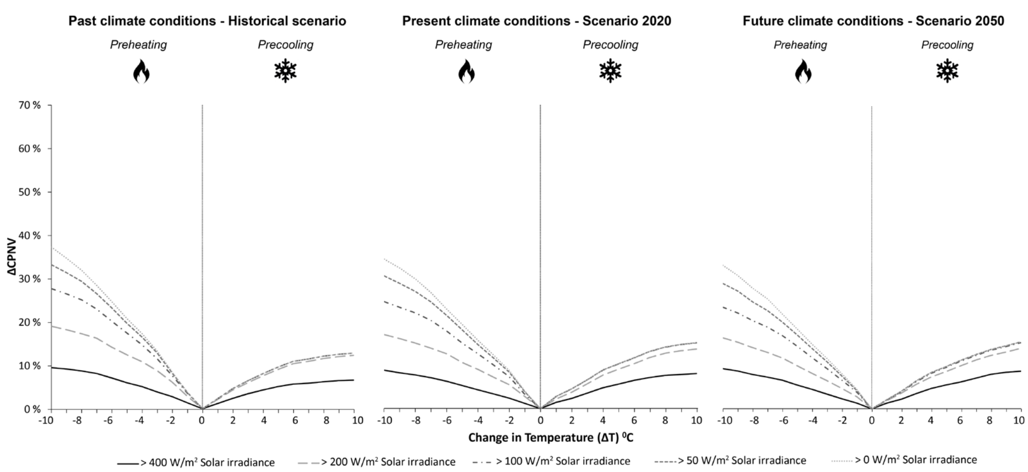

FIG. 18 Variation of the ΔCPNV when the preheating of the air is dependent on a minimum amount of solar irradiance on south facade at the time of preheating and precooling requirements in Madrid for historical, 2020 and 2050 scenarios

In Valletta, a ΔCPNV of 20% could be achieved through preheating the incoming air using an irradiance of 400 W/m^2 or more, but this possibility slightly decreased (by 4 %) in 2050. In Valletta, there was a quite small need for precooling. The solar availability maintained the same trend in the scenario for 2050 where a preheating system requiring a solar irradiance availability of 200 W/m^2 was sufficient to reach a ΔCPNV of 30% or more but a system requiring 400 W/m^2 only covered about 20% (Fig. 19).

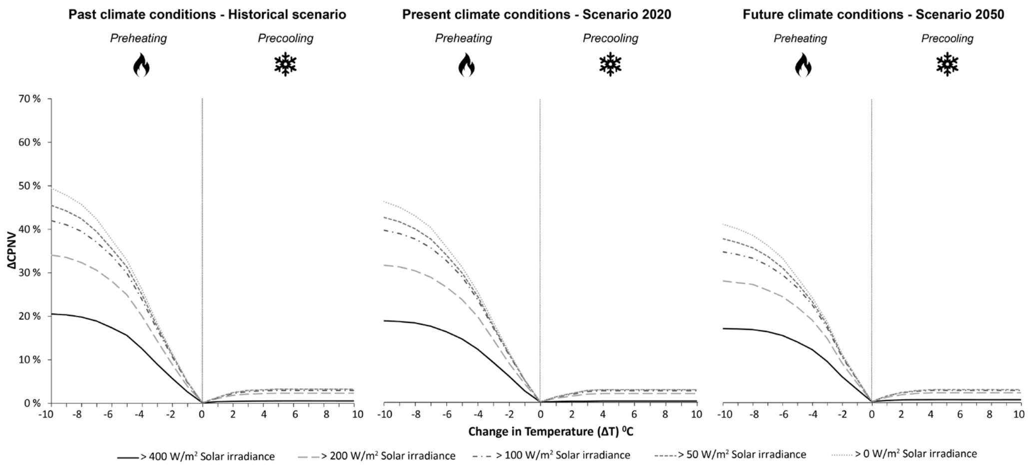

FIG. 19 Variation of the ΔCPNV when the preheating of the air is dependent on a minimum amount of solar irradiance on south facade at the time of preheating and precooling requirements in Valletta for historical, 2020 and 2050 scenarios

3.3.4 Discussion on the ΔCPNV by preheating and precooling inlet air through solar radiation

Regardless of the differences in latitude, in all locations except Valletta, similar behaviours were exhibit with regard to solar availability and their impact on the ΔCPNVs. In historical climatic condition scenarios, ΔCPNVs of less than 10% were achievable during the preheating season when the required availability of solar energy resulted in an irradiance of 400 W/m^2 or more for the system. This percentage decreased in the scenarios for 2020 and 2050 in all climate zones. This might suggest that other active strategies requiring lower values of solar irradiance should be investigated since passive heating (e.g. solar heat gain) did not have the capacity to preheat the inlet air and this ability will deteriorate further in the coming years. At low latitudes, except in Valletta, in the 2050 scenario there was a substantial increase of solar availability for precooling. In Madrid and in Milan the results showed that the preheating and precooling treatments became of equal importance by 2050. This implied the potential use of active strategies to convert the solar power into cooling energy (Fig. 20).

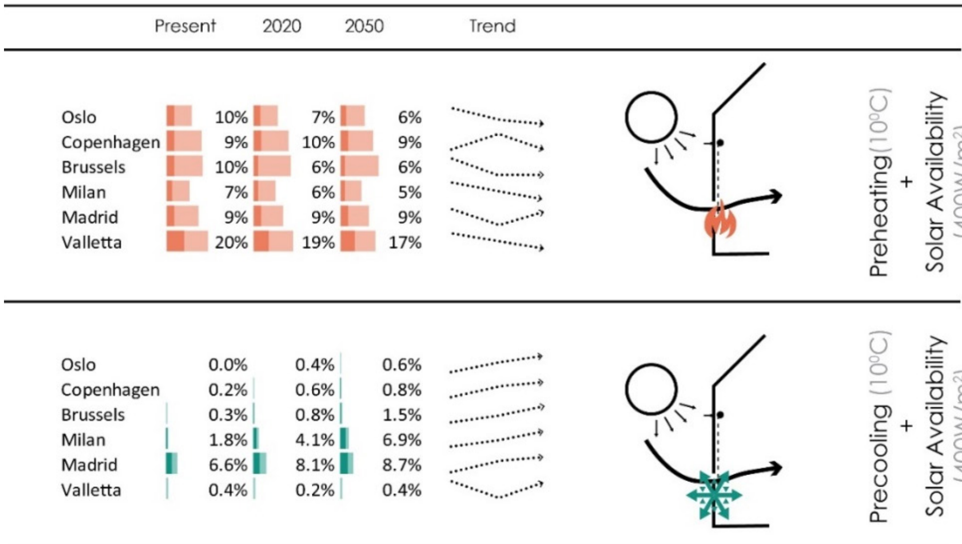

FIG. 20 Summary of ΔCPNV in historical, 2020 and 2050 scenarios and solar availability in the analysed cities

3.4 HEAT RECOVERY

The recovery of the heat contained in the exhaust airflow could be reused to maximize the potential for natural ventilation through the façade. Heat recovery is a standard feature in today's ventilation systems for highly efficient buildings, and the implementation of such a strategy at facade level has shown to significantly increase the potential to ventilate buildings through integrated systems in their facades. Coupling passive ventilation and heat recovery can lead to significant reductions in terms energy use for ventilation, heating and cooling by using the energy from the exhaust air to condition the incoming air and satisfy the thermal comfort levels desired by the occupants.

3.4.1 Nordic zone

In Oslo, using heat recovery with preheating provided a potential for natural ventilation over 40%, which was 10% more than could be achieved through preheating only (Fig. 21). In the 2050 scenario, this difference grows bigger because the ΔCPNV obtained by using heat recovery in combination with preheating increases while the ΔCPNV calculated for the preheating treatment only decreases.

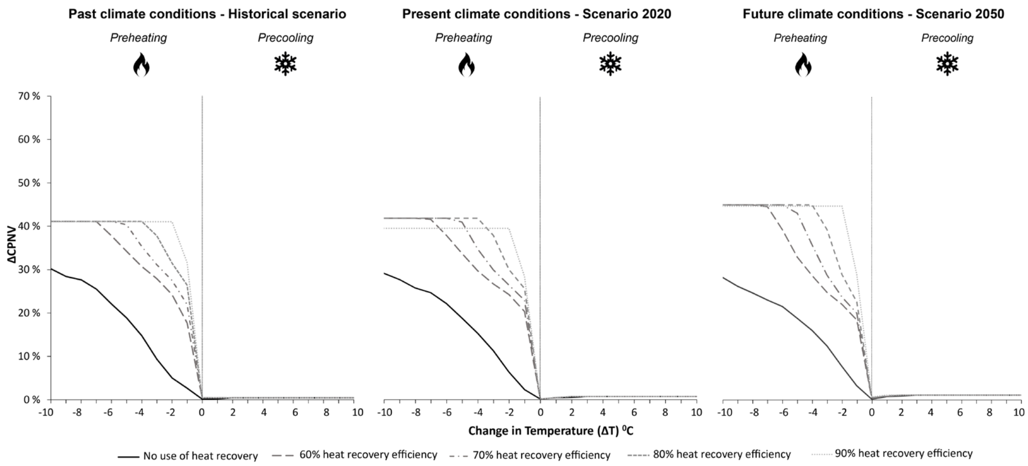

FIG. 21 Graph showing ΔCPNV, with different efficiency for heat recovery system along with preheating and precooling in Oslo for historical, 2020 and 2050 scenarios

The climatic conditions were favourable for heat recovery in Copenhagen too. In fact, the heat recovery system was able to provide a ΔCPNV of 56% in the historical scenario and this percentage increased to 60% in 2050 (Fig. 22).

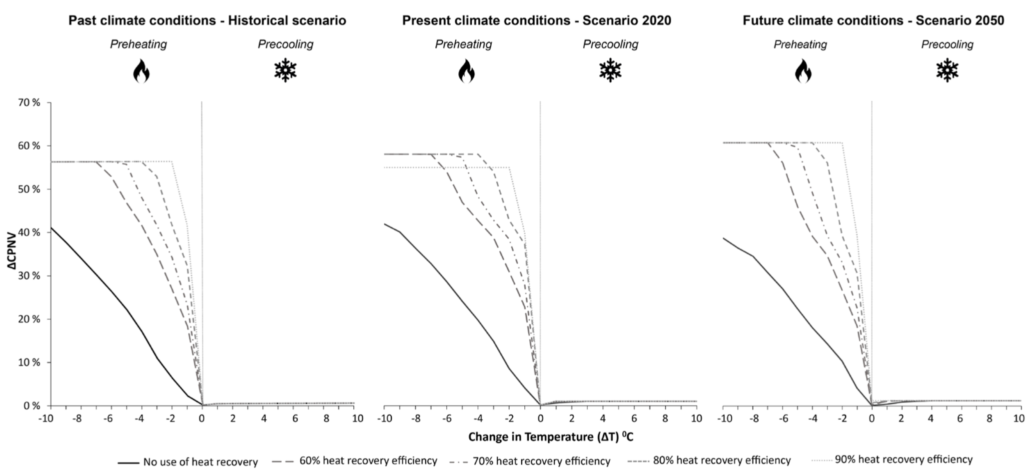

FIG. 22 Graph showing ΔCPNV, with different efficiency for heat recovery system along with preheating and precooling in Copenhagen for historical, 2020 and 2050 scenarios

All the different efficiencies of the heat recovery units in combination with preheating were able to obtain the maximum ΔCPNV. However, the difference was in the amount of required for the preheating before using the heat recovery. In that regard, a heat recovery with 90% efficiency could attain the max ΔCPNV with only 2˚C of preheating, while a heat recovery efficiency of 70% yielded the max ΔCPNV with 4 ˚C, and a 60 % efficiency with 6 ˚C preheating of the outdoor air (Fig. 21 and Fig. 22). In the Nordic zone, it could be seen that heat recovery did not have substantial contribution in the precooling season (Fig. 21 and Fig. 22).

3.4.2 Continental zone

In Brussels, heat recovery increased the potential of ventilation to up to 67%. This increased about 1% in the 2050 scenario similarly to in the Nordic zone (Fig. 23).

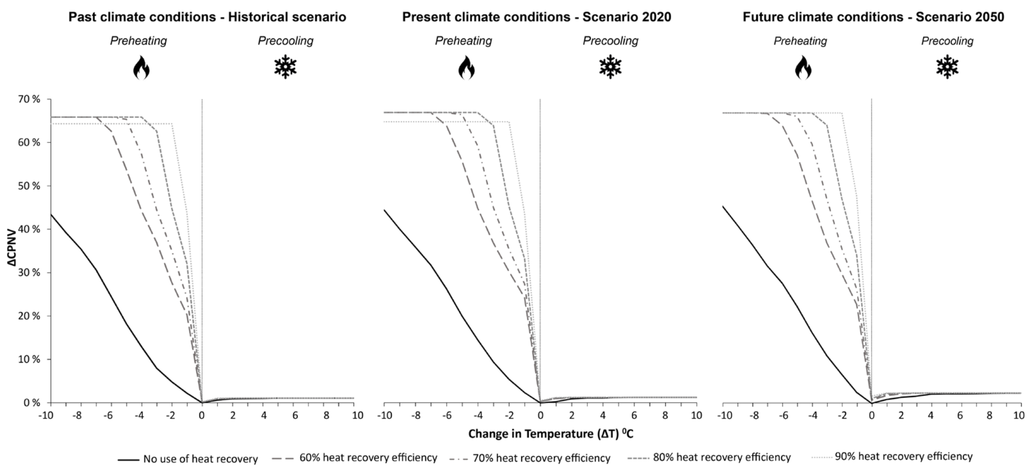

FIG. 23 Graph showing ΔCPNV, with different efficiency for heat recovery system along with preheating and precooling in Brussels for historical, 2020 and 2050 scenarios

For precooling season, the heat recovery did not have significant contribution in the historical climate, while it had a modest increase of up to 2% in the 2050 scenario (Fig. 23).

The climate in Milan revealed that heat recovery could be used for both preheating and precooling (Fig. 24).

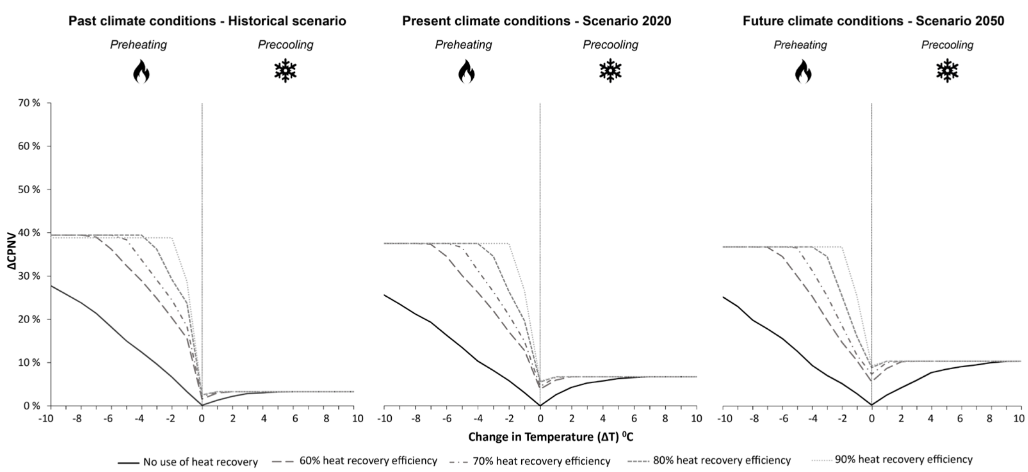

FIG. 24 Graph showing ΔCPNV, with different efficiency for heat recovery system along with preheating and precooling in Milan for historical, 2020 and 2050 scenarios

ΔCPNV reached up to 40% in historical scenario, while it declined by around 2%, in the scenario for 2050. Heat recovery for precooling showed a notable contribution to the ΔCPNV in the scenario for 2050 by rising from 2.5% in the past climate conditions to 10% in the future. In addition, heat recovery efficiency for cooling was not relevant because it quickly reached the peak with 2˚C of precooling. In 2050, the need for heat recovery will increase by 7% if both preheating and precooling are considered.

3.4.3 Mediterranean zone

In Madrid in the historical scenario, a ΔCPNV of 50% could be obtained by using a heat recovery system for preheating (Fig. 25).

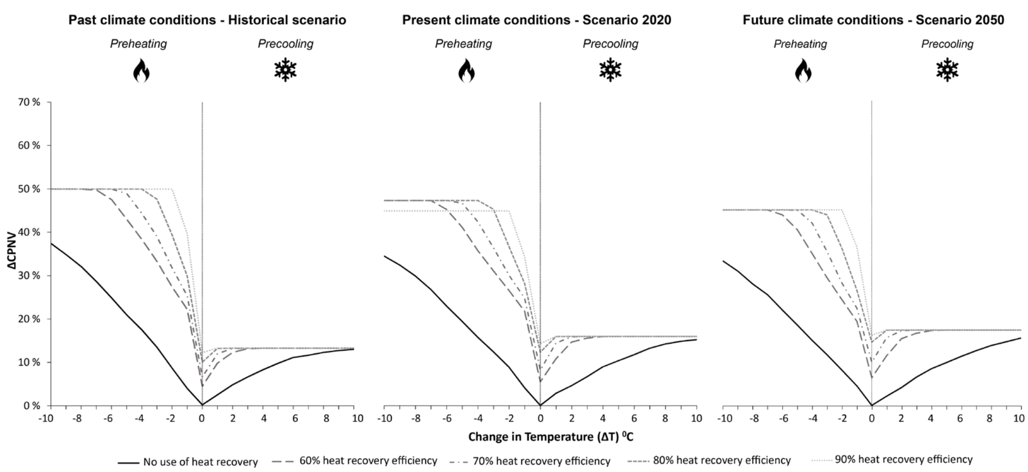

FIG. 25 Graph showing ΔCPNV, with different efficiency for heat recovery system along with preheating and precooling in Madrid for historical, 2020 and 2050 scenarios

This showed notably decreased by 5% in 2020 and in 2050. For cooling purposes, heat recovery played an important role with a ΔCPNV of 12% in the past climate conditions and up to 19% in future conditions of 2050. This means that in the future, the decrease preheating would be balanced out by the increase in cooling potential by using extract air to precool fresh air.

In Valletta, a ΔCPNV of 51 % could be obtained by using heat recovery for preheating and which was very close to the percentage previously determined to be achieved through preheating alone (50%). A sharp decline to 41% was registered in the use of heat recovery for preheating in the 2020 and 2050 scenarios. Surprisingly, the climate of Valletta showed no change in precooling with heat recovery both in present and future climate scenarios. This might be due to the mildness of the climate, given that there were previously no significant changes in the air treatment with only precooling as well (Fig. 26).

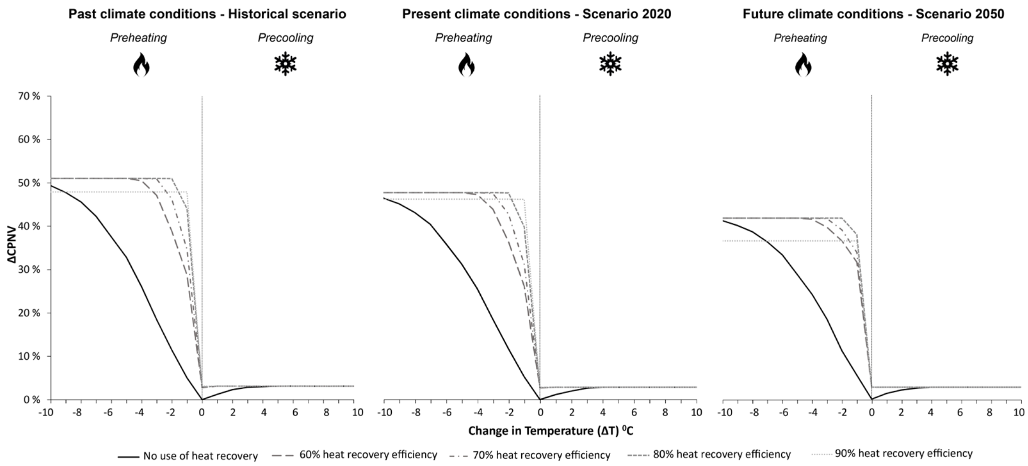

FIG. 26 Graph showing ΔCPNV, with different efficiency for heat recovery system along with preheating and precooling in Valletta for historical, 2020 and 2050 scenarios

3.4.4 Discussion

The amount of change in the potential for natural ventilation differs from climate to climate but a range of 40-70% ΔCPNV is attainable in all climate during the preheating season. Relatively colder climates, such as in the Continental zone, gained the most from heat recovery treatment, while cold climate in the Nordic zone could suffer from too dry indoor air when using heat recovery and consequently, would see a reduction in their potential for natural ventilation. However, some dryer air might not necessarily be unacceptable because it could to some extent be compensated by the naturally-occurring generation of water vapour from occupants. A heat recovery system with a 90% efficiency clearly showed the most gain of potential of natural ventilation requiring less than 2 ˚C of preheating to reach the maximum potential in all the cities and in all climate zones. It might even be enough to provide the air without preheating the air up to 2 ˚C in order to compensate for internal gains in a building.

In future climate scenarios, buildings located at higher latitudes showed that they would only see a minor increase in their ΔCPNV for both preheating and precooling with the aid of heat recovery (Fig. 27).

At lower latitudes and in relatively warmer climate, such as in Milan, Madrid and Valletta, there was a notable decrease in the preheating potential for heat recovery and at the same time as there was a significant increase in the cooling potential using heat recovery. Therefore, the needs balanced each other out, and the use of heat recovery remained the same or improved slightly.

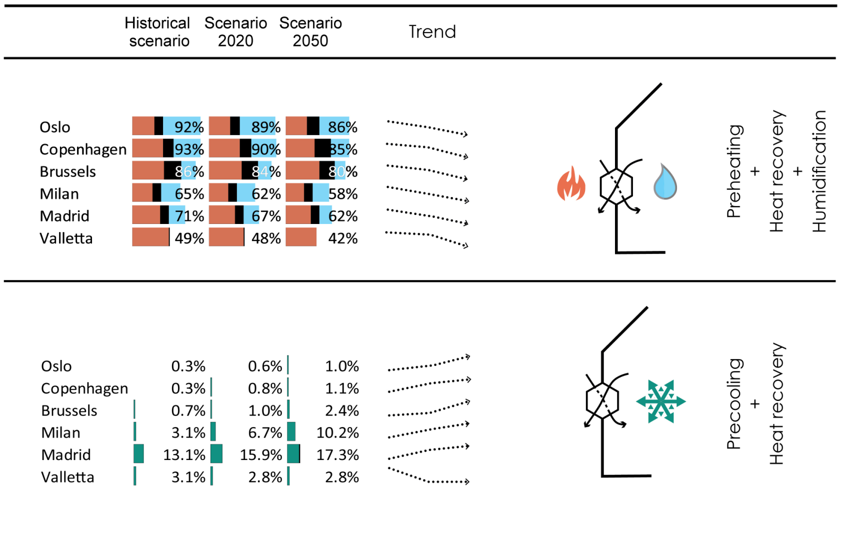

FIG. 27 Summary of the ΔCPNV attained through preheating (orange) and precooling (green) with humidification (blue) and using heat recovery (black) in historical, 2020 and 2050 scenarios in all the analysed cities

3.4.5 Implications of façade design and operation

Nowadays there exist a large range of possibilities for façade-integrated systems for exploiting renewable energy sources (RES). Such systems are primarily based on the integration of photovoltaic layers, solar thermal panels, and heat pumps which can be integrated into the building envelope and building energy concepts partly for pre-heating and pre-cooling of the air of the building. These technologies can also be integrated inside the cavity of double skin façades, which could work as an air-based solar thermal collector, allowing the preheating of the inlet air in winter and precooling (though a heat pump) in summer. These capabilities could make the double skin façade system a worthwhile field for further investigation, with a vast field of possible improvements regarding functionality and performance.

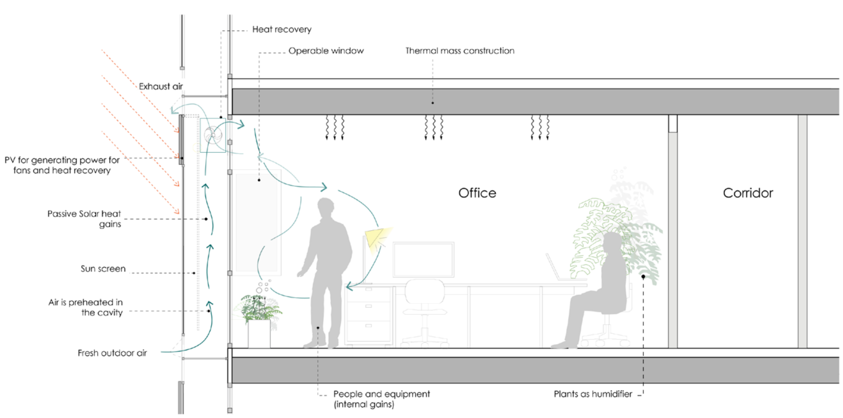

FIG. 28 Conceptual scheme of the section of hybrid ventilation system in integrated double skin facade system

Fig. 28 shows a conceptual scheme of a hybrid integrated double skin façade system where there could be a minor treatment of the air at the façade level with the use of fans and low-pressure drop heat recovery. The use of photovoltaic integrated shading devices (PVSD) (Taveres-Cachat, Lobaccaro, Goia, & Chaudhary, 2019) (Taveres-Cachat, Bøe, Lobaccaro, Goia, & Grynning, 2017), which can be either fixed or movable, installed in the facade cavity, may also be employed to power the heat recovery process.

4 LIMITATIONS OF THE STUDY

The analysis conducted in this study considers only the thermodynamic properties of the outdoor air, temperature and humidity to calculate the potential of natural ventilation of specific climates. However, it does not consider other factors that are also essential when considering naturally-driven airflows in a building. In that regard, the study does not consider the mechanism of airflows through the facade. It assumes that the incoming air would be treated at the façade level and enters the building without any impact on the air treatments in the cavity of the facade. In addition, even though wind data is also included in weather data climate files, it was not considered as it also relates more to the airflow mechanism.

5 CONCLUSION AND FURTHER DEVELOPMENT

This paper presents a methodology to investigate the potential of natural ventilation through the facade in office buildings in present and future climate scenarios (2020 and 2050). It reviews advantages, possible technologies, and strategies to maximize its use in a building. It analyses selected climates in Europe via numerical analysis, with the consideration of temperature and humidity. The main findings of the study can be summarized follows:

- The analysis on the future climate scenarios indicated that climate change scenarios will negatively influence the potential for natural ventilation in the future of Europe by increasing cooling needs and reducing heating needs.
- There is not enough solar availability in all analysed cities and climate zones during the preheating season and there is sufficient available solar radiation in the cooling season, which implies that there is a need for active technologies at the façade level to compensate for the periods without the potential for natural ventilation.
- Heat recovery systems can be successfully used to treat the air at the façade level and maximise the potential for low energy ventilation solutions for heating and cooling requirements in both present and future climates. This will bring about a 40-90% increase in the potential of natural ventilation through the façade in all climates during the heating season, and up to 15% in warmer climates during the cooling season.

A further development of the study implies a creation of a digital dashboard as graphical user-friendly interface (GUI) (Fig. 29).

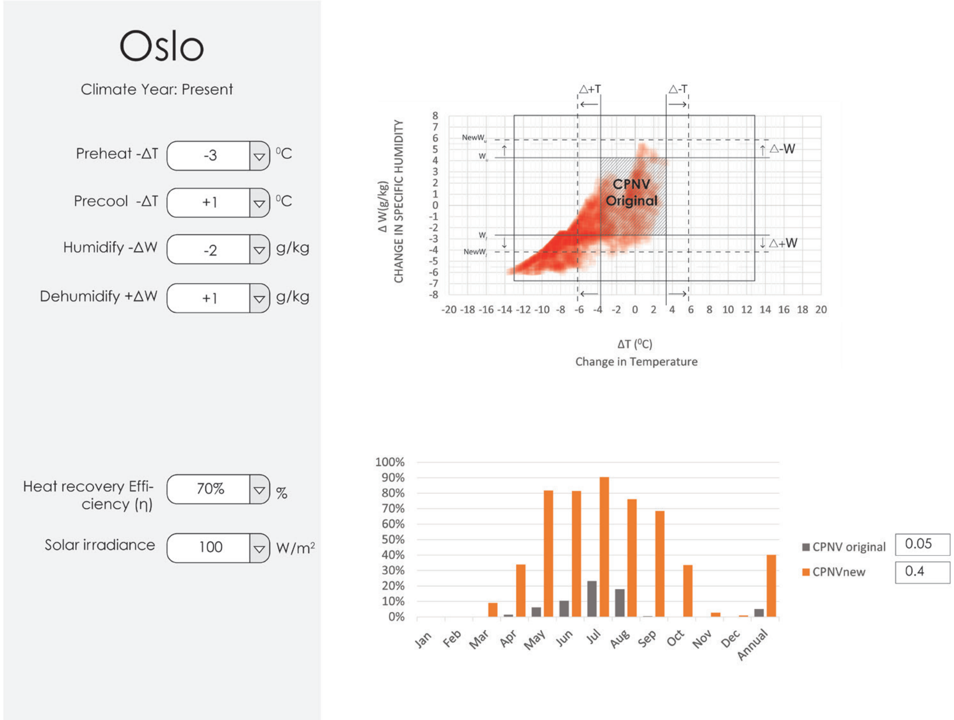

FIG. 29 Possible Digital dashboard as a user-friendly interface to calculate and optimize the climatic potential of natural ventilation of a given climate

This GUI will allow the users to easily comprehend at once glance the effects of changing the geographical parameters (e.g. location with latitude and longitude, comfort zone, year) and the air treatments parameters (i.e. preheating, precooling, humidifying, dehumidifying, heat recovery and solar availability). A user would be able to input the different changes in temperature and humidity (-ΔT, +ΔT, +ΔW, -ΔW) and get the CPNV extended and compared with the original potential (comfort zone hours) in real time. It would also be interesting to develop a functionality to maximize the climatic potential for natural/hybrid ventilation based on the optimum use of the combination of the different air treatments in any specific location.

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