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1 **Dynamic Metrics of Natural Ventilation Cooling Effectiveness for**
2 **Interactive Modeling**

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16 **Abstract**

17 The evaluation of natural ventilation potential for cooling indoor spaces during
18 the early design phases is of great interest to researchers and practitioners.
19 Among various definitions and usages for natural ventilation potential (NVP) in
20 early design evaluation, this paper reviews and identifies the key performance
21 indicators, and proposes two new dynamic metrics—natural ventilation cooling
22 effectiveness (NVCE) and climate potential utilization ratio (CPUR). The metrics

are dynamically responsive to various design options, in both steady and transient states, allowing consideration of thermal mass. Assisting in design development processes, the metrics quantify how well indoor spaces make use of natural ventilation's cooling capacity. Case studies are presented to demonstrate how NVCE and CPUR enable designers to evaluate the predicted performance and how to apply the information to improve building design. The results of the design iterations showed that the relationship among various design parameters should be dynamically understood in order to evaluate the performance of natural ventilation, confirming that "the more the airflow, the greater the potential," and "the heavier the thermal mass, the greater the energy saving" were not always true.

Keywords: natural ventilation; key performance indicators; interactive modeling; building simulation; ventilative cooling; thermal mass

1. Introduction

Building analyses using natural ventilation as an alternative cooling source have reported meaningful energy reductions world-wide. For instance, natural ventilation helped meet thermal comfort criteria in Bangkok, Thailand, with a steady airflow of 0.4 m/s [1]. Simulations of a building with a natural-ventilation-dedicated component in Tokyo, Japan, demonstrated a 35% reduction in electricity energy demand for cooling [2-4]. Also, analysis of a traditional Italian building reported that natural ventilation would save 43 - 53% of cooling energy depending on Italian local climates [5]. Some climates offer better opportunities than others. For example, a building in a hot and dry climate in Mexico would utilize more of natural ventilation's potential than one

48 in a hot and humid climate in the same country [6].

49 In addition to climate conditions, the benefits from natural ventilation could be
50 increased or decreased via a combination of various design strategies. For
51 example, two identical buildings in a hot and humid climate could lead to
52 different thermal environments depending on heat capacities of building
53 materials [6]. Thermal mass is known to have significant impact on natural
54 ventilation's cooling potential [7-9], and alternating cooling modes, namely
55 mixed-mode, is an effective way to utilize natural ventilation [10-13]. Window
56 operation controlling the timing of the use of natural ventilation is another
57 significant element in natural ventilation [14-16]. Particularly, night-time
58 ventilation, or night-time cooling, utilizes the lower air temperature during the
59 night to help cool the space and mitigate the peak cooling demand during the
60 day with the help of thermal inertia [17,18].

61 These multifaceted factors influencing natural ventilation's cooling potential
62 make it important to consider the interrelationship among building design
63 decisions. This paper aims to quantify natural ventilation's cooling performance
64 of a building with such factors, assisting in design iterations during early design
65 phases. It explores relevant metrics that indicate natural ventilation's cooling
66 potential, proposes new metrics to be used in early building design phases, and
67 investigates how these metrics inform the dynamics of various design
68 strategies combined with natural ventilation.

69 1.1. *Natural ventilation potential (NVP)*

70 Numerous studies have used a general term, natural ventilation potential
71 (NVP), to indicate natural ventilation's usage in buildings and sites. One major
72 purpose of these studies was to evaluate the suitability of using natural

ventilation at given sites or under given climates [19–26]. Researchers examined local conditions including meteorological, morphological, environmental, and thermal information to evaluate NVP. Researchers could then compare NVPs of various regions, countries, or worldwide. Another major purpose served by NVP evaluation was to describe a building’s potential to utilize natural ventilation with a given set of a building design options (for example, window location or opening areas) [27–29]. The foci of these studies were on building design or building components to identify better solutions utilizing natural ventilation. Previous studies on NVP of sites and buildings are listed in Table 1.

Table 1. Previous work on Natural Ventilation Potential (NVP) research on climates

	Location	Category	Evaluation purpose	NVP Metric
[20]	USA	Site	NVP of the US	Target ACH and potential cooling effect
[21]	Mediterranean coastal zones	Site	Climate comparison	Statistical wind rose and radar plot
[22]	Warm-humid climates in Asia	Site	City comparison	Thermal comfort improvement
[23]	European climates	Site	City comparison	Very high/ high/ medium/ poor
[24]	Sheffield District, UK	Site	NVP and urban morphology	Urban morphology indices (rugosity, porosity, sinuosity) and pressure coefficients
[26]	Geneva, Switzerland	Site	Site NVP	Good/medium/poor
[30]	Australia	Site	NVP comparison of Australian climates	NV hour and satisfied natural ventilation hour

				(SNVH)
[31]	China	Site	NVP of China	Annual cooling energy savings (kWh/m ² -year)
[32]	Canada	Site	Weather data set comparison	NV hour
[33]	China	Site	Re-evaluation of city's NVP with a more realistic building setting	Airflow rates
[17]	European climates	Site	Night-time cooling	Climate cooling potential
[25]	China	Site	City comparison	NV hour and pressure difference pascal hours (PDPH)
[34]	China	Site	City comparison, revised from [25]	PDPH
[35]	India	Site	NVP of India	PDPH
[27]	Turkey	Building	Indoor partitions	Air velocity
[28]	Hong Kong	Building	Various window opening degrees	ACH
[29]	General	Building	Window opening design	Natural ventilation effectiveness (NVE)
[36]	General	Building	New equation	Airflow rates
[37]	General	Building	Building design	NVE
[38]	Elblag, Poland	Building	Multiple chimneys and window tilts	ACH
[39]	California, USA	Building	Validation with occupants' window use, local weather conditions, indoor environmental conditions	ACH
[40]	General	Building	Window opening design	PMV and extended PMV measures
[41]	General	Building	Window opening size and atria	Ventilation performance indicator (VPI)

83 As revealed from the above literature, NVP has referred to various quantities

depending on the focus of the research. Some used conventional quantities including airflow rates, air speeds, air changes per hour (ACH), and the total number of hours in a year during which natural ventilation provides acceptable air conditions (NV hour). Others proposed new metrics to nondimensionalize or otherwise describe a certain aspect more effectively to suit their research objectives. Such customized metrics include climate potential for natural ventilation (CPNV) [19], pressure difference Pascal hours (PDPH) [25,34,35], climate cooling potential (CCP) [17], ventilation performance indicator (VPI) [41], satisfied natural ventilation hour (SNVH) [30], and natural ventilation effectiveness (NVE) [29,37].

1.2. *Evaluation metrics for an interactive design process*

This study proposes NVP metrics that can be used during early design but later than a site evaluation phase—namely, the design development (DD) phase. The DD phase is an important design phase where multidisciplinary issues, including energy-conscious design, acoustic design, lighting design, envelope design, indoor environmental design and more, are addressed. For this reason, partnership and arrangements among various disciplines are critical, and vigorous design efforts are ideally made during the DD phase [42]. The evaluation metrics, therefore, should not only consider site information but also reflect design specifics. The desired criteria of such metrics would include:

- Dynamic response to design alternatives, such as materials, room design, window design, etc.;
- Ability to consider both steady-state and transient thermal behavior of a building; and
- Information that directly gives design feedback.

109 1.3. *Research scope and methodology*

110 Among various purposes for using natural ventilation, including controlling air
111 quality, increasing work productivity, and cooling, this paper focuses on its
112 cooling effectiveness. The paper reviews existing NVP metrics and consolidates
113 their key characteristics into two new metrics—natural ventilation cooling
114 effectiveness (NVCE) and climate potential utilization ratio (CPUR)—in order to
115 meet the criteria described in Section 1.2. Lastly, the paper demonstrates the
116 usage of NVCE and CPUR in design phases, and how these metrics incorporate
117 and characterize design decisions as well as various climate zones.

118 **2. Review of natural ventilation performance metrics**

119 2.1. *Commonly used metrics in natural ventilation* 120 *prediction*

121 2.1.1. Volume airflow rates

122 As direct measures of airflow, volume airflow rates (m^3/s) and air speeds (m/s)
123 are often used in natural ventilation evaluation. Such metrics were determined
124 in experiments by using the tracer-gas decay method [43] and conducting wind
125 tunnel tests [44], as well as in numerical models including airflow network
126 (AFN) and computational fluid dynamics (CFD) [36,38,45–47].

127 For example, ASHRAE Standard 62.1 [48] requires a breathing zone to meet a
128 certain ventilation rate (V_{bz}) depending on the zone's population (P_z), floor
129 area (Z_z), and occupancy categories (e.g., bedroom, lobby, or office room). The
130 calculation is given by:

$$131 \quad V_{bz} = R_p P_z + R_a A_z,$$

132 where R_p is outdoor airflow rate required per person, P_z is zone population, R_a
 133 is outdoor airflow rate required per unit area, and A_z is zone floor area. R_p and
 134 R_a for different occupancy categories are listed in [48].

135 2.1.2. Air changes per hour

136 Air changes per hour (ACH) is another popular metric for natural ventilation
 137 evaluation ranging from indoor ventilation [20,28,49,50] to urban wind studies
 138 [51,52]. It measures the ratio of incoming airflow volume for an hour to the
 139 room volume, written as:

$$140 \quad ACH = \frac{3600(s)\dot{V}}{vol},$$

141 where $\dot{V}$ is the airflow rate (m^3/s) and vol is the room volume (m^3). In
 142 experimental settings, an ACH can also be calculated by using the tracer-gas
 143 decay method [39,53]. The ACH in this method is computed as:

$$144 \quad ACH = 3600 \ln \frac{C_0}{C_r} \frac{1}{\tau},$$

145 where C_0 is the initial CO_2 concentration, C_r is concentration at the time τ .

146 2.2. Customized metrics suggested by researchers

147 2.2.1. Natural ventilation 148 evaluation by site and climate conditions

149 Ref. [26] defined natural ventilation potential (NVP) as “the possibility to
 150 ensure an acceptable indoor air quality by natural ventilation only” and passive
 151 cooling potential (PCP) as “the possibility to ensure an acceptable indoor

thermal comfort using natural ventilation.” They described NVP levels of local districts of Geneva, Switzerland, with good, medium and poor NVP and visualized them on a map using GIS. No building information was considered since the purpose was to evaluate NVP of a site rather than of a building. Criteria of NVP included but were not limited to meteorological data, including wind speed, direction, and air temperature; mean height of buildings; mean orientation of the streets; and buildings’ adjacency with neighbors.

Similarly, but with different criteria, [23] evaluated NVP of five sites. Their criteria included undisturbed wind, local wind, stack effect, noise levels, and pollutant levels, as well as urban fabric and experts’ ratings. NVPs were rated as very high, high, medium and poor. In another study, the NVPs of Basel, Switzerland, were evaluated and categorized as highest, intermediate, and lower NVPs [54]. The study created maps for pollution hours, noise hours, stack hours, as well as wind hours and analyzed them to yield NVP.

A metric named climate potential for natural ventilation (CPNV) quantified a climate’s suitability for natural ventilation based on air temperature and humidity ratio [17]. The lower and the upper temperature criteria were determined by the adaptive model of ASHRAE Std. 55 [55], although the author indicated that other adaptive models might also be used, such as CEN Std. EN 15251 [56]. The lower and the upper humidity ratios were determined by the relative humidity of 30 % and 70 %. The CPNV was then calculated by the sum of the hours, during which climate condition met the criteria, divided by the total number of hours in a year. The metric is given as:

$$CPNV = \frac{\sum_{i=1}^n h_{NV,i}}{h_{tot}},$$

where h_{tot} is total number of hours in a year, and $h_{NV,i}$ is 1 if the climate condition at the i^{th} hour of the year meets thermal criteria, and 0 otherwise.

2.2.2. Natural ventilation evaluation by pressure difference

A natural ventilation performance indicator using pressure differences was proposed by [25]. The authors suggested the pressure difference Pascal hours (PDPH) as a means to predict NVP. The equation for the 'effective pressure difference (ΔP_{eff})' was calculated by the building's ventilation rate due to stack and wind effects, using the orifice flow equation.

Also, the 'required effective pressure difference (ΔP_R)' to meet the minimum ventilated rate per ASHRAE Std. 62.2P [57] was calculated. The PDPH is an index for air pressure semi-analogous to degree-days for temperature, which can be expressed as:

$$PDPH = 1 \text{ hr} * \sum_{\text{hours}} (\Delta P_{eff} - \Delta P_R), \text{ if } \Delta P_{eff} - \Delta P_R > 0.$$

This metric is counted only when $\Delta P_{eff} - \Delta P_R > 0$ as noted in the equation. In their study, the PDPHs of four cities in China were calculated with several assumptions: south-facing buildings, identical openings on the south and the north facades, and uniform indoor air temperature at 22 degrees Celsius. The required effective pressure difference was determined by the minimum requirements from ASHRAE Std. 62.2P neglecting possible internal loads. The approach using the pressure difference gave useful information about NVP at a city scale. Ref. [35] also used PDPH as an NVP metric.

2.2.3.

Natural ventilation

evaluation by temperature difference

A metric named climate cooling potential (CCP) was suggested to explain degree-hours for the difference between indoor and outdoor air temperature [17]. Defined as “a summation of products between building/external air temperature-difference and time interval,” the CCP represented the cooling potential of a climate and its impact on a building. The value of CCP was 1 if the temperature difference was the same or larger than the critical temperature difference for night-time ventilation, and the value was 0 otherwise. The metric is written as:

$$CCP = \frac{1}{N} \sum_{n=1}^N \sum_{h=h_i}^{h_f} m_{n,h} (T_{b,n,h} - T_{e,n,h}) \begin{cases} m=1 \text{ hr, if } T_b - T_e \geq \Delta T_{crit} \\ m=0, \text{ if } T_b - T_e < \Delta T_{crit} \end{cases}$$

where h is the time of a day ($h = 0, \dots, 23$), H_i and H_f are the initial and the final hour of the night-time ventilation respectively, T_b is building temperature, T_e is external temperature, and ΔT_{crit} is critical temperature difference for night-time ventilation, for which the authors used 3 K.

2.2.4.

Natural ventilation

evaluation by buoyancy effect

An indicator for stack ventilation in multi-story buildings, the ventilation performance indicator (VPI), was suggested by [41]. The authors provided a dimensionless metric that informs designers how to meet the ventilation rate and indoor temperature requirements via an atrium. VPI is defined as:

$$VPI = \left(\frac{Q^2}{g' H^5} \right)^{\frac{1}{2}},$$

where Q is airflow rate through the room (m^3/s), g' is reduced gravity due to buoyancy (m/s^2), and H is the height of a story (m). The term, g' , is interchangeable with the measure of temperature, as in, $g' = g\beta(T - T_o)$, where g is gravitational acceleration, β is the thermal expansion coefficient, and T and T_o are indoor and outdoor temperatures. Therefore, VPI can compare ventilation requirements to the stack effect resulting from the temperature difference and building height. The authors suggested that designers identify the “per-person VPI” per requirements, assign occupancy in a multi-story atrium building, and then determine the opening sizes to meet the designed VPI in each zone.

2.2.5. Natural ventilation evaluation of building design

To evaluate the natural ventilation potential of a customized building design, a metric called natural ventilation effectiveness (NVE) was suggested [37]. The metric compared the hourly airflow rate of a customized building to the airflow rate that was required to offset the cooling and ventilation load. The ratios of these two airflow rates were added for the hours of the test period and then divided by the total hours. The NVE was calculated as:

$$NVE = \frac{\sum \alpha}{n} \begin{cases} \alpha = 1 & , \text{ if } ACH_{avail} \geq ACH_{req} \\ \alpha = 1 & , \text{ if } ACH_{req} = 0 \\ \alpha = ACH_{avail} / ACH_{req} & , \text{ otherwise,} \end{cases}$$

where ACH_{avail} is the available air changes per hour to be provided through

240 openings, and ACH_{req} is the required air changes per hour, and n is the number
241 of hours in the simulation period. This equation works for a steady-state
242 condition. The authors retrieved the calculation of ACH_{req} from an energy
243 simulation result.

244 **3. Proposed and revised metrics to evaluate the effectiveness of** 245 **natural ventilation's cooling performance**

246 3.1. *Three key metrics: CPNV, NVCE and CPUR*

247 To suit the design procedure, this project focused on three key metrics,
248 including two existing metrics from literature. One of the two existing metrics is
249 climate potential for natural ventilation (CPNV), and the other is natural
250 ventilation effectiveness (NVE). CPNV is useful since it offers the baseline
251 information of the site based only on climate data, and is minimally revised in
252 this paper to allow for customized simulation periods and criteria. NVE is
253 helpful to investigate building design components as the formulation is
254 influenced not only by climate conditions, but also by building materials,
255 window configurations, internal and solar heat gains, and room sizes.

256 In this paper, we revise the NVE for three purposes. First, the metric needs
257 mathematical expressions to represent the above-mentioned building
258 components. Because the original NVE calculation depended solely on energy
259 simulation results, the effect of having different design options on the metric
260 would be shown only at the end of simulations. To overcome this limitation and
261 offer users a clearer preview, we provide explicit equations to calculate the
262 metric in this paper. The equations will also allow analytical approaches.
263 Second, this paper develops the formulation of the metric to work with thermal

mass, and thus, transient conditions; whereas the original NVE worked for steady-state conditions only. Lastly, while the original NVE has taken the minimum ventilation requirements and cooling demands into consideration, we name this revised metric Natural Ventilation Cooling Effectiveness, or NVCE, to clarify the purpose of the evaluation and focus on cooling performance.

With NVCE referring to a building's potential and CPNV a site's potential, a new supplementary metric that compares the NVCE and CPNV is also proposed, which we name Climate Potential Utilization Ratio, or CPUR. This metric indicates how well a building design has utilized the natural ventilation potential of the climate.

3.2. *Proposed metric: natural ventilation cooling effectiveness (NVCE)*

3.2.1. Definition of natural ventilation cooling effectiveness

Ranging from 0 to 1, the revised NVCE measures the effectiveness of natural ventilation as a cooling resource within a timestep. The NVCE of a single time step ($NVCE_{ts}$) is defined as:

$$NVCE_{ts} \equiv q_{avail}/q_{req} \quad (1)$$

where q_{avail} is the cooling power available through natural ventilation, and q_{req} is the required cooling power that would bring the indoor temperature to a desirable temperature. Unlike the original NVE, the proposed NVCE adopts cooling power, q , instead of ACH to consider transient cases more conveniently, as we elaborate in Section 3.2.3. The NVCE of a desired duration

286 (a year, a season, or a month) is then defined as an average of each $NVCE_{ts}$
 287 within the duration, as in Eq. (2):

$$NVCE = \frac{\sum_{n_{ts}} NVCE_{ts}}{n_{ts}}, \quad (2)$$

288 where n_{ts} is the number of time steps of the simulation period, which is 8760 if
 289 a time step is an hour and the simulation period is a year.

290 3.2.2. NVCE in a steady
 291 state

292 The key variables in NVCE are the available cooling power (q_{avail}) and the
 293 required cooling power (q_{req}). Equation (3) defines q_{avail} as below:

$$q_{avail} \equiv \begin{cases} 0, \wedge \text{if } T_{target} - T_{out} < 0 \\ -\rho c \dot{V}_{avail} (T_{target} - T_{out}), \wedge \text{otherwise,} \end{cases} \quad (3)$$

294 where ρ is air density, c is the specific heat of air at constant pressure, $\dot{V}_{avail}$ is
 295 intake airflow rate through natural ventilation obtained by simulations,
 296 calculations, or measurements, and T_{target} and T_{out} are target and outdoor
 297 temperatures. The indoor temperature (T_i) under a steady state can be
 298 calculated as in Eq. (4):

$$T_i = \frac{q_{gain}}{UA + \rho c \dot{V}_{avail}} + T_{out}, \quad (4)$$

299 where U is the thermal transmittance of the building envelope, A is the area of
 300 building envelope, and q_{gain} is the sum of heat gains from solar heat gain,
 301 occupants, lightings, and various home appliances, excluding the heat gains or
 302 losses through the envelope. However, if q_{avail} is not sufficient, such that

303 $T_{\dot{i}} > T_{target}$, there must be supplementary cooling power ($q_{\dot{i}}$) to achieve T_{target} as
 304 in Eq. (5).

$$T_{target} = \frac{q_{gain} + q_{\dot{i}}}{UA + \rho c \dot{V}_{avail}} + T_{out} \quad (5)$$

305 We define q_{req} as the sum of available and supplementary cooling powers as in
 306 Eq. (6). $NVCE_{ts}$ can then be written as in Eq. (7).

$$q_{req} \equiv q_{avail} + q_{\dot{i}} \quad (6)$$

$$NVCE_{ts} = \frac{q_{avail}}{q_{avail} + q_{\dot{i}}} = \frac{-\rho c \dot{V}_{avail} (T_{target} - T_{out})}{- [q_{gain} - UA (T_{target} - T_{out})]} \quad (7)$$

307 In a steady state, NVCE can also be expressed as Eq. (8).

$$NVCE_{ts} = \frac{q_{avail}}{q_{req}} = \frac{\dot{V}_{avail}}{\dot{V}_{req}} = \frac{ACH_{avail}}{ACH_{req}} \quad (8)$$

308 Equation (7) is elaborated from the original NVE, yet it still holds the same
 309 formula as NVE. Detailed steps from Eq. (4) through Eq. (8) are explained in
 310 Appendix A.

311 3.2.3. NVCE in a transient
 312 state

313 When thermal mass is present, Eqs. (4)-(5) need to be modified to consider the
 314 heat storage of the mass as in Eqs. (9)-(10):

$$T_{\dot{i}, n+1} = T_{\dot{i}, n} e^{\frac{-t}{\tau_n}} + (T_{out, n} + R_n q_{gain, n}) \left(1 - e^{\frac{-t}{\tau_n}} \right) \quad (9)$$

$$T_{target, n+1} = T_{\dot{i}, n} e^{\frac{-t}{\tau_n}} + (T_{out, n} + R_n (q_{gain, n} + q_{\dot{i}, n})) \left(1 - e^{\frac{-t}{\tau_n}} \right) \quad (10)$$

$$R \equiv (UA + \rho c \dot{V}_{avail})^{-1} \tau \equiv RC,$$

315 where $T_{\dot{i}, n+1}$ and $T_{target, n+1}$ denote the indoor and target temperatures of the

316 next time step, and t is the length of a time step in seconds. A target
 317 temperature is a desired temperature, which could be either fixed or varying,
 318 and supplemental cooling ($q_{\dot{c}}$) is varied each time step to maintain the target in
 319 a hypothetically conditioned building. The heat gain (q_{gain}) is varied throughout
 320 the day as solar gain changes and occupancy varies. As $\dot{V}_{avail}$ may vary each
 321 time step, so do R and τ . With these variables, NVCE can be written as below.

$$NVCE_{ts} = \frac{q_{avail}}{q_{avail} + q_{\dot{c}}} - \frac{\rho c \dot{V}_{avail} (T_{target} - T_{out})}{- \rho c \dot{V}_{avail} (T_{target} - T_{out}) - \left[q_{gain} - \left(\frac{T_{target, n+1} - T_{\dot{c}} e^{\frac{-t}{\tau}}}{1 - e^{\frac{-t}{\tau}}} - T_{out} \right) \frac{1}{R} \right]} \quad (11)$$

322 In Eq. (11), all variables except $T_{target, n+1}$ are of the current time step, n . As
 323 Eqs. (3)(7),(11) indicate, $NVCE_{ts}=0$ when no cooling power is available from
 324 natural ventilation ($q_{avail}=0$), and $NVCE_{ts}=1$ when no supplemental cooling is
 325 needed ($q_{\dot{c}}=0$). If NVCE is between 0 and 1, it is the fractional cooling capacity
 326 that natural ventilation can provide compared to the cooling capacity required
 327 to meet the target indoor temperature.

328 3.3. *Proposed metric: Climate potential utilization ratio*
 329 *(CPUR)*

330 While NVCE indicates the status quo of the current design in terms of natural
 331 ventilation's cooling performance, Climate Potential Utilization Rate (CPUR) is
 332 introduced to quantify how much room for improvement is left under the given
 333 climate. A CPUR is simply the ratio of NVCE to CPNV as described in Eq.(12). To
 334 use the metrics correctly, the duration, time step, and thermal criteria of NVCE

335 and CPUR must be the same.

$$CPUR \equiv NVCE / CPNV \quad (12)$$

336

337 3.4. *Understanding NVCE and CPUR together*

338 The metrics dynamically respond to building design and climate conditions as
339 explained in Table 2. The combination of the two metrics of NVCE and CPUR
340 can then provide useful information in interactive design and energy modeling.

341 Error: Reference source not found illustrates the conceptual workflow as to how
342 the metrics may be used during an early design phase. For example, architects
343 set a goal to achieve NVCE of 1 to replace mechanical cooling with natural
344 ventilation entirely. While evaluating the site, they notice that the given
345 climate has CPNV of 0.8. An initial design option may turn out to have an NVCE
346 of 0.4, which architects know it is only the half of what the climate has to offer,
347 as CPUR is 0.5. Through numerous design iterations, they keep track of NVCE
348 to identify the best design option. A CPUR that is greater than 1 may be
349 achieved by using thermal mass strategically. This is because a properly
350 calculated thermal storage amount may help a room remain at a comfortable
351 level, even when the outdoor air is warmer than the comfort criteria.

352 Figure 2 explains the interpretation of the combination. For example, a low
353 NVCE and a low CPUR indicate that natural ventilation cannot offer as much
354 cooling power as the specific building needs, but there still is room to improve
355 the NVCE since the building has not utilized the climate potential very well. A
356 low NVCE and a high CPUR may not be encouraging, as this combination
357 implies that the building requires significant mechanical cooling despite a high

utilization ratio of its climate resources. Having this information while developing a building design would allow architects to revise their design to better utilize natural ventilation.

Table 2. Dynamic nature of CPNV, NVCE, and CPUR.

		CPNV	NVCE		CPUR
			q_{avail}	q_{req}	
Site	Influenced by local climate	x	x	x	x
	Influenced by intake airflow (window sizes, single-sided ventilation, cross-ventilation, displacement ventilation, etc.)		x	x	x
	Influenced by heat gain and loss (Building materials, internal and solar heat gains, etc.)			x	x
	Influenced by thermal mass			x	x

Figure 1. Conceptual diagram of the usage of CPNV, NVCE, and CPUR.

Figure 2. Understanding NVCE and CPUR together.

4. Interactive modeling in a design process using NVCE and CPUR

4.1. Feasibility study description

A feasibility study was conducted to demonstrate a way to harness the dynamic metrics within an interactive design framework, and to understand building design options that influence the NVCE in various climates. Three cities were examined: Phoenix, AZ; Fresno, CA; and Denver, CO. The cities are located in the 2B, 3B, and 5B climate regions, respectively, per [58]. The study used a set of 3D parametric design platforms including Rhino 3D [59], a computer-aided design application, and Grasshopper [60], a visual programming language, to allow an interactive design procedure. Two Grasshopper plug-ins, Ladybug [61] and Honeybee [62], were used to import weather data and run building energy simulations using EnergyPlus within the Grasshopper environment.

4.2. A base case model description and variations to consider

The base case building (Figure 3 (A)) was the prototypical single-family detached house model developed by the Pacific Northwest National Laboratory

384 (PNNL) [63]. Originally intended for the U.S. Department of Energy's Building
385 Energy Codes Program, the residential prototype building models for various
386 climate regions have been widely used in simulation research by either using
387 the building properties only and/or using building geometries [64–71]. We
388 downloaded EnergyPlus Input Files (IDF) for the three climate zones (2B, 3B,
389 and 5B) from [63]. These files included building properties in compliance with
390 the 2018 International Energy Conservation Code (IECC). The settings applied
391 in this study are detailed in Appendix B.

392 For natural ventilation, this test used the
393 ZoneVentilation:WindandStackOpenArea class of EnergyPlus made available
394 through Honeybee. This model automatically decided a ventilation mode
395 between buoyancy-driven or wind-driven ventilation modes, depending on
396 window's height and angle towards the wind direction. All windows created in
397 this test were at the same heights, therefore, no stack effect was considered.
398 Users may choose other ventilation models offered in Honeybee, including a
399 custom ventilation type for chimneys or cowls, and a fan-driven ventilation with
400 a fixed airflow rate. Integration into the proposed workflow of models not yet
401 supported by Honeybee, including the airflow network model of EnergyPlus or
402 customized analytical models, would require further development.

403 The reference IDF data consisted of only two zones for a three-story house: an
404 attic zone and a living unit zone. Two floors were bundled as a living unit zone,
405 so we separated the floors to represent the ground floor and the second-floor.
406 Thermal zoning and distributions of internal heat gains should be determined
407 by the floor plans of a specific building. However, since this feasibility study
408 focuses on the demonstration of the workflow, we used the traditional core-
409 perimeter zoning method of EnergyPlus. Since the room is not as large as other

reference commercial buildings and a core zone would not have any natural ventilation, only perimeter thermal zones were created with a zone depth of 4.55 [m], which is a reasonable size for perimeter zones [72].

Figure 3. (A) A simulation model for a single-family detached house developed by the Pacific Northwest National Laboratory (PNNL) for U.S. Department of Energy's Building Energy Codes Program; and (B) Thermal zoning of the second-floor. The whole building was simulated, from which the second-floor (highlighted in (a)) was analyzed.

Based on the base case, various design options listed in Table 3 were explored to reveal their impacts on natural ventilation metrics under different climates, and thus demonstrating how these metrics help make design decisions. Two simulation periods, one from January to December and the other from May to October, were chosen to represent seasonal impacts.

Table 3. Model set-ups for Study.

Design factors	Variables
(1) Climates	Fresno, CA Phoenix, AZ Denver, CO

(2) Simulation period	Annual (Jan-Dec) Seasonal (May-Oct)
(3) Operable window area	5 %, 25 %, 50 %, and 75 % airflow rates of base case
(4) Shading devices, glazing sizes, occupancy, light fixture efficiency, appliances, etc.	5 %, 25 %, 50 %, and 75 % solar and internal heat gains of base case
(5) Thermal mass	5 %, 25 %, 50 %, and 75 % thermal capacity of base case

425

426 After obtaining NVCE of each city for a base-case building, other variables
427 including airflow rates, solar and internal heat gains (hereinafter heat gains),
428 and thermal capacities were tested with reduced values to represent different
429 design options. For example, the reduced airflow rates may represent reduced
430 opening areas, and the reduced heat gains may represent enhanced shading
431 strategy or reduced occupant density. With a combination of variations in Table
432 3 (3)-(5), 125 cases for each city were examined by post-processing the
433 simulation results in Python codes, which led to 375 cases for each simulation
434 period. The target temperature, T_{target} , for CPNV and NVCE calculations was set
435 monthly according to the adaptive model proposed by [73]. Humidity is not of a
436 major concern in the chosen cities, and was not considered in the criteria.

437 4.3. *Simulation work flow*

438 The non-design metric, CPNV, was calculated based on thermal criteria (target
439 temperatures only in this case) and weather data imported through Ladybug.
440 Honeybee translated the 3D Rhino geometry into a thermal zone for energy
441 simulation, and read climate information via Ladybug. Then the energy
442 simulation results including zone air temperature, total heat gains, and airflow

443 rates were plugged to a customized component written in Python. The Python
 444 component extracted the total heat gains (q_{gain}) by summing up solar gain, and
 445 internal heat gains from lighting, equipment and occupancy. The airflow rates
 446 caused by infiltration and natural ventilation were summed to calculate the
 447 total airflow rates ($\dot{V}_{avail}$). This component used Eqs. (3)-(4, (10(11) to calculate
 448 NVCE and CPUR. Figure 4 describes the work flow.

Figure 4. Parametric design frameworks.

5. Results and discussion

5.1. *Climate Potential of natural ventilation (CPNV)*

The climate potential of natural ventilation (CPNV) of each city was calculated

using weather data, analysis period, and target temperatures, and is shown in Table 4. Unlike the original CPNV calculation [19], this study only considered outdoor dry bulb temperature in order to be consistent with NVCE’s criteria.

Table 4. CPNV of three cities

City	Annual: Jan - Dec CPNV	Seasonal: May-Oct CPNV
Phoenix, AZ	0.66	0.41
Fresno, CA	0.83	0.68
Denver, CO	0.94	0.88

5.2. *Natural Ventilation Cooling Effectiveness (NVCE)*

5.2.1. NVCE of base cases

Having followed the workflow (**Figure 4**) and applied building conditions (Appendix B, Table B1), the base-case tests of three cities yielded NVCEs and CPURs as listed in Table 5. As there were four zones on the second-floor, the numbers presented in this section are the average values of the floor. The results show that the cooling potentials of sites (CPNV) and buildings (NVCE) may disagree although the difference between these values can be small. In fact, the reason why CPURs of these cases were very close to 1 was due to the optimistic design assumptions including widely-open windows and high thermal storage.

Table 5. NVCE and CPUR of base cases.

City	Annual: Jan - Dec Base case NVCE (CPUR)	Seasonal: May-Oct Base case NVCE (CPUR)
Phoenix, AZ	0.63 (0.95)	0.36 (0.88)
Fresno, CA	0.81 (0.98)	0.65 (0.96)
Denver, CO	0.93 (0.99)	0.86 (0.98)

5.2.2. NVCEs of various design options

Different sets of design decisions led to wide ranges of consequences in NVCE as shown in Table 6. In Phoenix, the least airflow (5% of base case) with the highest heat gains (100% of base case) and thermal mass (100 % of base case) led to the minimum NVCE, while the most airflow with the lowest heat gains led to the maximum NVCE with little to no impact from thermal mass. In Fresno, the minimum NVCE was observed with the least airflow and the highest heat gains, regardless of thermal mass. The maximum NVCE of Fresno was achieved by the lowest airflow rate and the heat gains with the highest thermal mass. Lastly, in Denver, the least airflow and thermal mass with the highest heat gains resulted in the lowest NVCE; while the lowest airflow rate and heat gains with the highest thermal mass offered the maximum NVCE.

Table 6. Minimum and maximum NVCE and CPUR of various design options.

	Annual: Jan – Dec		Seasonal: May-Oct	
City	Minimum NVCE (CPUR)	Maximum NVCE (CPUR)	Minimum NVCE (CPUR)	Maximum NVCE (CPUR)
Phoenix, AZ	0.31 (0.46)	0.68 (1.04)	0.04 (0.09)	0.43 (1.04)
Fresno, CA	0.44 (0.53)	0.90 (1.08)	0.09 (0.13)	0.79 (1.17)
Denver, CO	0.68 (0.73)	0.99 (1.06)	0.43 (0.49)	0.99 (1.13)

The correlation between the tested variables and NVCE varied, too, suggesting that natural ventilation cannot be evaluated by a single factor, i.e., airflow. Below we describe how this metric helped identify better design options among various alternatives in detail. Figures 5-7 present the results of the test cities.

489 Each plot presents 125 test results with variations listed in Table 3 (3)-(5), in
490 which results with extreme settings are highlighted.

491 5.2.2.1. Airflow rate

492 Airflow rate impacted NVCE in most cases as shown in Figures 5-7 (A).
493 Generally, higher airflow rates yielded higher NVCE. For Fresno and Phoenix,
494 securing a certain level of airflow was critical when heat gains were at base-
495 case, high values (Figures 5-6 (A) red and orange lines). In all test cities, airflow
496 did not significantly impact NVCE when both heat gains and thermal heat
497 capacity were reduced to 5% of the base case (Figures 5-7 (A) blue dashed
498 lines). This indicates that if a building is equipped with highly effective shading
499 devices, highly efficient light fixtures, and light thermal mass, sizing airflow
500 openings may not be an important decision to make.

501 On the other hand, some cases showed that higher airflow rates could have an
502 adverse effect on NVCE. For example, in Fresno and Denver, the maximum
503 NVCE was observed with the least airflow given low heat gains and base-case
504 thermal mass as shown in Figures 6-7 (A), green dashed lines. This means that
505 the indoor air can stay cooler than the outdoors and having more airflow from
506 outside can diminish the effect of the thermal delay and reduce NVCE.

507 5.2.2.2. Solar and internal heat gains

508 In some cases, controlling heat gains was found to be the most significant
509 factor in NVCE, and the impact range of reducing heat gains was at maximum
510 with low airflow rates and base-case mass (Figures 5-7 (B), green dashed
511 lines). In other cases, the impact was minimal when the base case, high airflow
512 was provided (Figures 5-7 (B), red and orange lines). Unlike airflow rates or

thermal mass, the impact of heat gains on NVCE was consistent: the higher the heat gains, the lower the NVCE in all tests. In design practice, this would mean that strategic building orientation, shading design, low occupancy rates, or highly reflective building envelopes would help enhance the cooling effect from natural ventilation.

5.2.2.3. Thermal mass

The influence of thermal mass on NVCE depended strongly on other settings, including climate, airflow rate, and heat gains. While most cases in Phoenix showed negative responses to the increased mass, most cases in Denver showed otherwise, as shown in Figures 5 (C) and 7 (C). Furthermore, the blue and green dashed lines of Figure 6 (C) reveal that NVCE may correlate positively or negatively with thermal mass even under the same climate. The results support many researchers' findings that thermal mass should be chosen after a close examination of other building and climate conditions to avoid overly warm situations [59–61]. The cases which showed negative correlations of NVCE with thermal storage, as mostly found in Phoenix (Figure 5 (C)), indicate that the building would require more cooling power with an increased mass when mechanical cooling is used in addition to natural ventilation.

However, it should not lead to a misunderstanding that thermal mass would not be beneficial in such climates. For example, if the building in Phoenix relied solely on natural ventilation and the goal was to mitigate the peak temperature during a hot day, one should look at the temperature profile in addition to NVCE to make the right decision. As shown in the temperature graphs of Phoenix (**Figure 8**), heavy mass could be a better option, if avoiding heat exhaustion due to high indoor temperature was more important than having

greater number of hours that met the target temperature.

Figure 8. Indoor air temperature graphs with heavy and light mass in Phoenix, AZ, June 20-June 27.

5.3. *Climate Potential Utilization Ratio (CPUR)*

During the iterations of test cases, CPUR provided a sense of scale as to how far the case is from what was expected from the climate condition. For example, when the case in Phoenix had 95% airflow rate reduction with high heat gains and high heat capacity (Figure 5 (A), red line), its seasonal NVCE was merely 0.04 and CPUR was 0.09. Without looking at other case results for comparison, a CPUR of 0.09 indicated that there was still a chance to improve NVCE if a different option was selected.

In a steady state, in which no mass is considered, CPUR is always less than or equal to 1, as indoor temperatures would be always higher than the outdoors as long as internal heat gains exist. However, results from this study showed that a CPUR that is greater than 1 ($NVCE > CPNV$) would be possible through choosing the right thermal capacity, thanks to the thermal lag it carries. Error: Reference source not found

555 5.4. *Limitation and future work*

556 As the name of the metric indicates, NVCE focused on the cooling effect only. A
557 future step would be to consider the quality of the intake air, including
558 humidity and air pollution, within an NVCE evaluation, as many researchers
559 have addressed the importance of these factors [16,77–81]. Doing so would
560 allow the use of various comfort criteria, such as Standard Effective
561 Temperature (SET) and Heat Index (HI), in addition to dry bulb temperature.

562 Although the test cases used fixed building configurations, the results implied
563 that operation strategies would also significantly influence the parameters of
564 NVCE. One may bring up questions, such as “what time of a day will a smaller
565 opening area benefit?” or “how do we incorporate this analysis when the space
566 is not occupied, thus allowing overwarming during unoccupied times of a day?”
567 Therefore, further studies should investigate how various building dynamics,
568 including dynamic shading design, window operations, and occupancy, would
569 determine NVCE.

570 In the workflow of a feasibility case study, the calculation of the metrics was
571 linked with EnergyPlus via custom programming, as solar and internal heat
572 gains and airflow needed to be retrieved from energy simulations. In the
573 EnergyPlus model, we applied building settings as close as possible to the
574 assumptions of the NVCE equations discussed in Section 3.2, which limited the
575 choice in test buildings and settings. To apply this approach in a more complex
576 building, it would be desirable to incorporate the NVCE equations within
577 EnergyPlus. This would reduce calculation errors as the equations can use the
578 uninterpreted, native EnergyPlus values. The incorporation of NVCE into
579 EnergyPlus would also make the NVCE analysis accessible to users who do not

580 code.

581 **6. Conclusion**

582 A complex set of conditions in buildings, variations in occupancy, and weather
583 conditions should be considered to evaluate the cooling capacity from natural
584 ventilation, in addition to asking a simple question—"is there airflow?" This is
585 why the "availability" of natural ventilation for a given building cannot solely
586 represent its "effectiveness" in cooling the space. This study reviewed
587 evaluation metrics used for natural ventilation in buildings, selected useful
588 metrics for design procedures, and revised them to further include the
589 transient behavior of thermal mass in the evaluation of natural ventilation's
590 performance. The three key performance indices identified in this paper were
591 climate potential of natural ventilation (CPNV), natural ventilation cooling
592 effectiveness (NVCE), and climate potential utilization ratio (CPUR). The study
593 further demonstrated the applicability of such metrics within a design
594 procedure as follows:

- 595 • During a site evaluation and schematic design phase, CPNV informs
596 general ideas as to how much cooling potential the site can expect from
597 natural ventilation.
- 598 • During a design development phase, in which various design options and
599 specifications of a building are tested, NVCE provides the key
600 information about cooling effectiveness of a given design solution. A
601 supplementary metric, CPUR, explains how the building performs
602 compared to the expected CPNV.

603 The main advantage of having these metrics is the interactive feedback they
604 offer during numerous design iterations. In the feasibility study, we

parameterized important building components in the 3D modeling environment, including thermal capacity, overall heat transfer coefficients, internal heat gains, climate conditions, and comfort criteria. We then linked the building parameters with NVCE calculation, such that NVCE and CPUR were calculated each time the 3D model or a criterion was changed.

The wide ranges of NVCE shown by the feasibility tests support the hypothesis that the relationship among various design parameters should be dynamically understood in order to evaluate the performance of natural ventilation, since “the more the airflow, the better,” or “the heavier the thermal mass, the better” are not always true. The newly proposed metrics, NVCE and CPUR, offer clearer perspectives on how the chosen settings influence natural ventilation’s performance. The equations can be easily incorporated into a spreadsheet and computer scripts for a simple case, and can be used in combination with energy simulations and additional scripting for more comprehensive studies.

Author contributions

Nari Yoon: Conceptualization, Methodology, Software, Formal analysis, Investigation. Writing – original draft, Writing – Review & Editing, Visualization, Funding acquisition. **Leslie Norford:** Methodology, Investigation, Writing – Review & Editing, Supervision. **Ali Malkawi:** Resources, Writing – Review & Editing, Supervision. **Holly Samuelson:** Writing – Review & Editing, Supervision. **Mary Ann Piette:** Writing – Review & Editing, Supervision.

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894

Figure 5. Results of Phoenix, AZ ($\dot{V}$, airflow rate; q_{gain} , internal heat gains; C , thermal storage).

Figure 6. Results of Fresno, CA ($\dot{V}$, airflow rate; q_{gain} , internal heat gains; C , thermal storage).

Figure 7. Results of Denver, CO ($\dot{V}$, airflow rate; q_{gain} , internal heat gains; C , thermal storage).

896 Appendix A. Detailed steps through Eqs. (4-8)

897 In a steady state, the total heat gains and losses is equal to zero as in Eq. (A.1):

$$0 \quad \dot{q}_{solar} + \dot{q}_{\dot{i}} + q_{wall} + q_{inf+vent} \dot{i} \quad (A.1)$$

898 where q_{solar} is solar heat gain, $q_{\dot{i}\dot{i}}$ is internal heat gains from occupancy,

899 lighting, appliances, etc., q_{wall} is heat loss through the overall wall (including

900 opaque and glazing materials), and $q_{inf+vent}$ is heat loss through infiltration and

901 ventilation. Defining $q_{gain} = \dot{q}_{solar} + \dot{q}_{\dot{i}\dot{i}}$, we get Eqs. (A.2) and (4):

$$0 \quad \dot{q}_{gain} + UA(T_{out} - T_{\dot{i}}) + \rho c \dot{V}_{avail}(T_{out} - T_{\dot{i}}) \quad (A.2)$$

$$T_{\dot{i}} \quad \dot{i} \frac{q_{gain}}{UA + \rho c \dot{V}_{avail}} + T_{out} \quad (4)$$

902

903 Starting from Eq. (5) in the main text, Eq. (7) was derived as in Eqs. (5), (A.3),

904 (6), and (A.4):

$$T_{target} \quad \dot{i} \frac{q_{gain} + q_{\dot{i}}}{UA + \rho c \dot{V}_{avail}} + T_{out} \quad (5)$$

$$q_{\dot{i}} \quad \dot{i} (T_{target} - T_{out})(UA + \rho c \dot{V}_{avail}) - q_{gain} \quad (A.3)$$

$$q_{req} \quad \equiv q_{avail} + q_{\dot{i}} \quad (6)$$

$$\dot{i} - \rho c \dot{V}_{avail}(T_{target} - T_{out}) + (T_{target} - T_{out})(UA + \rho c \dot{V}_{avail}) - q_{gain} \\ \dot{i} - \{q_{gain} - UA(T_{target} - T_{out})\} \quad (A.4)$$

$$NVCE_{ts} \quad \dot{i} \frac{q_{avail}}{q_{avail} + q_{\dot{i}}} = \frac{-\rho c \dot{V}_{avail}(T_{target} - T_{out})}{- \{q_{gain} - UA(T_{target} - T_{out})\}} \quad (7)$$

905

906 If we assume that the supplementary cooling power, $q_{\dot{i}}$, comes from natural

907 ventilation,

$$q_i = \dot{V}_i - \rho c \dot{V}_i (T_i - T_{out}), \quad (A.5)$$

908 where $\dot{V}_i$ is the supplementary airflow rate from natural ventilation. Eqs. (6)

909 and (7) can be expressed as Eqs. (A.6) and (A.7):

$$q_{req} \equiv q_{avail} + q_i \quad (6)$$

$$\dot{V}_i - \rho c \dot{V}_{avail} (T_{target} - T_{out}) - \rho c \dot{V}_i (T_{target} - T_{out}) = \dot{V}_i - \rho c (\dot{V}_{avail} + \dot{V}_i) (T_{target} - T_{out}) \quad (A.6)$$

$$NVCE_{ts} = \frac{\dot{V}_i \frac{q_{avail}}{q_{avail} + q_i} - \rho c \dot{V}_{avail} (T_{target} - T_{out})}{\dot{V}_i - \rho c (\dot{V}_{avail} + \dot{V}_i) (T_{target} - T_{out})} \frac{\dot{V}_{avail}}{\dot{V}_{req}}, \quad (A.7)$$

910 where $\dot{V}_{avail}$ is the available airflow rate from natural ventilation, and $\dot{V}_{req}$ is the

911 ideal airflow rate $(\dot{V}_{avail} + \dot{V}_i)$ required from natural ventilation. Airflow rate is

912 used to define air changes per hour (ACH) as:

$$913 \quad ACH = \frac{3600 [s] \dot{V}}{vol},$$

914 where vol is the volume of the room. Therefore, Eq. (A.7) leads to Eq. (8):

$$NVCE_{ts} = \frac{q_{avail}}{q_{req}} = \frac{\dot{V}_{avail}}{\dot{V}_{req}} = \frac{ACH_{avail}}{ACH_{req}}, \quad (13)$$

915 where ACH_{avail} is the available ACH from natural ventilation, and ACH_{req} is the

916 required ACH.

917

918 Appendix B. Detailed settings used in the feasibility test

919 **Table B1.** Base case model settings for three cities.

		Phoenix, AZ (IECC Climate Region 2B)		Fresno, CA (IECC Climate Region 3B)		Denver, CO (IECC Climate Region 5B)	
		SI units ^c	IP units ^d	SI units	IP units	SI units	IP units
Fenestration	U-Factor ^a	2.271	0.400	1.817	0.320	1.703	0.300
Glazed fenestration	SHGC ^a	0.250	0.250	0.250	0.250	Not Required	Not Required
Ceiling	R-Value ^a	6.697	38	6.697	38	8.635	49
	Equivalent U-Factor ^b	0.170	0.030	0.170	0.030	0.148	0.026
Wood frame wall	R-Value	2.291	13	3.525	20	3.525	20
	Equivalent U-Factor	0.477	0.084	0.341	0.060	0.341	0.060
Floor	R-Value ^a	2.291	13	3.348	19	5.287	30
	Equivalent U-Factor ^b	0.363	0.064	0.267	0.047	0.187	0.033
Slab	R-Value ^a	0	0	0	0	1.762	10
	Depth ^a	-	-	-	-	0.610	2.000
Glazing area		4.13 [m ²] each					
Opening area		1.24 [m ²] each					
Thermal storage per area		25,200 [J/K- m ²] (Second-floor only)					
Equipment load per area		5 [W/m ²]					
Lighting power density		7 [W/m ²]					
Number of people per area		0.02 [ppl/m ²]					

920 ^a Value reference: IECC [82] Table R402.1.2, *Insulation and Fenestration*
 921 *Requirements by Component.*

922 ^b Value reference: IECC [82] Table R402.1.4, *Equivalent U-Factors.*

923 ^c SI units used are [W/(m²·K)] for U-Factor, [m²·K /W] for R-Value, [m] for depth.
 924 The values were converted from the IECC tables, which were originally

925 provided in the IP units.
926 ^d IP units used are [Btu/(h·ft²·°F)] for U-Factor, [°F·ft²-h/Btu] for R-Value, [ft] for
927 depth.