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Natural ventilation effects on a residential building sensible and latent energy loads in Toronto

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ABSTRACT

Natural Ventilation (NV) is a passive approach to reduce the building energy demand in suitable climate zones. However, most studies considering NV models or experiments only focus on the sensible load (cooling) reduction of buildings, while they do not investigate the implications of NV in latent load (humidification and dehumidification) changes in buildings. This study uses an urban physics model, the Vertical City Weather Generator (VCWG v1.4.7) software, to address this research gap. Simulations are executed for the climate of Toronto (zone 5) in 2020 to analyze the NV potential for single-detached two-story residential homes. A rule-based controller is implemented to make decisions on opening/closing windows based on indoor/outdoor temperatures, humidities, and sensible cooling/heating loads, while targeting temperature and humidity setpoints. The base case building of interest exhibits features (envelop thermal resistance, infiltration rate, ventilation rate, glazing ratio, and solar heat gain coefficient) according to common codes and standards in the region. Some sensitivity tests are performed to understand the effects of building envelop infiltration and thermal resistance in the performance of the NV system. Additional cases exhibit air tight buildings, high insulation buildings, and air tight/high insulation buildings associated with the Passive House standard. Using NV, annual energy savings around $\sim$ 10 kW-hr m^{-2} are possible for combined sensible and latent loads. The implications of latent load, envelop infiltration, and envelop thermal resistance are discussed.

Keywords: building energy modeling, natural ventilation, sensible and latent loads.

INTRODUCTION

To moderate the impact of buildings on climate change [9], Natural Ventilation (NV) is a suitable technique to lower the sensible cooling demand of buildings in favorable climates. However, most typically, NV is only analyzed by considering the sensible cooling demand of buildings, while ignoring the implications on the latent demand. For instance, by opening windows, the sensible cooling demand of a building may be reduced, but air that is either too moist or too dry can enter the building and increase the latent demand, i.e. by dehumidification or humidification demands, respectively [7, 8, 16, 15]. In this study, an urban physics model is used to consider the implications of both sensible and latent demands when using NV for the climate of Toronto. Simulations are conducted for a full year in 2020. A rule-based controller is developed and implemented to decide when windows shall be opened to enhance NV ventilation based on environmental and building performance variables.

METHODS

Model Description

The Vertical City Weather Generator (VCWG v1.4.7) is a microscale and multiphysics urban physics model that predicts the urban environmental and building performance variables. As shown in Figure 1, it integrates various submodels to account for exchanges of momentum, heat, humidity, and water through soil, urban surfaces, and the atmosphere. The modelling paradigms employed are the Resistance Capacitance (RC) thermal network, Navier-Stokes transport in the vertical direction, Monin-Obukhov Similarity Theory (MOST), and lump energy modeling [1]. Full descriptions of the model are provided in prior literature [4, 10, 11, 2, 15, 14]. VCWG is forced with weather data generated by another software titled the Vatic Weather File Generator (VWFG v1.0.0), which uses the ERA5 dataset from the European Centre for Medium-Range Weather Forecasts (ECMWF) and prepares data in the EnergyPlus Weather (EPW) file format at hourly resolution [3]. The rule-based controller for NV is discussed in our previous study [15]. Briefly, NV is considered under cooling mode. If $T_{\mathrm{out}} < T_{\mathrm{in}}$ & $T_{\mathrm{set}} < T_{\mathrm{in}}$ [K] then a specific humidity condition is checked to trigger NV. For this condition either of the following criteria must be met: $q_{\mathrm{in}} > q_{\mathrm{set}}$ & $q_{\mathrm{out}} < q_{\mathrm{in}}$ or $q_{\mathrm{in}} < q_{\mathrm{set}}$ & $q_{\mathrm{out}} > q_{\mathrm{in}}$ [kgv kga^{-1}]. To trigger NV, windows are opened and a new air exchange rate is calculated due to ventilation, infiltration, and NV.

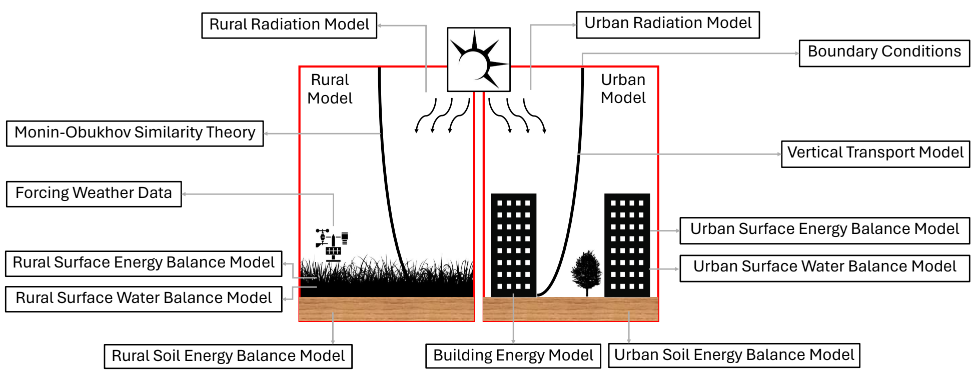

Figure 1. Schematic of the Vertical City Weather Generator (VCWG v1.4.7).

Simulation Cases

Two sets of simulations are conducted with and without NV. Four buildings are considered according to Table 1. The base building is associated with relevant codes and standards [12, 6, 5]. The air tight or high insulation buildings exhibit a low infiltration rate or a high envelop thermal resistance. The Passive House building exhibits both a low infiltration rate and a high envelop thermal resistance [13]. It is primarily intended to conduct the simulations for the year 2020, although some months (February, March, April) have been substituded in prior years (2018 and 2019), for which the forcing weather data have not been reliable in 2020.

Building Energy Loads

NV is formulated in the context of the building sensible and latent load calculation. The sensible load, $\pm[Q_{\mathrm{vent}} + Q_{\mathrm{inf}} + Q_{\mathrm{int}} + Q_{\mathrm{mass}} + Q_{\mathrm{wall}} + Q_{\mathrm{ceil}} + Q_{\mathrm{win}} + Q_{\mathrm{tran}}]$, involves ventilation load Q_{vent}, infiltration load Q_{inf}, internal heat from occupants and equipment Q_{int}, heat from the building's mass Q_{mass}, heat from walls Q_{wall}, heat from ceilings Q_{ceil}, heat conduction through windows

Table 1. Building features for Toronto (zone 5) based on codes and standards.

Parameter	Base	Air Tight	High Insulation	Passive House
Roof Resistance [m^2 K W^{-1}]	6.41	6.41	11.5	11.5
Wall Resistance [m^2 K W^{-1}]	3.6	3.6	7.0	7.0
Window U-value [W m^{-2} K^{-1}]	1.9	1.9	1.9	1.9
Infiltration Rate [ACH]	3.0	0.6	3.0	0.6
Ventilation Rate [L s^{-1} m^{-2}]	0.3	0.3	0.3	0.3
Glazing Ratio [-]	0.4	0.4	0.4	0.4
Solar Heat Gain Coefficient [-]	0.4	0.4	0.4	0.4

Q_{win}, and radiant heat passing through windows Q_{tran} [W]. In this formulation, the positive sign (+) will be used to calcaulte the sensible cooling demand, and the negative sign ($-$) will be used to calculate the sensible heating demand. Except for Q_{int}, which is scheduled in VCWG, the other terms are parameterized using the heat balance method:

$$
\begin{aligned}
Q_{\text{vent}} &= V_{\text{vent}}\rho_a c_{pa}(T_{\text{out}} - T_{\text{set}}) \\
Q_{\text{inf}} &= V_{\text{inf}}\rho_a c_{pa}(T_{\text{out}} - T_{\text{set}}) \\
Q_{\text{mass}} &= A_{\text{bui}} h_m (T_{\text{mass}} - T_{\text{set}}) \\
Q_{\text{wall}} &= A_{\text{wall}} h_w (T_{\text{wall}} - T_{\text{set}}) \\
Q_{\text{ceil}} &= A_{\text{bui}} h_c (T_{\text{ceil}} - T_{\text{set}}) \\
Q_{\text{win}} &= A_{\text{win}} U_w (T_{\text{out}} - T_{\text{set}}) \\
Q_{\text{tran}} &= A_{\text{win}} S \times SHGC,
\end{aligned} \tag{1}
$$

where V_{vent} and V_{inf} [m^3 s^{-1}] are ventilation and infiltration air flow rates, ρ_a [kg m^{-3}] is density of air, c_{pa} [J kg^{-1} $°C^{-1}$] is heat capacity of air, A_{bui} [m^2] is building footprint area, T_{mass}, T_{wall}, T_{ceil}, T_{set}, and T_{out} [°C] are mass, wall, ceiling, set-point, and outdoor temperatures, A_{bui}, A_{wall}, and A_{win} [m^2] are building footprint, wall, and window areas, h_m, h_w, and h_c [W m^{-2} $°C^{-1}$] are convective heat transfer coefficients, U_w [W m^{-2} $°C^{-1}$] is the window U-value, S [W m^{-2}] is the shortwave radiation flux through the window, and $SHGC$ [-] is the solar heat gain coefficient for the window. The sensible load is met by the building's sensible cooling/heating equipment. The latent load, $\pm[Q_{\text{latvent}} + Q_{\text{latinf}} + Q_{\text{latint}}]$, involves latent heat from ventilation Q_{latvent}, latent heat from infiltration Q_{latinf}, and latent heat from internal heat from occupants and equipment Q_{latint} [W]. In this formulation, the positive sign (+) will be used to calcaulte the dehumidification demand, and the negative sign ($-$) will be used to calculate the humidification demand. These loads are met by the building's humidification/dehumidification equipment. Except for Q_{latint}, which is scheduled in VCWG as a fraction of sensible heat from occupants and equipment Q_{int}, the other terms are parameterized using the humidity balance method:

$$
\begin{aligned}
Q_{\text{latvent}} &= V_{\text{vent}}\rho_a L_v (q_{\text{out}} - q_{\text{set}}) \\
Q_{\text{latinf}} &= V_{\text{inf}}\rho_a L_v (q_{\text{out}} - q_{\text{set}}),
\end{aligned}
$$

where L_v [J kg_v^{-1}] is latent heat of vaporization for water, and q_{out} and q_{set} [kgv kga^{-1}] are outdoor and set-point specific humidities, respectively. When NV is deployed, the model enhances the infiltration rate V_{inf} [m^3 s^{-1}] and thus captures the physics properly. In this version of VCWG, latent load is only computed if the building is cooled or heated, regardless of building sensible (cooling or heating) demands. The cooling is triggered when the sensible cooling load is positive and canyon air temperature is greater than 288 K. The heating is triggered when the sensible heating load is positive and canyon air temperature is less than 288 K. The buildings are arranged in rows with a separation of 30 m maintained in each horizontal direction (x and y). Temperature, specific humidity, and wind (the x and y components) data within the urban roughness sub-layer were extracted along the vertical direction (z) from VCWG. The buildings are low-rise residential units designed with dimensions of 13.8 m $\times$ 13.8 m $\times$ 6 m. Each story features two windows on each side, with an equivalent area of 26.4 m^2 per facade. The NV system model assumes a single equivalent window on each building side and is based on the ASHRAE Fundamentals handbook. The calculation of the NV system air flow rate is performed by $Q_{NV} = CAU$, where Q_{NV} [m^3 s^{-1}] is flow rate, $C = 0.5$ [-] is a coefficient describing the effectiveness of windows (it can be assumed to be 0.5 to 0.6 for normal winds and 0.25 to 0.35 for diagonal winds), A [m^2] is the free area of inlet openings, and U [m s^{-1}] is the wind speed normal to the facade. Once Q_{NV} is known, it can be added to the base infiltration rate V_{inf} [m^3 s^{-1}] in the VCWG model.

Diagnostic Equations for Indoor Temperature and Specific Humidity

Following the sign conventions discussed above, the heat balance equation can be rewritten in the following form, which separates terms including or excluding the unknown indoor temperature

$$\underbrace{\text{Cooling Load} - \text{Heating Load} - Q_{\text{tran}} - Q_{\text{int}}}_{Q} = Q_{\text{vent}} + Q_{\text{inf}} + Q_{\text{mass}} + Q_{\text{wall}} + Q_{\text{ceil}} + Q_{\text{win}} \tag{2}$$

$$\begin{aligned} Q = & \underbrace{V_{\text{vent}}\rho_a c_{pa} T_{\text{out}} + V_{\text{inf}}\rho_a c_{pa} T_{\text{out}} + A_{\text{bui}} h_m T_{\text{mass}} + A_{\text{wall}} h_w T_{\text{wall}} + A_{\text{bui}} h_c T_{\text{ceil}} + A_{\text{win}} U_w T_{\text{out}}}_{H1} \\ & - [\underbrace{V_{\text{vent}}\rho_a c_{pa} + V_{\text{inf}}\rho_a c_{pa} + A_{\text{bui}} h_m + A_{\text{wall}} h_w + A_{\text{bui}} h_c + A_{\text{win}} U_w}_{H2}] T_{\text{in}} \end{aligned} \tag{3}$$

Likewise the specific humidity balance equation can be rewritten as the following form, which separates terms including or excluding the unknown indoor specific humidity

$$\underbrace{\text{Dehumidification Load} - \text{Humidification Load} - Q_{\text{latint}}}_{QL} = Q_{\text{latvent}} + Q_{\text{latinf}} \tag{4}$$

$$QL = \underbrace{V_{\text{vent}}\rho_a L_v q_{\text{out}} + V_{\text{inf}}\rho_a L_v q_{\text{out}}}_{HL1} - [\underbrace{V_{\text{vent}}\rho_a L_v + V_{\text{inf}}\rho_a L_v}_{HL2}] q_{\text{in}} \tag{5}$$

In VCWG v1.4.7, the resulting two equations $T_{\text{in}} = (H1 - Q)/H2$ and $q_{\text{in}} = (HL1 - QL)/HL2$ are re-evaluated in each timestep to give the indoor temperature and specific humidity.

Waste Heat Rejection into the Urban Environment

Under cooling mode, we assume that both sensible cooling and dehumidification demands are met by a refrigeration cycle with a known Coefficient Of Performance (COP). Using the first law of thermodynamics, the waste heat rejected to the environment will be given by,

$$\text{Waste Heat} = (\text{Sensible Demand} + \text{Dehumidification Demand}) \left(1 + \frac{1}{COP}\right). \tag{6}$$

Under heating mode, we assume that both sensible heating and humidification demands are met by a furnace with a known thermal efficiency (η). Using the first law of thermodynamics, the waste heat rejected to the environment will be given by,

$$\text{Waste Heat} = (\text{Sensible Demand} + \text{Humidification Demand})\left(\frac{1}{\eta} - 1\right). \quad (7)$$

What if the building has a humidification demand under cooling mode, or dehumidification demand under heating mode? In this case, latent demand is properly logged, but its associated waste heat is not considered by the model. In another word, the waste heat for latent demand in our model is formulated for dry climates under heating mode and humid climates under cooling mode.

RESULTS AND DISCUSSION

Figure 2 shows the monthly energy demands for the base and Passive House cases with and without using NV. Compared to the base case, the Passive House exhibits lower heating, dehumidification, and humidification demands, but it exhibits greater cooling demand. Under cooling mode, the energy savings using NV is greater for the Passive House than the base case. However, NV causes greater dehumidification demand for the Passive House compared to the change in dehumidification demand for the base case. Reasons for these findings are justified in our previous study [15]. Figure 3 shows the hourly results for temperatures, specific humidities, sensible energy demands, latent energy demands, and window state for the greater part of the month of May. This month, in shoulder season, is suitable to assess the effectiveness of NV because the building can be under sensible cooling, sensible heating, or neither. The indoor temperature is maintained strictly between the cooling set point (297.05 K) and heating set point (291.15 K). On the other hand, although mostly maintained within the corresponding cooling relative humidity (60 %) and heating relative humidity (40 %), the specific humidity can deviate outside this range. This is due to the fact that humidification and dehumidification only occur when there is sensible cooling or heating. When there is no sensible cooling or heating, the indoor specific humidity approaches that of the outdoor specific humidity. The window state time series show that windows are only opened when indoor/outdoor temperature and specific humidities are favorable for NV. For example, for the last third of the month (>600 hr), the windows actively open when the building has sensible cooling demand and indoor/outdoor temperature and specific humidity meet the conditions of the NV controller. Table 2 shows the annual energy savings by using NV. Since the rule-based control algorithm primarily attempts to save the sensible energy demand, we can note that the greatest energy saving is associated with the sensible cooling demand. Under heating mode, the indoor and outdoor conditions are seldom met for NV, so no savings are possible for the sensible heating demand. The saving in sensible cooling demand is notably more for air tight buildings. Further, increasing thermal insulation of the building envelop does not impact the building energy loads as far as NV is concerned. It can be seen that NV implicates the latent loads, but since the control is designed to operate windows considering indoor and outdoor humidities, the changes in latent loads are an order of magnitude less than those of the sensible cooling loads as a result of triggering NV.

CONCLUSIONS

Our study shows that consideration of both sensible and latent energy demands are possible when using Natural Ventilation (NV). Using the simulations for Toronto in 2020, we find that up to 10

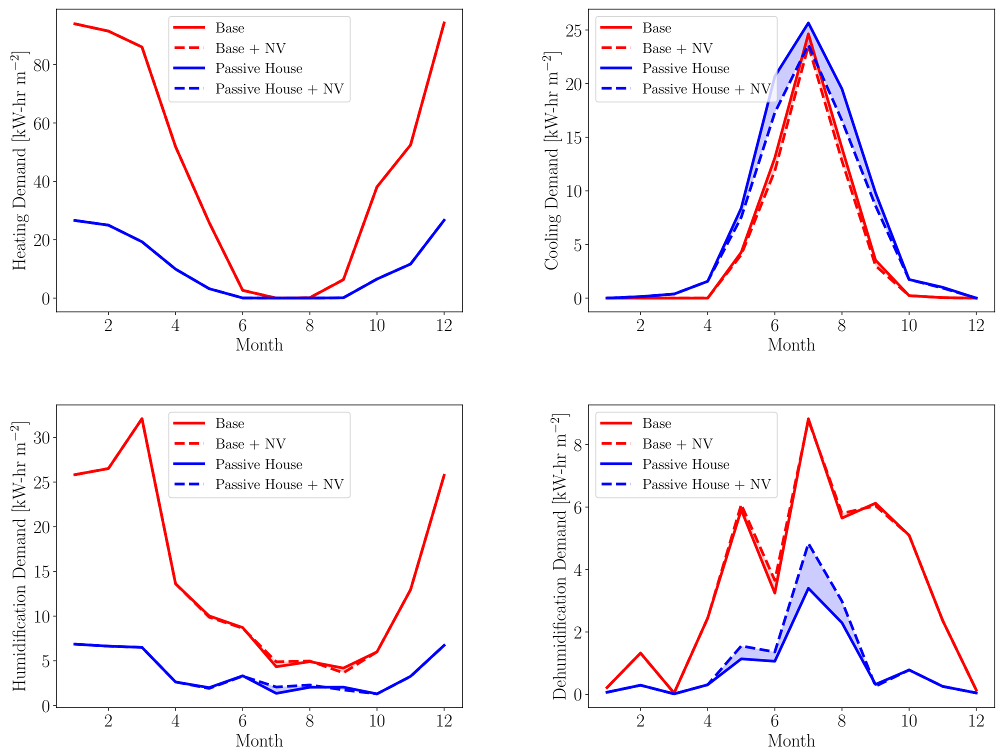

Figure 2. Monthly building energy demands for the base and Passive House cases; the difference between employing no Natural Ventilation (NV) and employing NV is shown with shaded color.

Table 2. Annual energy savings (+) and losses (−) due to using Natural Ventilation (NV).

Building Energy Demand	Base	Air Tight	High Insulation	Passive House
Sensible Heating [kW-hr m^{-2}]	−0.10	−0.08	−0.11	−0.07
Sensible Cooling [kW-hr m^{-2}]	+4.28	+10.86	+4.13	+10.51
Dehumidification [kW-hr m^{-2}]	−0.59	−0.90	−1.8	−2.78
Humidification [kW-hr m^{-2}]	+0.12	−0.68	+0.33	−0.51

kW-hr m^{-2} of sensible cooling energy can be saved per year by employing NV, with implications on latent demand being less than one order of magnitude compared to the sensible cooling demand. We also find that the effectiveness of NV is most sensitive to the building's air tightness, as opposed to the envelop's thermal resistance. Air tight buildings exhibit greater potential for energy savings using NV. Our findings suggest that NV has a potential to reduce building energy loads under cooling conditions. These simulation findings are yet to be corroborated by field experiments.

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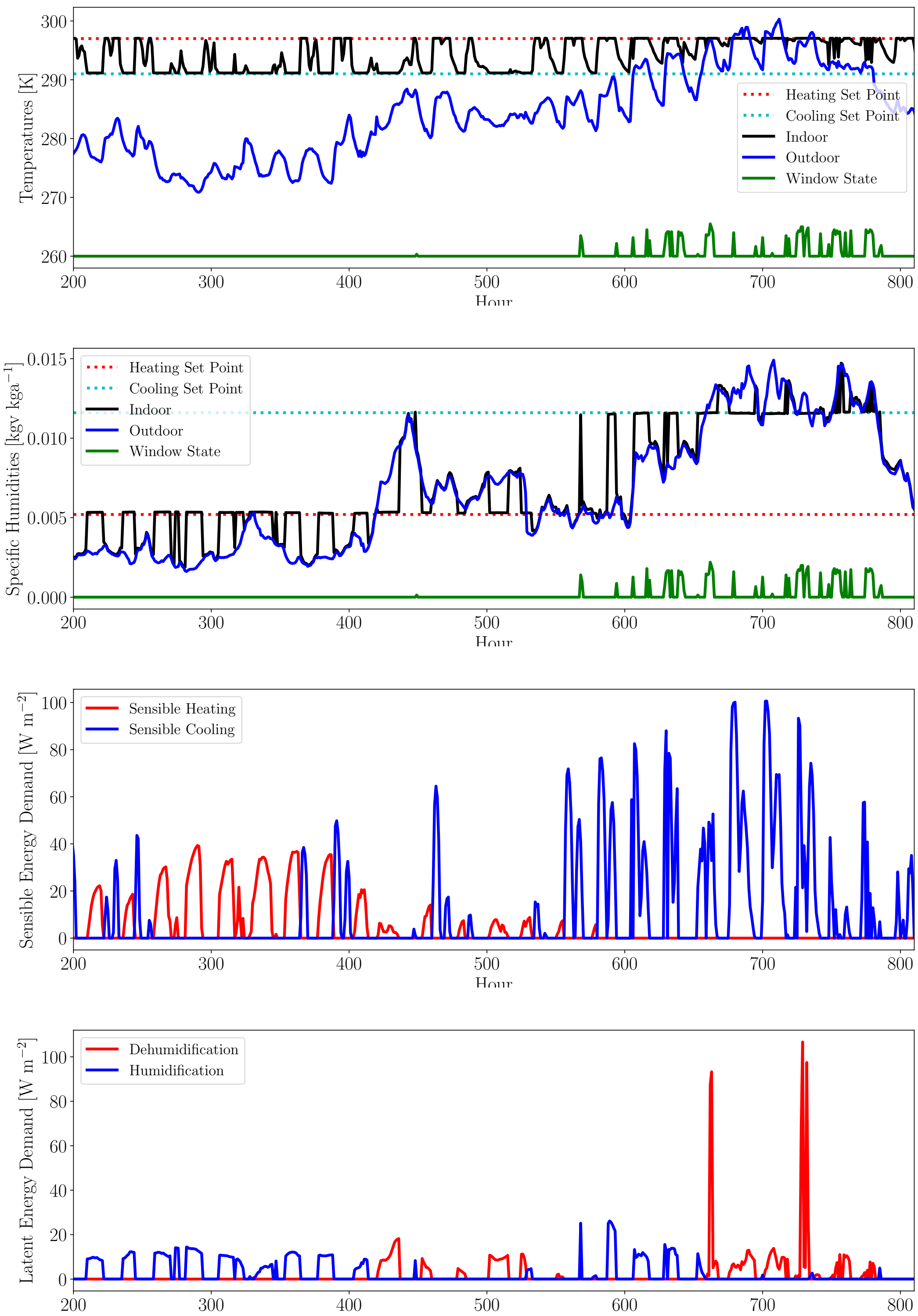

Figure 3. Hourly time series for temperatures, specific humidities, sensible building energy demands, and latent building energy demands; Passive House with Natural Ventilation (NV); selected hours in the month of May; window state shown at the bottom of temperature and specific humidity plots.

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