Renewable ventilative cooling? Insights from an Irish perspective

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ABSTRACT

The future needs of indoor spaces in our buildings are likely to be cooling focused. With the widespread use of air-conditioning (AC) on the horizon there is now a need to ensure our systems perform as renewables (under the relevant definitions). A key part of tackling the uptake in energy intensive AC is likely to be the balancing of AC with renewable natural and mechanical ventilative cooling (VC). It is evident that a total reliance on AC could have significant ramifications for any building sector emissions targets but could also leave building occupants vulnerable to power outages from increased pressure on electricity grids. It is therefore critical that existing design practices encourage the use of passive systems, which take advantage of natural and renewable sources of energy be they as primary, supplementary, or secondary cooling systems or featured as part of a hybrid cooling system. To address this, the aim of this work was to determine the potential renewable energy contribution that natural ventilative cooling systems (NVCs) or mechanical ventilative cooling systems (MVCs) can have under favourable conditions in a temperate climate. Three different stages to this evaluation are presented: 1) a cooling demand using cooling degree hour (CDH) analysis in current and future conditions, 2) a simplified design stage evaluation of the potential of single-sided NVC and MVC, and 3) a calculation of the seasonal performance factor for NVC and MVC systems. In addition to this, the potential for NVC is discussed in relation to the existing building stock in Ireland. Initial results indicate that the NVC potential in supply terms is currently outstripping demand by greater than 3.5 times. Current calculations for NVC and MVC renewable status show a strong basis for their consideration in future, but more detail is required. The results also indicate that NVC and MVC systems are likely to be a renewable source that is currently not officially accounted for.

KEYWORDS

Renewable status, ventilative cooling, natural ventilation, mechanical ventilation

1 INTRODUCTION

The future needs of our buildings are going to be cooling focused. With the widespread use of air-conditioning (AC) on the horizon there is now a need to ensure our systems perform as renewables (under relevant definitions). A key part of tackling the uptake in energy intensive AC is likely to be the balancing of AC with renewable natural and mechanical ventilative cooling (VC). It is evident that a total reliance on AC could have significant ramifications for any building sector emissions targets but could also leave building occupants vulnerable to power outages (Attia et al. 2021). It is therefore critical that existing design practises encourage the use of passive systems, which take advantage of natural sources of energy be they as primary, supplementary, secondary cooling systems or featured as part of a combined cooling system. The use of natural or mechanical VC systems have been shown to be very effective at cooling buildings (O’Sullivan and O’Donovan 2018) and has been shown to have potentially very high co-efficients of performance (COP’s) (Holzer and Stern 2019). Indeed, where systems like NV are used it is likely that COP’s or seasonal performance factors (SPFs) could be particularly high if humans operate openings, even if actuation energy is considered it is likely that SPFs for NV or MV systems will be well in excess of the SPFs required for heat pumps for them to be considered renewable (Nowak 2011; O' Donovan and P. O' Sullivan 2023).

Up until now the renewable status of VC has been presented very little, this is because previous iterations of renewable cooling calculations have excluded passive cooling systems based on building design (e.g. insulation, green roofs, building mass) or VC systems that supplied fresh air for air quality purposes (see sections 2.6.2.3 in (Kranzl et al. 2021)). However, it is now understood that "free cooling" which uses natural heat flow from hot to cold which is intentional and is supplied by pumps or fans (Kranzl et al. 2021) can be classified as a renewable for cooling purposes. To qualify as a renewable system for space cooling purposes a minimum SPF must be achieved, which is similar to definitions for heat pumps using for heating or cooling. In this paper, we present an example of renewable NVC and MVC and how this could be accounted for at design stage under the mild conditions of Ireland and consider and argument to consider NV to be a renewable when "intentional" through when it is actuated via a control system. This work is particularly relevant as currently Ireland is indicated as having no energy consumption requirement for cooling its residential building stock (SEAI 2022). This work will be presented in three stages: 1) a cooling demand assessment using cooling degree hour (CDH) analysis in current and future conditions, 2) a simplified design stage evaluation of the potential of single-sided NVC and MVC, and 3) a calculation of the seasonal performance factor for NVC and MVC systems.

2 MATERIALS AND METHODS

2.1 Case study building used

As part of this paper a case study building will be used in order to demonstrate the cooling demand and supply. The selected building presented in this paper was studied previously (O'Donovan, Psomas, and O' Sullivan 2022) and is example of a deep energy retrofit. The building is a bungalow located in an inland location, this type of building has been seen as being vulnerable to overheating based on previous overheating assessments in Ireland (Washan 2019). Table 1 indicates the buildings thermo-physical characteristics which have been taken from its energy certificate file.

Table 1: Thermo-physical characteristics of case study building used to evaluate renewable NVC and MVC

Variable	Units	Value
Roof U-value	$W/m^2 K$	0.13
Wall U-value	$W/m^2 K$	0.2-0.23
Floor U-value	$W/m^2 K$	0.12-0.13
Window U-value	$W/m^2 K$	1.4
Effective air change rate	h^{-1}	0.522
Floor area	m^2	182.09
Volume	m^3	491.64
Heat loss co-efficient	W/K	292

Previous work focused on this building (O'Donovan et al. 2022) highlighted that it was vulnerable to overheating in the living space if evaluated using Category I of EN16798-1 (CEN 2019) (i.e. considering vulnerable occupants), however, it should be noted that despite this overheating in the living space was limited to less than 1% of the occupied hours less than 28°C

(O'Donovan et al. 2022). Additionally, the empirically calculated overheating escalation factor for the same building indicated a degree of resistance to external conditions that was favourable.

2.2 Cooling demand and ventilative cooling supply

Cooling energy demand calculations

Cooling demand in buildings can be estimated by using a cooling degree hour (CDH) approach (De Rosa et al. 2015). In this example, we will use a base temperature that is more appropriate to low energy buildings (Rahif et al. 2021) (e.g. 14°C). However, this could be lower or higher depending on the building characteristics. Therefore, we present CDH's for different base temperatures initially before focusing on low energy buildings. The cooling demand for the case study building was calculated using Equation 1 below (which is similar to (De Rosa et al. 2015)):

$$CD_h = \sum_{h=1}^{h=8760} (T_e - T_b)^+ \tag{1}$$

Where, CD_h are the number of cooling degree hours (°Ch), T_e is the hourly external air temperature and T_b is the base temperature for cooling. The demand in energy terms (kWh) was calculated using Equation 2 (which is similar to (Rosa et al. 2014; De Rosa et al. 2015)), this was done assuming that the building had a 5% opening area to floor area ratio (or POF) (in line with national regulations (Dept of Housing 2019)).

$$E_{tot,c} = \frac{H \cdot CD_h}{1000} \tag{2}$$

Where, $E_{tot,c}$ is the energy demand for cooling (in kWh) for a specific building (which is similar to other relevant work in this area (Li, Allinson, and Lomas 2020), taken from Table 1 above).

Ventilative cooling potential (natural and mechanical supply)

To account for natural ventilative cooling potential or supply at the design stage, the approach of O'Donovan and O'Sullivan was adopted (O' Donovan and P. D. O' Sullivan 2023). In this approach, the work of Warren and Parkins (Warren and Parkins 1985) is used which evaluates airflow rates independently for two momentum sources: buoyancy and wind. The most widely used buoyancy driven airflow equation is shown in Equation 3 (taken from (Fan et al. 2021)) and, for wind driven airflow, indicated in Equation 4 (using reference wind speeds). There are many limitations in the use of the wind speed local at the opening, (also recommended by Warren and Parkins) not least that data on the local wind at the opening is seldom available to practitioners or may not be suitable for a given location. Therefore, the reference conditions were used to calculate NV airflow rates which would offer a maximum potential value for NVC. Equations 3 and 4 are presented below.

$$Q_b = \frac{1}{3} C_d A_{op} \sqrt{gH \frac{T_i - T_e}{T_i}} \tag{3}$$

$$Q_w = F_R A_{op} U_R \tag{4}$$

Where, Q_b is the volumetric airflow rate due to buoyancy (in m^3/s), C_d is the discharge coefficient (-), A_{op} is the effective opening area (in m^2), T_i is the internal temperature (in K), T_e is the external air temperature (in K), H is the opening height in metres, U_R is the reference wind velocity (in m/s). It was proposed by Warren and Parkins (Warren 1977) that for single-sided flow with one opening (typically abbreviated as SS1) that the maximum of either buoyancy or wind driven flows be taken, as is indicated in Equation 5.

$$Q_{nv} = \max(Q_b, Q_w) \tag{5}$$

To scale the wind velocities to the building height, Equation 6 (taken from CIBSE AM10 (CIBSE 2005)) was used:

$$U = U_{met} k z^a \tag{6}$$

Where, U is the wind speed (in m/s) at height z (in m) and k and a are coefficients determined by the terrain in which the building lies. For all VC supply estimates considered in this paper a value of k = 0.35 and $a = 0.25$ was used with a building height of 10m. This is closer to an urban environment than a rural one. As this is intended as a design stage NVC potential assessment, the internal air temperature (T_i, see Equation 3) is assumed depending on the outside conditions. The exponentially weighted external mean temperature was calculated using Equation 6 for the first day and using Equation 7 for every day after this according to TM52 (CIBSE 2013). For external mean temperatures of greater than or equal to 10°C the internal temperature was assumed to follow the neutral operative temperature (t_c) according to EN 16798-1 (CEN 2019) (see Equation 8) for external mean values less than 10°C a fixed internal condition of 22°C was adopted.

$$t_{rm} = (T_{od-1} + 0.8T_{od-2} + 0.6T_{od-3} + 0.5T_{od-4} + 0.4T_{od-5} + 0.3T_{od-6} + 0.2T_{od-7})/3.8 \tag{7}$$

$$t_{rm} = (1 - \alpha)T_{od-1} + \alpha t_{rm-1} \tag{8}$$

$$t_c = 0.33 t_{rm} + 18.8 \tag{9}$$

Where, T_{od-1} is the daily average temperature from the day before today and so on, and α is a weighting factor which was assumed be 0.8. It should be noted that in order to calculate the cooling energy available by NVC all summations of energy were made with data greater than or equal to the base temperature. To calculate the energy supplied by NVC, Equation 10 was adopted.

$$E_{sup,nv} = \frac{Q_{nv} \cdot \rho_a \cdot C_{p,a} \cdot (T_i - T_e)}{1000} \tag{10}$$

Where, $E_{sup,nv}$ is the total available energy from natural ventilation (in kWh), ρ_a is the density of air (assumed to be 1.2 kg/m^3) and $C_{p,a}$ is the specific heat capacity of air (assumed to be 1000 J/kg K). To estimate a typical MV system an air change rate (ACR) was assumed to be delivered by fans only. Equation 11 indicates this relationship,

$$Q_{mv} = \frac{ACR_{MV} \cdot V}{3600} \tag{11}$$

Where, $ACR_{MV}$is a designed ACR (in h^{-1}) for a hypothetical MVC system being used in said dwelling and V is the dwelling volume (in m^3). Equation 12 indicates how the total energy available from MVC is calculated (which is similar to (Wouters et al. 1987)).

$$E_{sup,nv} = \frac{Q_{mv} \cdot \rho_a \cdot C_{p,a} \cdot (T_i - T_e)}{1000} \tag{12}$$

Where, Q_{mv} is mechanical ventilation rate (in m^3/s).

2.3 Seasonal performance factor calculation for NVC and MVC

To confirm and illustrate the renewable status of ventilative cooling, it was assumed that the natural and mechanical systems were actuated and that they were deliberately operated, based on a schedule. This aspect fulfils the intentionality requirement in the operation of the system which was a key aspect of the RED II definition in order to achieve renewable cooling status. The seasonal performance factor (SPF) for renewable cooling was calculated using Equation 13.

$$SPF_{vc} = \frac{Q_{supply}}{E_{INPUT}} \tag{13}$$

Where, Q_{supply} is calculated as the potential heat removed from a building using VC (in kWhs) for natural and/or mechanical systems and E_{INPUT} is the energy input for actuation of openings, energy use by fans, and energy use by control systems (see Table 2 for more information typical power consumption values for NVC and MVC systems from the literature). It should be noted that generally ventilation is considered passive cooling under current definitions (see section 2.6.2.3 (Kranzl et al. 2021)), however, where ventilation is intentional for cooling purposes, (which is ventilation supplied in excess of ventilation supplied for hygienic purposes) this can be considered as part of the renewable definition. To satisfy this renewable definition, heat loss for ventilation purposes should be excluded. To do this, all-annualised NVC or MVC energy supply values were calculated to exclude a value of $0.3l/s/m^2$ to comply with Irish regulations (Dept of Housing 2019) (this equates to $197m^3/h$ for the specific building studied in this paper). In this example, we present the SPF for a NVC system and a MVC system separately, however, a combined system could also be used. The potential SPF was calculated using design stage information, without the use of any dynamic simulation. This was done during the typical during the periods of time where demand was present (i.e. >14°C outside).

Table 2: Examples of typical energy consumed to operate MVC or NVC systems

Reference	System type	Units	Values reported
(Cho et al. 2021)	Hybrid systems	$kWh/m^2/a$	0.3 – 2.8
(Agency and Programme 2018)	NVC	$kWh/m^2/a$	~1.2
(Santos, Hopper, and Kolokotroni 2016)	NVC + phase change materials	$kWh/m^2/a$	~0.77
(Yan et al. 2022)	NVC	$kWh/m^2/a$	0.7-1.3
(Holzer and Stern 2019)	MVC	$W/(m^3/s)$	<200
(Holzer and Psomas 2018)	MVC	$W/(m^3/h)$	0.07 - 0.14

Additionally, the SPF for both daytime and night-time performance is taken into account (Day-time hours considered between 8am to 8pm). In this study, we assume that the NVC system will use about 2.4 $kWh/m^2/a$ (50W of continuous consumption) for the operation of controls and actuation of openings. For the MVC system we assume that the system will consume about $0.1W/(m^3/h)$ for fans and controls. However, it is evident from the literature that NVC and MVC systems can consume less energy than this.

2.4 Weather data and boundary conditions

To calculate the cooling demand, supply as well as estimating the SPF for VC a series of local meteorological station data from Irelands Met Éireann were downloaded from Met Eireann's historical weather databases (Met Éireann 2023). Table 3 indicates the locations considered and any substitutions that were made where data wasn't present. All future weather files were produced using Meteonorm version 8.1.4 (Meteotest 2022).

Table 3: Weather data used for different aspects of the work presented

<table>
<tr><th>Location
(Name, County)</th><th>Elevation
(m)</th><th>Weather files considered for demand estimates</th><th>Weather files used for case study demonstration</th></tr>
<tr><td>Athenry, Galway</td><td>40</td><td rowspan="11">2022,
2030 (RCP 2.6), 2030 (RCP 4.5), 2030 (RCP 8.5), 2040 (RCP 2.6), 2040 (RCP 4.5), 2040 (RCP 8.5), 2050 (RCP 2.6), 2050 (RCP 4.5), 2050 (RCP 8.5)</td><td rowspan="11">2022,
2050 (RCP 8.5)</td></tr>
<tr><td>Belmullet, Mayo</td><td>9</td></tr>
<tr><td>Shannon Airport, Clare</td><td>15</td></tr>
<tr><td>Cork Airport, Cork</td><td>155</td></tr>
<tr><td>Phoenix Park*, Dublin</td><td>48</td></tr>
<tr><td>Valentia, Kerry</td><td>24</td></tr>
<tr><td>Ballyhaise, Cavan</td><td>78</td></tr>
<tr><td>Malin Head, Donegal</td><td>20</td></tr>
<tr><td>Gurteen, Tipperary</td><td>75</td></tr>
<tr><td>Johnstown Castle, Wexford</td><td>62</td></tr>
<tr><td>Finner, Donegal</td><td>33</td></tr>
</table>

*Wind speed and wind direction for Dublin Airport used in the absence of available data

3 RESULTS AND DISCUSSION

3.1 Cooling demand in Ireland (Current and Future)

Despite recent research indicating that the there is no cooling needs in Ireland (Agency and Programme 2018; SEAI 2022) or at least that NV systems are sufficient at present (O' Donovan, Murphy, and O'Sullivan 2021), it is evident that there will be a need for cooling in Ireland in the future and this is starting the manifest itself now, where existing software may be behind the trend of cooling need for Ireland in even the worst emissions scenarios.

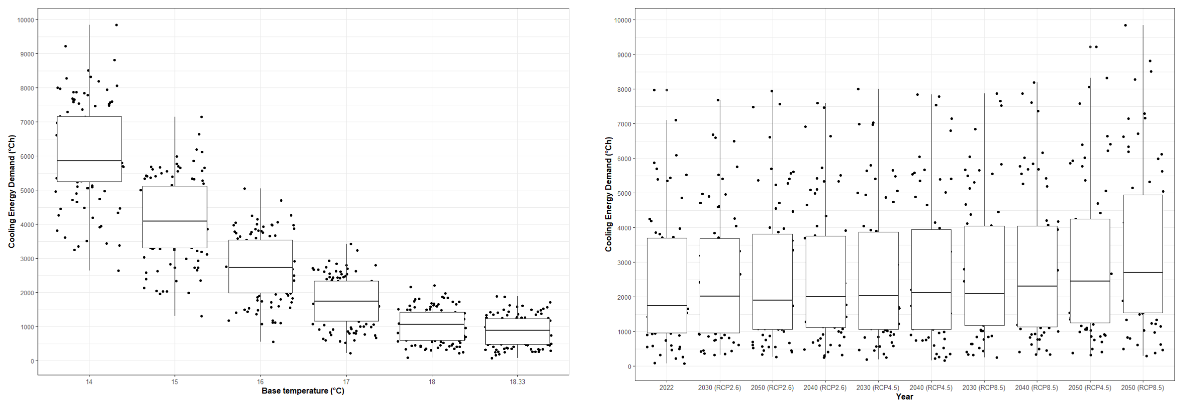

Figure 1: Relationship between cooling degree hours and base temperature and different climate scenarios

What is evident is that change in cooling demand because of the assumptions around base temperatures has a much greater effect in this case than that of existing projections for changes in the climate going forward (see Figure 1). The effect of different weather files in climate scenario has less of an overall effect on cooling demand. Overall, it is expected that demand (in CDH terms) for cooling in Ireland could increase by 591% on average by lowering the base temperature for cooling (through the retrofit of exiting building stocks or increasing fabric performance, from 18.33°C to 14°C), whereas the projected increase in external air conditions could lead to an increase of 41% on average in cooling demand between conditions in 2022 and 2050 in the projected worst case (2050 RCP8.5).

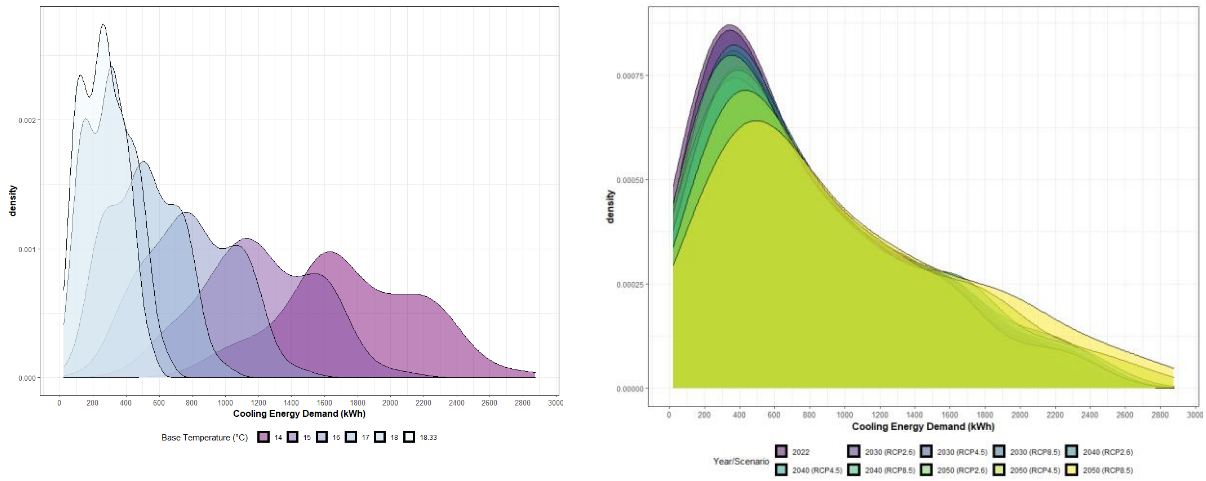

Figure 2: Density plots of estimated cooling energy demand (in kWh) for the case study building indicated in section 2.1. (Left: cooling demand different base temperatures, Right: cooling demand for different years and climate scenarios)

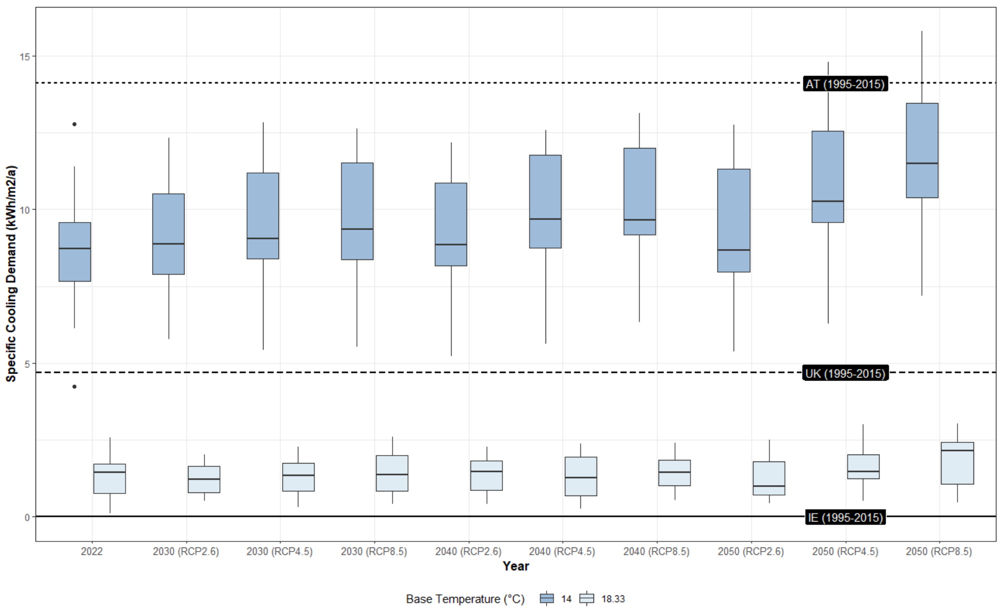

Figure 3: Boxplots of specific cooling demand with respect to climate scenario and different assumptions for base temperature. (Dashed lines indicate different specific cooling demands indicated in the work of (Jakubcionis and Carlsson 2018), for Ireland (IE), United Kingdom (UK), and Austria (AT)).

It should be noted that the use of a standardised base temperature for cooling (e.g. 18.33°C) can result in very different conclusions when compared to a base temperature that is more appropriate for cooling demand in low energy buildings (e.g. 14°C). If we take a specific building as an example (see Figure 2), this can become more evident that the base temperature chosen leads to very different conclusions. It is therefore important that future research considers an effective calculation procedure for the determination of the base temperature for cooling in more detail, given its relative importance in the Irish context. Figure 3 indicates the specific cooling demand for the same building and indicates different reference levels of specific cooling demand from a cognate study in residential buildings in Europe (Jakubcionis and Carlsson 2018). This indicates that current demand levels in Ireland are above previous thresholds irrespective of assumptions on base temperatures. Additionally, current and future cooling demand levels in Ireland are likely to be above that of the UK in specific cooling demand terms (between the period 1995-2015).

3.2 Comparison of demand and supply of VC

Despite demand levels increasing in the coming years, currently it is estimated that MVC and NVC systems are capable of supplying enough cooling energy to offset the existing demands of low energy buildings. Figure 4 highlights the difference between current and future demand and supply levels depending on different VC systems (i.e. MVC or NVC). Based on the results presented in Figure 4, it can be observed that currently supply outstrips demand by between 4.0 to 5.8 times in 2022 and by between 3.5 and 4.9 in 2050 on average depending on the two proposed systems. The reduction in the ratio between supply and demand between now and 2050 would appear to be driven by increases in mean cooling demand levels between now and 2050.

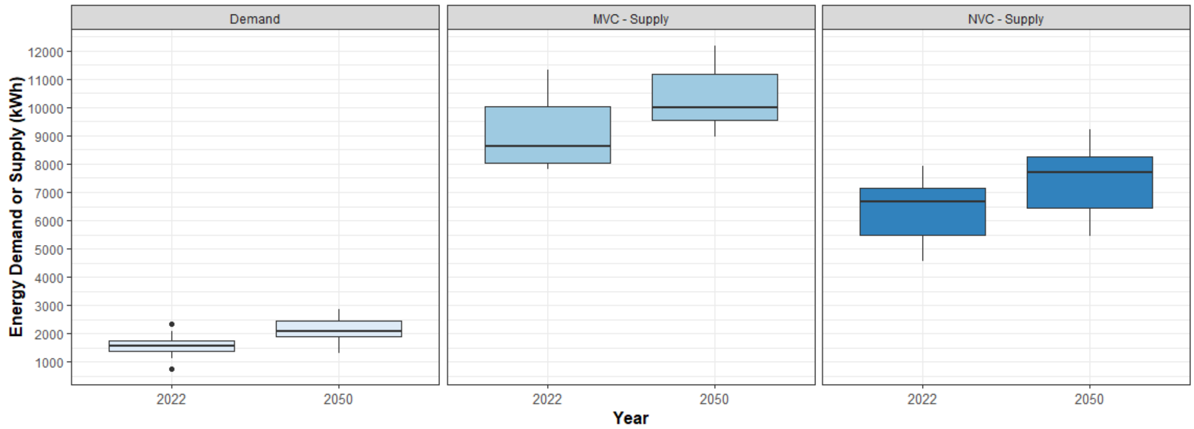

Figure 4: Boxplots of energy demand and supply for cooling with respect to year. (Facet grid represents demand, or supply type for MVC and NVC systems. Note: 2050 refers to RCP 8.5 scenario).

It should be noted that by in large these cumulative demand and supply values, highlight the total per annum performance, but this may not account for seasonal variance where overheating may be present despite cooling potential existing. This is because the cumulative value presented does not indicate hourly or sub-hourly periods where the supply of NVC or MVC is not sufficient. Additionally, because of the supply and demand being calculated based on external temperatures being greater than 14°C, and because this temperature will be below the neutral temperature, this leads to more supply accounted for in parts of the year where supply may not be typical. Resultantly, it is expected that 2% to 6% more hours of the year will have cooling needs in 2050 compared with 2022. This leads to increase in supply terms of between 4% and 39% for the NVC system studied and between 7% and 26% for the MVC system studied is observed between 2022 and 2050. This change is also highlighted by (Bravo Dias, Soares, and Carrilho da Graça 2020) where in their work it is expected that the potential for NV will increase by 6 weeks in Northern Europe (between now (1971-2000) and the future (2070-2100)). It should also be noted that Bravo Diaz et al. highlighted that Dublin is likely to see no change in days that are too warm (TW), a decrease in days that are too cold (TC), less weeks where NV is possible, but an increase in the number of weeks where VC is applicable. Regarding the removal of energy for hygienic ventilation, it should be noted that the reduction of available supply for NVC and MVC was reduced by 10-15% to remove the ventilation need from each system for calculating SPFs. This ventilation supply is likely to contribute to cooling supply in reality but has been excluded in this case.

3.3 SPF calculations

Considering the definition described in previous sections it is important to note that some countries set a minimum thresholds or ranges for renewable cooling these typically lie between 2.8 and 9.5 (Kranzl et al. 2021). Examples of MVC in the real world indicate that these systems can achieve COP values of up to 20 (Holzer and Stern 2019). With hybrid VC systems achieving COP's of 18.3 in reality (Yan et al. 2022). Figure 5 indicates the performance of NVC and MVC in both 2022 and in future conditions where demand is likely (>14°C outside). What is evident is that both MVC and NVC systems are likely to achieve very high SPFs in both 2022 and 2050 (RCP 8.5). On average NVC and MVC systems are likely achieve SPFs of 63 and 23 respectively (considering all years). Overall, the NVC system studied is likely to be providing between 25.1kWh/m^2/a and 50.6 kWh/m^2/a of specific cooling energy supply for the studied building, while, MVC systems are likely to be providing between 42.9 kWh/m^2/a and 66.9kWh/m^2/a in specific cooling energy supply for the same building type depending on the location and climatic year considered.

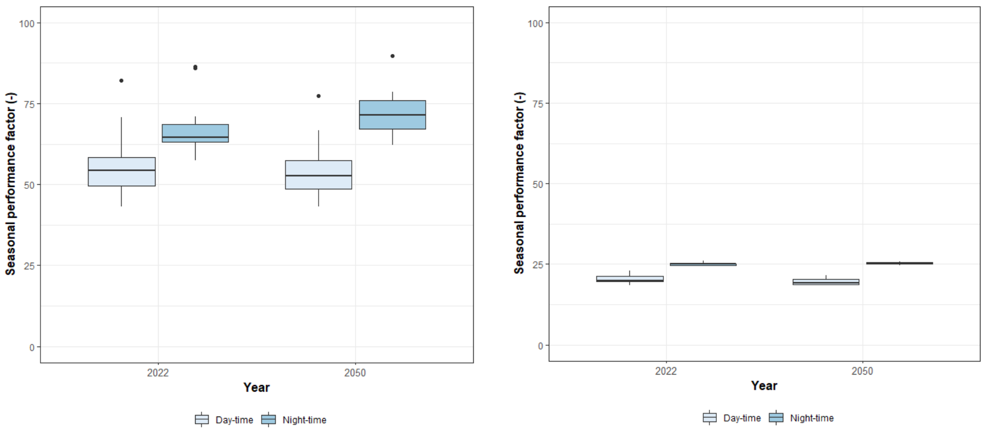

Figure 5: Boxplots of seasonal performance factor with respect to year (Left: SPF values for NVC, Right: SPF values for MVC, colour indicates SPF for day or night-time)

3.4 General discussion and future work in relation to Irish residential stock

The most recent report on the housing stock in Ireland indicated that there were 2,003,645 houses or apartments in Ireland in 2016 (CSO 2016), most of these homes use single-sided natural ventilation for cooling purposes, which are stipulated in current building regulations for purge ventilation purposes. A survey in 2019 by the CSO in Ireland indicated that the average floor area for dwellings in Ireland was 111m^2 (CSO 2019). Based on the combination of these two facts as well as the typical specific cooling energy supply values shown earlier it is estimated that between 5.6TWh/a and 11.3TWh/a is currently available from NVC in Ireland. Based on the ratio between demand and supply (shown earlier) it is likely that over one third of this potential is being utilised by the housing stock on a per annum basis. This cooling energy is supplied as amongst the most energy efficient compared with even modern MVC systems as the energy usage for opening windows is likely to be manual in nature. As such, NVC is currently offsetting a significant amount of the existing cooling demand and currently this is not officially recognised as a renewable energy source. The work in this paper indicates that it is likely that if these systems are controlled or actuated that a significant amount of renewable cooling potential is available for the Irish housing stock and that the extent of this needs further examination. Future work should; 1) consider the effective determination of the cooling base temperatures for different building types, but particularly for low energy buildings as this value can have a significant effect on cooling demand calculations (see section 3.3), 2) consider simulating different archetypal buildings to interrogate the SPF values that can be achieved, 3) evaluate the SPF of real NVC and MVC systems in-use and 4) evaluate the current cooling energy supply in the building stock by using available energy rating databases for Ireland (as the estimates presented here are subject to variation).

4 CONCLUSIONS

In this paper, three stages were proposed to evaluate the status of renewable ventilative cooling in Ireland. Firstly, a cooling degree hour analysis was used to estimate the current demand levels for different base temperatures and weather data. Secondly, the potential for cooling energy supplied by a NVC and MVC system was estimated. Finally, the potential seasonal performance factor was calculated for an NVC and MVC system. The results presented have indicated that the current cooling energy supplied by VC appears to be outstripping estimated demand levels (on an annualised basis). The results also indicate that NVC and MVC systems are likely to be a renewable source that is currently not officially accounted for.

5 ACKNOWLEDGEMENTS

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