IEA EBC Annex 80 - Dynamic simulation guideline for the performance testing of resilient cooling strategies: Version 2

Zhang, Chen; Kazanci, Ongun Berk; Attia, Shady; Levinson, Ronnen; Lee, Sang Hoon; Holzer, Peter; Rahif, Ramin; Salvati, Agnese; Machard, Anaïs; Pourabdollahtootkaboni, Mamak ; Gaur, Abhishek ; Olesen, Bjarne; Heiselberg, Per

Publication date:
2023

Document Version
Publisher's PDF, also known as Version of record

BUILD DEPARTMENT OF THE BUILT ENVIRONMENT

AALBORG UNIVERSITY

IEA EBC Annex 80 - Dynamic simulation guideline for the performance testing of resilient cooling strategies - Version 2

Chen Zhang
Ongun Berk Kazanci
Shady Attia
Ronnen Levinson
Sang Hoon Lee
Peter Holzer
Ramin Rahif
Agnese Salvati
Anaïs Machard
Mamak Pourabdollahtootkaboni
Abhishek Gauri
Bjarne W. Olesen
Per Kvols Heiselberg

ISSN 1901-726X
DCE Technical Report No. 306

Aalborg University
Department of the Built Environment
Division of Sustainability, Energy and Indoor Environment

DCE Technical Report No. 306

IEA EBC Annex 80 - Dynamic simulation guideline for the performance testing of resilient cooling strategies
Version 2

by

Chen Zhang
Ongun Berk Kazanci
Shady Attia
Ronnen Levinson
Sang Hoon Lee
Peter Holzer
Ramin Rahif
Agnese Salvati
Anaïs Machard
Mamak Pourabdollahtootkaboni
Abhishek Gauri
Bjarne W. Olesen

Feb 2023

Published 2023 by
Aalborg University
Department of the Built Environment
Thomas Manns Vej 23
DK-9220 Aalborg E, Denmark

Printed in Aalborg at Aalborg University

ISSN 1901-726X
DCE Technical Report No. 306

List of authors

Chen Zhang[a], Ongun Berk Kazanci[b], Shady Attia[c], Ronnen Levinson[d], Sang Hoon Lee[d], Peter Holzer[e], Ramin Rahif[c], Agnese Salvati[f], Anaïs Machard[g], Mamak Pourabdollahtootkaboni[h], Abhishek Gaur[i], Bjarne W. Olesen[b], Per Kvols Heiselberg[a]

a. Department of the Built Environment, Aalborg University, Denmark
b. International Centre for Indoor Environment and Energy - ICIEE, Department of Civil Engineering, Technical University of Denmark, Denmark
c. Sustainable Building Design Lab, Dept. UEE, Faculty of Applied Sciences, Université de Liège, Belgium
d. Building Technology and Urban Systems Division, Lawrence Berkeley National Laboratory, USA
e. Institute of Building Research & Innovation, Austria
f. Institute for Energy Futures, Brunel University London, UK
g. Laboratoire des Sciences de l'Ingénieur pour l'Environnement – LaSIE, La Rochelle, France
h. Department of Energy, Politecnico di Torino, Italy
i. National Research Council Canada, Canada

Acknowledgments

The material presented in this publication has been developed within IEA EBC Annex 80 - Resilient Cooling of Buildings. We thank all our colleagues from Annex 80 who provided insights and expertise that greatly assisted in developing the simulation guideline.

Contents

1. Introduction

The objective of Annex 80 is to develop, assess and communicate solutions for resilient cooling. The systematic assessment of resilient cooling strategies is one of the main activities of Annex 80. As stated in Annex Text:

> ***Activity B.1*** *includes a systematic assessment of potential benefits, limitations and performance indicators of resilient cooling systems under a wide range of application scenarios and other boundary conditions. We generate Resilient Cooling 'Technology Profiles' to clearly summarize and promote the operational characteristics and benefits of each technology/system. Recommendations for good implementation, commissioning and operation are being developed. Barriers to application and further research opportunities are being identified, which will inform the research activities of Subtask B.*

The previous approach for assessing the resilience of cooling strategies is mainly based on qualitative comparison and based on results from individual research, which lacks common boundary conditions and universal indicators for resilience evaluation.

This study aims to provide a consistent approach for assessing the resilience of different cooling strategies by dynamic simulation. Various cooling strategies will be tested on the reference buildings under present and future weather conditions in different climate zones, and proposed key performance indicators will be applied to evaluate summertime overheating risk and climate resistance of cooling strategies.

2. Methodology

The methodology of the dynamic simulation activity is modified based on the framework developed by Annex 80 Thermal Condition Task Force (Attia et al., 2021). The workflow to evaluate the resilience of different cooling technologies is illustrated in Figure 1. Detailed instructions for each step are explained in the following sections.

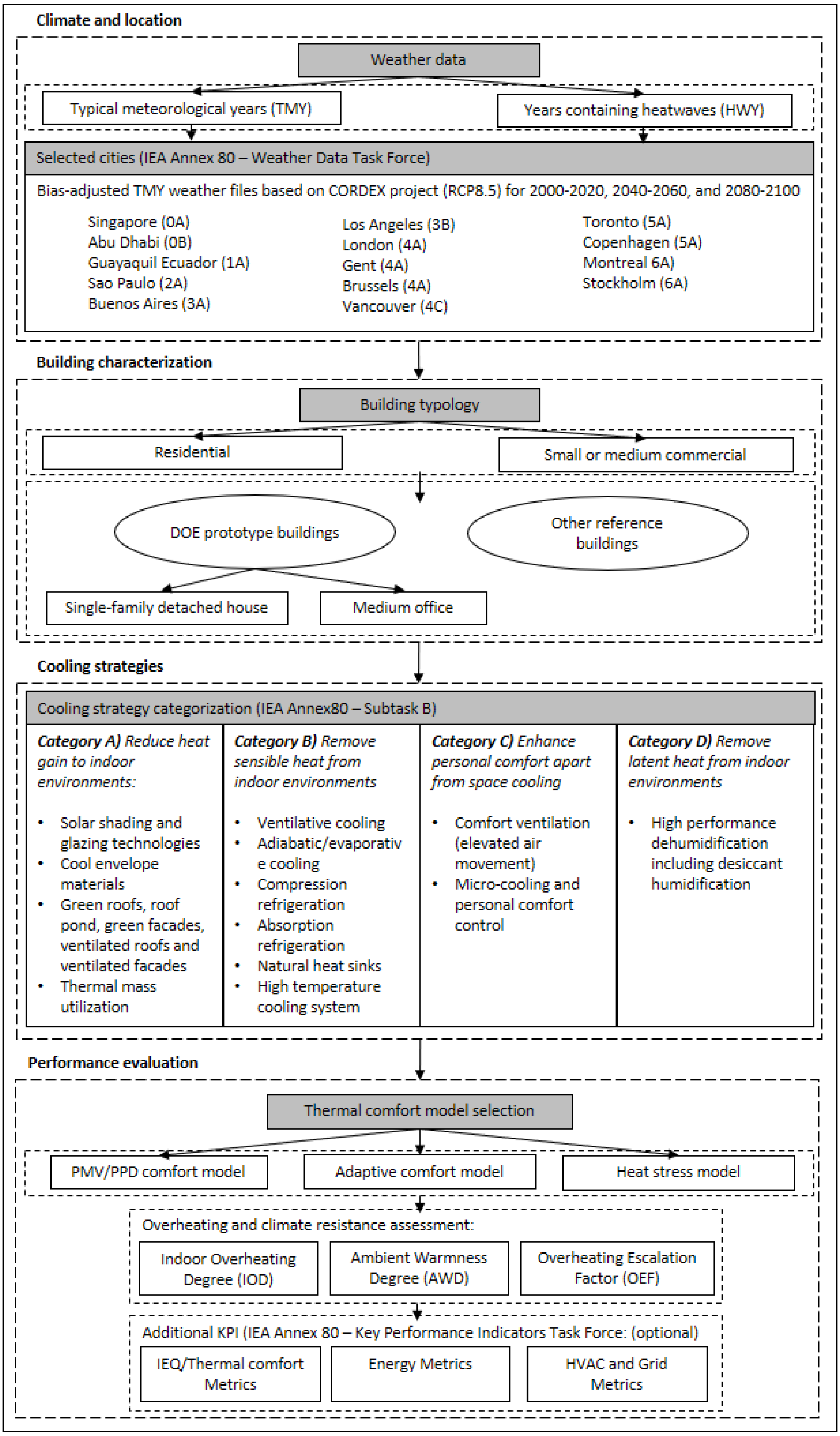


Figure 1. Framework for evaluating the resilience of different cooling technologies, modified based on the framework developed by Annex 80 Thermal Condition Task Force (Attia et al., 2021)

3. Climate and location

3.1 Weather files generation methodology for selected cities

The performance of cooling strategies is evaluated under different climate zones. The climate zones are classified based on the ASHRAE definition (ASHRAE, 2013), as shown in Figure 2. The representative cities for each climate zone are selected based on the population and growth of the cities, their distribution in different continents, and the preference of the Annex 80 participants.

Two types of weather files were generated for the purpose of Annex 80: typical meteorological years and years containing extreme heatwaves. The climate zones and cities for which these files are produced are listed in Table 1.

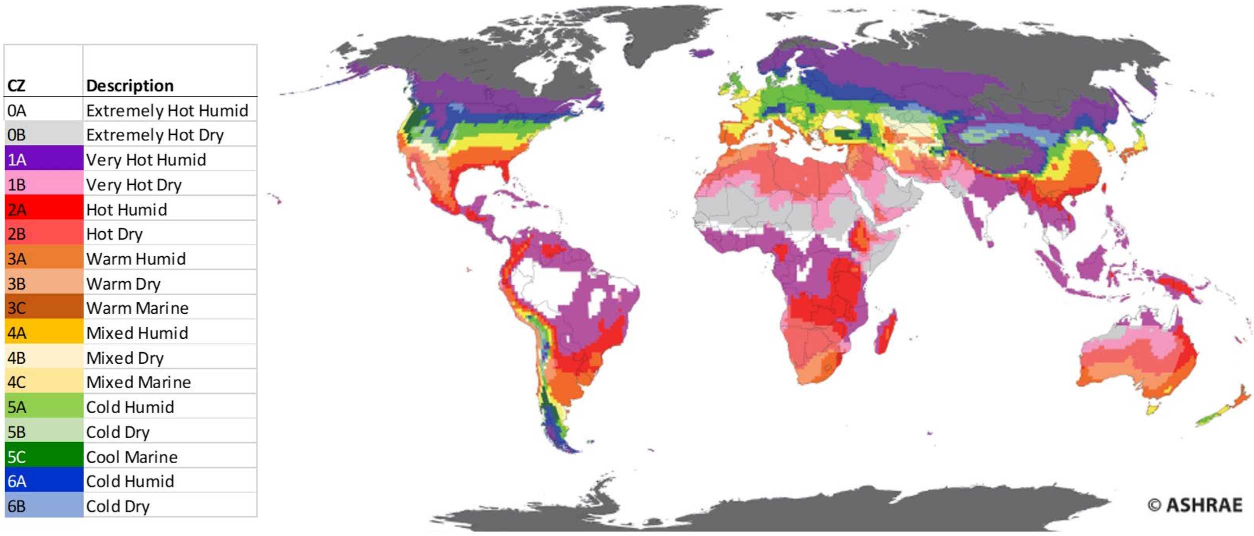


Figure 2. World climate zones map based on ASHRAE Standard 169-2013 (ASHRAE, 2013)

The weather files were generated by the Annex 80 Weather data task force. The methodology was shared during a workshop organized by the Weather data task force leaders (Machard, P.tootkaboni, et al., 2020). The methodology is introduced in Figure 3.

It consists of consecutive steps and methods as described in the flow chart in Figure 3. Multi-years climate data (20 years for each period), based on the regional climate model simulation results from the CORDEX and historical multi-years observations were first collected. The database for the climate data is CORDEX, the selected model MPI-REMO and the socio-economic worst-case scenario RCP 8.5 of the 5th IPCC Assessment Report. In the second step, the raw climate model data were corrected by applying the multivariate bias correction method using the observations of the different weather variables for each location (Cannon, 2018). Finally, weather files were assembled from the multi-year bias-adjusted datasets:

- Typical meteorological years (TMYs) based on the EN ISO 15927-4 standard (ISO, 2005)
- Years containing heatwaves (HWYs), based on the method to detect the heatwaves on a CORDEX dataset proposed by (Ouzeau et al. 2016).

Table 1. Representative climate zones, cities and authors of the weather files generated based on the methodology proposed by the Annex 80 Weather data Task Force.

CLIMATE ZONE	City	Country	Continent	Institution	Authors and contacts
0A	Singapore	Singapore	**Asia**	Concordia University	Fuad Baba <fuadbaba_15@hotmail.com>, Hua Ge <hua.ge@concordia.ca>
0B	Abu Dhabi	UAE	**Asia**	Fraunhofer Institute for Building Physics IBP	Afshari, Afshin <afshin.afshari@ibp.fraunhofer.de>
1A	Guayaquil	Ecuador	**South America**	KU Leuven	Hoang Ngoc Dung Ngo <hoangngocdung.ngo@kuleuven.be>
2A	Sao Paulo	Brazil	**South America**	Federal University of Santa Catarina	Marcelo Salles <marcelosooo@gmail.com>
3A	Buenos Aires		**South America**	CIMEC/LabEEE CONICET	Facundo Bre <facubre@cimec.santafe-conicet.gov.ar>;
3A	Rome	Italy	**Europe**	Politecnico di Torino & ENEA	Mamak Pourabdollahtootkaboni <mamak.pourabdollahtootkaboni@polito.it>
3B	Los Angeles	USA	**North America**	LBNL	Xuan Luo <xuanluo@lbl.gov>
4A	London	UK	**Europe**	Brunel University	agnese.salvati@brunel.ac.uk , maria.kolokotroni@brunel.ac.uk
4A	Gent	Belgium	**Europe**	KU Leuven	abantika.sengupta@kuleuven.be
4A	Brussels	Belgium	**Europe**	BBRI	Jade Deltour, BBRI, jade.deltour@bbri.be Xavier Kuborn, BBRI, xavier.kuborn@bbri.be Nicolas Heijmans, BBRI, nicolas.heijmans@bbri.be
4C	Vancouver	Canada	**North America**	NRC & Concordia University	Jiwei Zou <jiwei.zou@mail.concordia.ca> ; abhishek.gaur <abhishek.gaur@nrc-cnrc.gc.ca>; Liangzhu Wang <leon.wang@concordia.ca>
5A	Toronto	Canada	**North America**	NRC & Concordia University	Jiwei Zou <jiwei.zou@mail.concordia.ca> ; abhishek.gaur <abhishek.gaur@nrc-cnrc.gc.ca>; Liangzhu Wang <leon.wang@concordia.ca>
5A	Copenhagen	Denmark	**Europe**	Aalborg University	Chen Zhang <cz@build.aau.dk>
5A	Vienna	Austria	**Europe**	Institute of Building Research & Innovation	Philipp Stern <philipp.stern@building-research.at>
6A	Montreal	Canada	**North America**	NRC & Concordia University	Jiwei Zou <jiwei.zou@mail.concordia.ca> ; abhishek.gaur <abhishek.gaur@nrc-cnrc.gc.ca>; Liangzhu Wang <leon.wang@concordia.ca>
6A	Stockholm	Sweden	**Europe**	University of Gävle	Sana Sayadi <Sana.Sayadi@hig.se>

***Note**: The weather data files in the following cities are still under revision or development: Rome, Vienna. The validated files will be uploaded soon.*

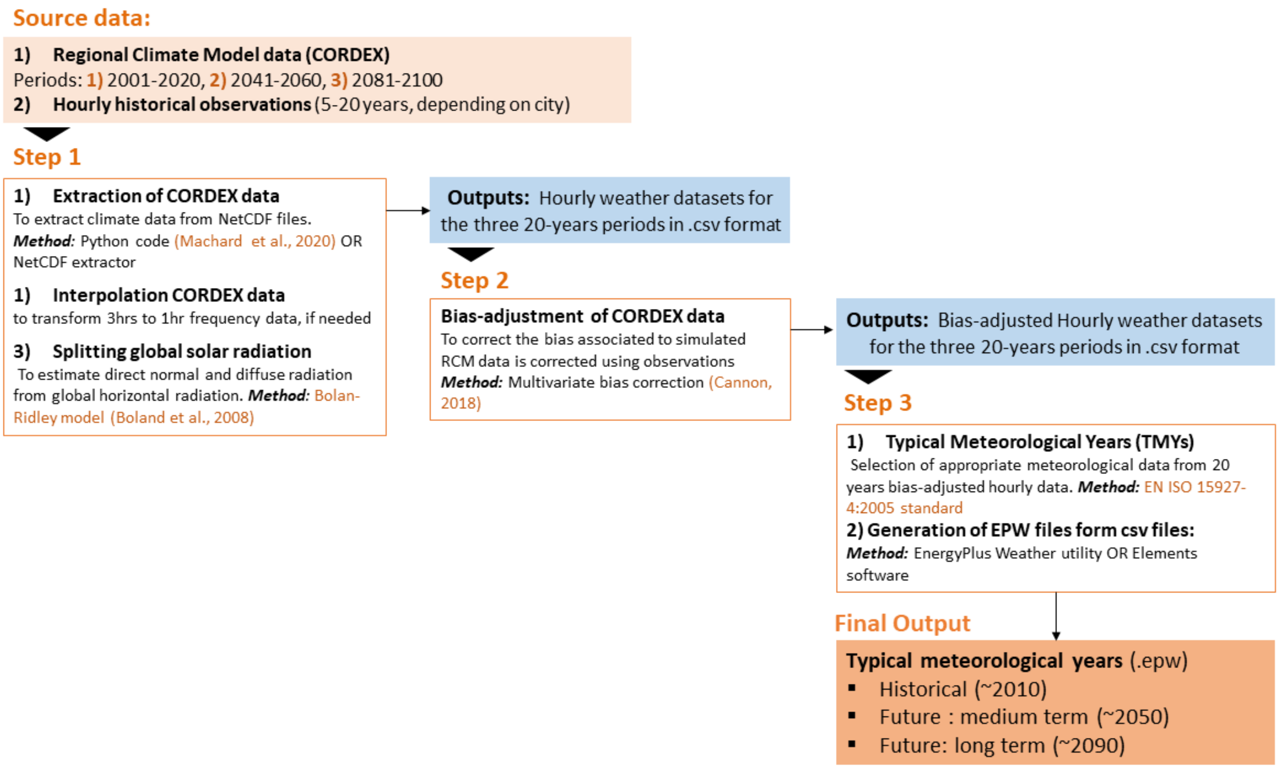


Figure 3. Methodology overview and references for the generation of present and future weather files for building simulations for Annex 80 (Machard, P.tootkaboni, et al., 2020)*(Machard, et al., 2020)*(Ouzeau et al., 2016)*(Boland et al., 2008)*(Cannon, 2018)(ISO, 2005)

For each representative climate zone and city, the weather files (TMYs and HWYs) were developed for three periods:

- Contemporary: 2001-2020 (~2010)
- Medium-term future: 2041-2060 (~2050), RCP 8.5
- Long-term future: 2081-2100 (~ 2090), RCP 8.5

One TMY was developed for each period. Three HWYs (most intense, most severe, and longest) were developed for each period. Only one HWY (the most severe) is required for the analysis, the other two HWYs can be used for further analysis (optional).

The TMY and most severe HWY are available at: http://files.iea-ebc.org

Annex80 > Task Group Weather Data > VALIDATED TMYs and Severe HWYs for SIMULATIONS

3.2 Use of the Typical Meteorological Year files

The TMYs for the cities reported in Table 1 have been checked and validated by the Annex 80 Weather data task force leaders and are ready to be used in dynamic simulations.

At the moment, the weather files need to be tested by the simulation task force. For this reason, the use of the weather data is for now restricted to the simulation activities within Annex 80 only. The Weather data task force leaders are working on a data paper that will be submitted before the end of 2021, once the first set of building simulations has been carried out. Any other activity (i.e. conference/scientific publications) involving the use of these datasets needs to be agreed with the authors of the weather data.

3.3 Use of the heatwave weather files

The HWYs for the cities reported in Table 1 have been checked and validated by the Annex 80 Weather data task force leaders and are ready to be used in dynamic simulations.

Each HWY header contains the heatwave period. Simulations must be carried out one week before and one month after the heatwave to analyze the building thermal behavior after the shock. Note that in some cities, some heatwaves might last up to three months. The same as for the TMYs applies concerning the use of the weather files.

For any issue with the weather files, please contact the weather file author, and in copy the three weather forecast leaders Anaïs Machard, Agnese Salvati and Mamak Pourabdollahtootkaboni.

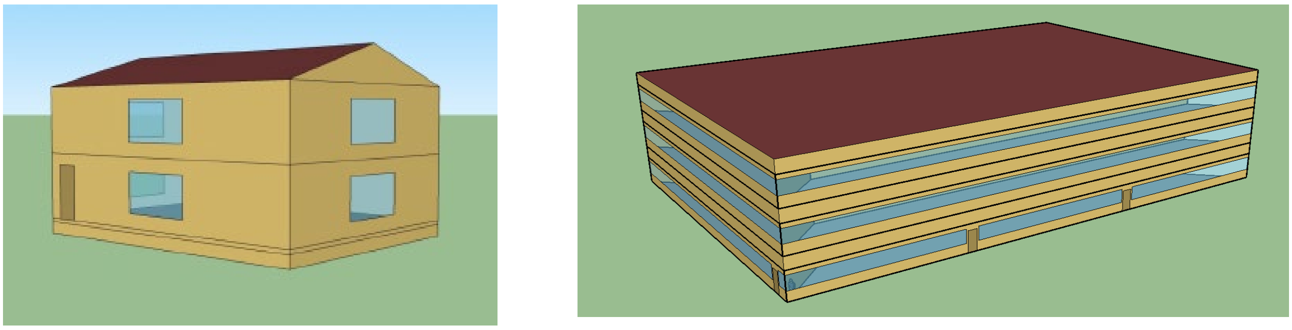
NB: Different KPIs must be used for TMY and HWYs, these are defined in section 9 of this document.

4. Reference building

4.1 DOE prototype buildings

Two building typologies are included in the simulation study: residential building (low-rise) and medium-rise commercial buildings.

The prototype building models developed by the U.S. Department of Energy (DOE) (DOE, 2021) are suggested as reference buildings. The prototype building models include 16 commercial building types and 2 residential types. We selected a **single-family detached house** to represent residential buildings, and a **medium office** to represent commercial buildings, as shown in Figure 4.



(a) (b)

Figure 4. Reference buildings based on DOE prototype building models (a) single-family detached house; (b) medium office

The geometry and characteristics of prototype buildings are listed in Table 2. Both buildings are newly constructed (after 2000), which comply with the current building codes and standards. The envelope characteristics must comply with ASHRAE 90.1 (ASHRAE, 2016a) for commercial buildings and IECC specifications for low-rise residential buildings envelope requirements for each climate zone.

The prototype building models are EnergyPlus models and can be downloaded at the link below:

- Single-family detached house (2018 IECC version): https://www.energycodes.gov/prototype-building-models
- Medium office (90.1-2019 version): https://www.energycodes.gov/prototype-building-models

For detailed descriptions on where to download the prototype building models, which files to download, and which version of EnergyPlus to use please refer to Appendix A.

Table 2. Building geometry and characteristics of prototype building models

Building types	**Single-family house**	**Medium office**
Floors	2	3
Conditioned floor area [m^2]	221	4,982
Footprint [m^2]	110	1,660
Floor-to-ceiling height [m]	2.59	2.74
Window area fraction	15% for all four orientations	33% for all four orientations
Thermal zone	Two thermal zones, each floor is a thermal zone[a]	Each floor has four perimeter zones, one core zone and an attic zone Percentages of floor area: Perimeter 40%, Core 60%
Heating system	Natural gas furnace, heat pump, electric furnace, or oil-fired furnace[b]	Gas furnace inside the packaged air conditioning unit
Cooling system	Central electric air conditioning	Packaged air conditioning unit

a. In the 2018 version, there is only one thermal zone for both the bottom and top floor. Please separate the thermal zones based on the instruction in Appendix A.

b. Please describe clearly which heating system is selected in your model.

The building models should be considered with mechanical cooling and without mechanical cooling (free-running). Thermal comfort model should be selected accordingly, as explained in Section 7.3.1.

4.2 Other reference buildings

The DOE prototype buildings are recommended as reference buildings in this study. However, if participants would like to use other building models (for example, single-zone/multi-zone model, or real building model), please make sure the building envelopes and characteristics are representative of the specific climate zones and specific construction periods.

Please use the same metrics to describe your reference building, as used by DOE prototype building. The example on reference building model specifications could be found: https://www.energycodes.gov/sites/default/files/2019-09/PNNL_Scorecard_Prototypes_Office_Medium.xls

5. Occupancy and schedule

DOE prototypes building models provide occupancy schedule and other basic function input, which are based on ASHRAE 62.1 (ASHRAE, 2016b). If participants use DOE models as reference buildings, we recommend keeping the default settings provided by the DOE.

Alternatively, occupancy and schedules suggested by ISO 17772-1:2017 (ISO, 2017a) and ISO/TR 17772-2:2018 (ISO, 2018a) should be followed. ISO 18523-1: 2016 (ISO, 2016) and ISO 18523-2: 2018 (ISO, 2018b) can be used as a complementary standard.

During a power outage, equipment load will be setup according to building typologies:

- Residential buildings: no equipment load
- Commercial buildings: only the IT-related equipment loads (for example, PC, printers, etc.) are considered.

6. Minimum outdoor ventilation air

For DOE prototype building models, ASHRAE standard 62.1 is used to calculate the minimum outdoor ventilation air. For the other reference building, ISO 17772-1:2017 (ISO, 2017a) and ISO/TR 17772-2:2018 (ISO, 2018a) are used to calculate the minimum outdoor ventilation air.

7. Cooling strategies

Annex 80 has created four cooling-strategy categories based on their approaches to cooling people or the indoor environment.

A. **Reduce heat load to indoor environments and people indoor**
   - Advanced solar shading/advanced glazing technologies
   - Cool envelope materials
   - Green roofs, roof pond, green facades, ventilated roofs, and ventilated facades
   - Thermal mass utilization including, PCM, and off-peak ice storage

B. **Remove sensible heat from indoor environments**
   - Ventilative cooling
   - Adiabatic/evaporative cooling
   - Compression refrigeration
   - Absorption refrigeration, including desiccant cooling
   - Natural heat sinks, such as ground water, borehole heat exchangers, ground labyrinths, earth tubes, and sky radiative cooling
   - High-temperature cooling system: Radiant cooling, chill beam
   - District cooling

C. **Enhance personal comfort apart from space cooling**
   - Comfort ventilation (elevated air movement)
   - Micro-cooling and personal comfort control

D. **Remove latent heat from indoor environments**
   - High performance dehumidification including desiccant humidification

Each cooling strategy can be further classified into several sub-strategies, for example, ventilative cooling can be classified into natural ventilation, mechanical ventilation, and hybrid ventilation, with or without integration with chillers. Participants should specify which exact cooling strategy is applied and if it integrates with other cooling strategies, and provide a detailed description of the cooling system setup and its control strategies. This study mainly focuses on a single cooling strategy, however, some technology might not able to apply alone and it could integrate with other strategies. For example, thermal mass with ventilative cooling, ice storage with compression refrigeration.

To be able to have a relative comparison with conventional cooling strategies, a reference cooling system is defined as an air-conditioning unit. Central electric air conditioning is used in the single-family house, and packaged air conditioning unit is used in the medium commercial building, as default cooling system in DOE mode (see Table 2). Please note that the packaged air conditioning unit used in ASHRAE 90.1-2019 medium office prototype building model might overcool the supply air and reheat it by using an electric heating coil, which results in simultaneous heating and cooling. Detailed description about this issue and suggestions on modifying the HVAC system in the prototype building model please refer to Appendix A.

The air conditioning is auto-sized to design day at present weather condition (participants are welcome to compare the scenarios with sizing for today and sizing for the future, but it is optional). The efficiency of air conditioning needs to fulfill the minimum equipment efficiency for air conditioners and condensing units according to ASHRAE standard 90.1 (ASHRAE, 2016a). It is possible to consider national conventional cooling strategies; however, an air-conditioning system is preferred. When simulating passive cooling technologies, the auto-sizing of the HVAC system will result that the energy saving or thermal comfort improvement are not from pure passive cooling technologies but from the compound effect from the cooling technologies combined with the HVAC system sizing changes. Thus, the HVAC capacities in heating furnaces and cooling coils should be determined in the baseline model, and these fixed capacities should be used throughout the passive cooling technology performance evaluation. Detailed discussion about the auto-size issue please refer to Appendix A.

8. Simulation cases

For each resilient cooling strategy, we will simulate under three time periods (contemporary, medium-term future and long-term future), with different operating conditions and consider the availability of mechanical cooling.

Operating conditions:

- Typical weather conditions: Use TMY files in three periods
- Heatwaves: Use HWY files in three periods (most sever heatwave is the mandatory case, the other two heatwave scenarios are optional; run the simulation 1 week before heat wave, and 1 week after heat wave)
- Heatwaves + power outages: Use HWY files in three periods and assume no electricity from grid during the heatwaves

Regarding mechanical cooling availability, we need to distinguish the resilient cooling strategies into mechanical cooling (refrigerant compressors or absorbers, desiccant dehumidifiers, or other systems that require energy from depletable sources to directly condition an indoor space), for example, absorption refrigeration, compression refrigeration, etc., and natural cooling (passive cooling strategies and strategies use natural cooling resource), for example, green roofs, ventilative cooling (both natural ventilation and mechanical ventilation without chiller), etc.

For natural cooling strategy, four cases will be simulated:

- Free-running building (no mechanical cooling)
- Free-running building with the resilient cooling strategy to be studied (no mechanical cooling) (e.g., with green roof)
- Mechanical cooled building with air conditioning (reference case)
- Mechanical cooled building with air conditioning and with the resilient cooling strategy to be studied (e.g., with green roof)

For mechanical cooling strategy, two cases will be simulated:

- Mechanical cooled building with air conditioning (reference case)
- Mechanical cooled building with the resilient cooling strategy to be studied (e.g., radiant ceiling panels)

9. Performance evaluation

9.1 Thermal comfort model selection

Thermal comfort model should be applied to define thresholds for comfortable indoor temperature. There are two main thermal comfort models based on ISO 17772-1 (ISO, 2017a): adaptive model and PMV-PPD model.

• For buildings with mechanical cooling systems: PMV-PPD model, Category III ($-0.7<PMV<0.7$) based on the ISO 17772-1 Annex H.1 is applied to this study.

• For buildings without mechanical cooling systems: adaptive model, Category III is applied to this study. The allowed indoor operative temperature is calculated as a function of the running mean outdoor temperature based on the ISO 17772-1 Annex H.2.

9.2 Heat stress model selection

During the heatwaves, for free-running buildings and the buildings experiencing a power outage, the occupants will face health risks or even life-threatening consequences. Therefore, the threshold for the indoor environment should be selected by considering the impact on occupants' health. Standard effective temperature (SET) adapted in ASHRAE 55-2017 (ASHRAE, 2017) is recommended to evaluate human response to heat stress in this study. The SET index is defined as the equivalent dry bulb temperature of an isothermal environment at 50% relative humidity in which a subject, while wearing clothing standardized for the activity concerned, would have the same heat stress (skin temperature) and thermoregulatory strain (skin wetness) as in the actual test environment. For the calculation method of SET please refer to ASHRAE 55-2020 Appendix D or CBE Thermal Comfort Tool: https://comfort.cbe.berkeley.edu/.

Use SET threshold of 28 °C for buildings with power but under a heat wave and SET 30 °C for buildings during a power outage and under a heat wave as the baseline and threshold temperatures, respectively, to calculate the unmet hours (Sun et al., 2021)

We suggest using the following:

- For buildings with mechanical cooling systems, thermal comfort thresholds (-0.7<PMV<0.7) are to be used under normal operation (no heatwave, no power outage). Heat stress thresholds are to be used if there is a power outage or heat wave.
- For buildings without mechanical cooling systems, adaptive thermal comfort thresholds are to be used under normal operation or if there is a power outage. Heat stress thresholds are to be used if there is a heat wave or if there is a power outage and heat wave.
- For systems that can provide air movement or increase air velocity (for example, fan or personal systems), the indoor operative temperature correction could apply. The correction value depends on the air speed range of the appliance. For detail see ISO 17772.1 Table H.4.

9.3 Output

The outputs of building simulation include (for the residential building please include all thermal zones and for the office building please include the zone with the highest peak cooling load i.e., the most critical zone):

- Hourly indoor operative temperature [°C]
- Hourly PMV value/SET value (depending on operating conditions)
- Hourly cooling demand (cooling thermal load) per conditioned floor area [kW/m²]
- Hourly heating demand (heating thermal load) per conditioned floor area [kW/m²]
- Hourly cooling site energy use per conditioned floor area (indicate gas, electricity or other energy) [kWh/m²]
- Hourly heating site energy use per conditioned floor area (indicate gas, electricity or other energy) [kWh/m²]
- Hourly HVAC system total primary energy use per conditioned floor area (HVAC = heating, cooling, ventilation, and auxiliary, indicate national or regional primary energy factors) [kWh/m²]

All outputs should be generated for each simulation case, see Section 8.

The outputs enable us to do further analysis on the simulation results, test other key performance indicators (KPI) developed during the Annex 80 working period, and conduct relative comparisons between different cooling strategies.

9.4 Key performance indicators (KPI)

The following KPIs are suggested for cooling technology performance assessment. They are selected from the report developed by Key Performance Indicators Task Group of Annex 80 (Holzer, 2022).

Please note that KPIs are only calculated during the occupied hours. For example, if office buildings have no occupants during the weekend and weekday night-time, those unoccupied hours should not be included in the thermal comfort related KPI calculations. Residential buildings are occupied 7 days 24 hours.

9.4.1 Overheating and climate resistance assessment

As suggested by Annex 80 Thermal Condition Task Force (Attia et al., 2021), the impact of climate change on the overheating risk in buildings with different cooling strategies can be evaluated by the methodology proposed by (Hamdy et al., 2017) (Rahif et al., 2022). The method consists of three indicators: Indoor Overheating Degree (IOD), Ambient Warmness Degree (AWD), and Climate Change Overheating Resistivity (CCOR). The methodology allows a multi-zonal approach considering the intensity and frequency of high indoor operative temperatures.

1. IOD [°C] multi-zonal indicator is the summation of positive values of the difference between zonal indoor operative temperature Tin,o,z and the zonal thermal comfort limit (obtained from Section 9.1 Thermal comfort model selection) T comf,z averaged over the sum of the total number of zonal occupied hours Nocc(z) [-],

$$IOD \equiv \frac{\sum_{z=1}^{Z}\sum_{i=1}^{N_{occ}(z)}\left[\left(T_{fr,i,z} - TL_{comf,i,z}\right)^{+} \cdot t_{i,z}\right]}{\sum_{z=1}^{Z}\sum_{i=1}^{N_{occ}(z)} t_{i,z}} \quad (1)$$

Where *t* is the time step [s], *i* is the occupied hour counter [-], *z* is building zone counter [-], *Z* is the total building zones [-]. Both fixed and adaptive temperature limits can be assumed as comfort thresholds.

2. AWD [°C] metric is used to quantify the severity of outdoor thermal conditions. *AWD* is the summation of the positive difference between the outdoor air temperature T_{out} and a base temperature T_b. The selection of base temperature is context-specific based on the building typology and climate.

$$AWD_{18°C} \equiv \frac{\sum_{i=1}^{N}\left[(T_{out,i} - T_b)^{+} \times t_i\right]}{\sum_{i=1}^{N} t_i} \quad (2)$$

Where *N* is the total number of building occupied hours. Base temperature T_b set at 18 °C in our analysis.

3. The Climate Change Overheating Resistivity (CCOR) metric is introduced to couple the outdoor and indoor environments quantifying the climate change overheating resistivity of cooling strategies in buildings (Rahif et al., 2022). The CCOR shows the rate of change in the IOD with an increasing AWD due to the impact of climate change. It can be calculated using the linear regression methods assuming linearity between the IOD and AWD.

$$\frac{1}{CCOR} = \frac{\sum_{Sc=1}^{Sc=M}\left(IOD_{Sc} - \overline{IOD}\right) \times \left(AWD_{Sc} - \overline{AWD}\right)}{\sum_{Sc=1}^{Sc=M}\left(AWD_{Sc} - \overline{AWD}\right)^2} \qquad (3)$$

Where *Sc* is the weather scenario counter, *M* is the total number of weather scenarios, and IOD and AWD are the averages of total IODs and AWDs. CCOR > 1 means that the building is able to suppress the increasing outdoor thermal stress due to climate change, and CCOR < 1 means the building is unable to suppress increasing outdoor thermal stress due to climate change.

Matlab code and Excel file for the calculation of IOD, AWD, CCOR are available: https://doi.org/10.5281/zenodo.7326901.

(Please cite the documents as:

Rahif, Ramin, & Attia, Shady. (2022). IOhD (Calculation & illustration), IOcD (Calculation & illustration), AWD (Calculation & illustration), ACD (Calculation & illustration), CCOhR (Calculation), CCOcR (Calculation), Zonal OpT (illustration), and HWs (illustration) (Version 01). Zenodo. https://doi.org/10.5281/zenodo.7326901)

9.4.2 Thermal comfort metrics

• Weighted exceedance Hours: The number of hours of occupation outside a zonal comfort criterion within a given time of zone occupation. Depending on different comfort criteria (operative temperature or PMV/PPD) we could select:

- Degree hours criteria: The time during which the actual operative temperature exceeds the specified range during the occupied hours is weighted by a factor which is a function depending on how many degrees the range has been exceeded.
- PMV/PPD weighted criteria: The time during which the actual PMV exceeds the comfort boundaries is weighted by a factor that is a function of the PPD.

For the detailed calculation method please refer to ISO 17772-2 (ISO, 2018a). The exceedance hours only consider the occupied hours.

9.4.3 Energy metrics

- Annual HVAC system total primary energy use per conditioned floor area (HVAC = heating, cooling, ventilation, and auxiliary, indicate national or regional primary energy factors) [kWh/m².a]

9.4.4 Emission metrics

• Annual CO2-equivalent emission per conditioned floor area from HVAC energy use [$kgCO_2/m^2.a$] (use national or regional carbon emission factor, please indicate the carbon emission factor)

• Ozone Depletion Potential (ODP) and Global Warming Potential (GWP) of the refrigerant

9.4.5 Other resilience metrics

The other indicators could be used to assess cooling strategies' performance, including IEQ/thermal comfort metrics, energy metrics, and HVAC and grid metrics. Please refer to Annex 80 key performance indicators report (Holzer, 2022) for detailed explanations on these key performance indicators.

Note regarding the comparison of time-integrated metrics:

While comparing time-integrated metrics (e.g., weighted exceedance hours, IOD, AWD) between different heat-wave episodes, we suggest normalizing their values to the number of days in the episode e.g., if one episode lasts 5 days and another lasts 30 days, the number of unmet cooling hours for the latter will tend to be much higher than that for the former even if the daily experience is similar. The same normalization technique (dividing by number of days) should also be applied to daily energy use when comparing different heat waves or other periods such as summer months or cooling season.

10. Outcomes and uploading files

After the simulation and analysis, we expect the participants to upload the following outcomes:

- A short report to describe the simulation model, including critical information: software used for simulation; climate and location; reference building (if other reference building than DOE prototype building, please describe the building geometry and characteristics); occupancy and schedule (please indicate your model is based on DOE default setup, ISO 17772 or user-defined); cooling system (capacity, setup, and control strategies); output and KPIs analysis.
- Output (8760 hourly values of outputs described in Section 9.3 for TMY scenario, HWY scenario depending on heat wave duration) presented in Excel (CSV), named file as 'Cooling strategies – City- Building typology – Time period', for example, 'Ventilative cooling-Copenhagen-Office-2050.xlsx'.

Each participant is invited to create a folder on the Annex 80 platform:

- IEA EBC file server: http://files.iea-ebc.org/login.aspx
- Go to the folder Annex80 > Subtask B > Dynamic simulation > Final simulation outputs
- Create a folder for your institution
- Create a sub-folder for each cooling strategy you studied
- Upload the report and excel files

Terminology

Energy need for cooling (cooling thermal load): Heat to be extracted from a thermally conditioned space to maintain the intended space temperature conditions during a given period of time.

Energy use for cooling: Energy input to the cooling system to satisfy the energy need for cooling.

Primary energy: Energy that has not been subjected to any conversion or transformation process (including non-renewable energy and renewable energy).

Indoor Overheating Degree (IOD): The overheating of an indoor space. Summation of positive values of the difference between zonal indoor operative temperature and the zonal comfort limit temperature averaged over the sum of zonal occupied hours.

Ambient Warmness Degree (AWD): The heat stress of an outdoor environment. The summation of positive values of the difference between the outdoor air temperature and a fixed base temperature. The value of this base temperature must be defined and declared.

Overheating Escalation Factor (α): The proportion of IOD and AWD.

Unmet hours: The number of hours of occupation outside a zonal comfort criterion within a given time of zone occupation. Unmet hours can be applied to a wide range of comfort criteria, such as operative temperature, PPD, thermal comfort categories and others. The comfort criteria may be static or dynamic. Unmet hours are thus suitable to control, hybrid mode as well as free-running mode buildings.

Thermal Autonomy: The fraction of time a building can passively maintain comfort conditions without active systems. Unit: % of the occupied hours.

Annual cooling source energy saving intensity: The annual reduction of source energy for cooling, per conditioned floor area, that can be achieved by a specific (resilient) cooling measure, against a conventional cooling solution without this specific (resilient) cooling measure.

Seasonal Energy Efficiency Ratio (SEER) and Seasonal Coefficient of Performance (SCOP): The coefficient of performance (COP), identic with the Energy Efficiency Ratio (EER) of a refrigerator, chiller or air conditioning system is the ratio between useful cooling output and power input, at a given state of operation. The Seasonal Coefficient of Performance (SCOP), identic with the seasonal Energy efficiency Ratio (SEER) is the same ratio over a full cooling period.

COP and EER can be applied not only to active cooling technologies but also to automated passive ones. In this case the power input is limited to auxiliary energy inputs, such as fans, circuit pumps, actuators or controls.

Reference

ASHRAE. (2013). ANSI/ASHRAE Standard 169-2013, Climatic Data for Building Design. ASHRAE.

ASHRAE. (2016a). ANSI/ASHRAE/IES Standard 90.1-2016 - Energy Standard for Buildings Except Low-Rise Residential Buildings (I-P Editio). ASHRAE.

ASHRAE. (2016b). ANSI/ASHRAE Standard 62.1-2016, Ventilation for Acceptable Indoor Air Quality. ASHRAE.

ASHRAE. (2017). ASHRAE 55-2017: Thermal Environmental Conditions for Human Occupancy.

Attia, S. mailto, Rahif, R., Corrado, V., Levinson, R., Laouadi, A., Wang, L., Sodagar, B., Machard, A., Gupta, R., Olesen, B., Zinzi, M., & Hamdy, M. (2021). Framework to evaluate the resilience of different cooling technologies. https://doi.org/http://dx.doi.org/10.13140/RG.2.2.24588.13447

Boland, J., Ridley, B., & Brown, B. (2008). Models of diffuse solar radiation. *Renewable Energy*, 33(4), 575–584. https://doi.org/10.1016/j.renene.2007.04.012

Cannon, A. J. (2018). Multivariate quantile mapping bias correction: an N-dimensional probability density function transform for climate model simulations of multiple variables. *Climate Dynamics*, 50(1–2), 31–49. https://doi.org/10.1007/s00382-017-3580-6

DOE. (2021). Development | Building Energy Codes Program. https://www.energycodes.gov/development

Hamdy, M., Carlucci, S., Hoes, P. J., & Hensen, J. L. M. (2017). The impact of climate change on the overheating risk in dwellings—A Dutch case study. *Building and Environment*, 122(August 2003), 307–323. https://doi.org/10.1016/j.buildenv.2017.06.031

Holmes, S. H., Phillips, T., Wilson, A., Holmes, S. H., Phillips, T., Overheating, A. W., Holmes, S. H., Phillips, T., & Wilson, A. (2016). Overheating and passive habitability : indoor health and heat indices Overheating and passive habitability : indoor health and heat indices. 3218. https://doi.org/10.1080/09613218.2015.1033875

Holzer, P. (2022). Annex 80 - Resilient Cooling of Buildings Task Group Key Performance Indicators.

ISO. (2004). ISO 7933:2004 Ergonomics of the thermal environment — Analytical determination and interpretation of heat stress using calculation of the predicted heat strain (ISO (ed.)). ISO.

ISO. (2005). ISO 15927-4:2005 Hygrothermal performance of buildings — Calculation and presentation of climatic data — Part 4: Hourly data for assessing the annual energy use for heating and cooling. ISO.

ISO. (2016). ISO 18523-1:2016 Energy performance of buildings — Schedule and condition of building, zone and space usage for energy calculation — Part 1: Non-residential buildings.

ISO. (2017a). ISO 17772-1:2017 Energy performance of buildings – Indoor environmental quality – Part 1 : Indoor environmental input parameters for the design and assessment of energy performance of. ISO.

ISO. (2017b). ISO 7243:2017 Ergonomics of the thermal environment — Assessment of heat stress using the WBGT (wet bulb globe temperature) index (ISO (ed.)). ISO.

ISO. (2018a). ISO/TR 17772-2:2018 Energy performance of buildings — Overall energy performance assessment procedures — Part 2: Guideline for using indoor environmental input parameters for the design and assessment of energy performance of buildings. ISO.

ISO. (2018b). ISO 18523-2:2018 Energy performance of buildings — Schedule and condition of building, zone and space usage for energy calculation — Part 2: Residential buildings.

Machard, A., Inard, C., Alessandrini, J.-M., Pelé, C., & Ribéron, J. (2020). A Methodology for Assembling Future Weather Files including Heatwaves for Building Thermal Simulations from Regional Climate Models Multi-years Datasets. *Energies*, 1–34. https://doi.org/doi:10.3390/en13133424

Machard, A., P.tootkaboni, M., Gaur, A., & Salvati, A. (2020). Annex 80 - Weather Data Task force-Workshop to generate present and future weather files and heat wave data for building simulations Methodology overview.

Sun, K., Zhang, W., Zeng, Z., Levinson, R., Wei, M., & Hong, T. (2021). Passive cooling designs to improve heat resilience of homes in underserved and vulnerable communities. *Energy and Buildings*, 252, 111383. https://doi.org/10.1016/J.ENBUILD.2021.111383

Rahif, R., Hamdy, M., Homaei, S., Zhang, C., Holzer, P., & Attia, S. (2021). Simulation-based framework to evaluate resistivity of cooling strategies in buildings against overheating impact of climate change. Building and Environment, September, 108599. https://doi.org/10.1016/j.buildenv.2021.108599

Appendix A - DOE prototype building modelling issues

Sang Hoon Lee (SHLee@LBL.gov), Ronnen Levinson (RMLevinson@LBL.gov)
Lawrence Berkeley National Lab
2021-11-18

Medium office

Where to download the ASHRAE 90.1 2019 models

ASHRAE 90.1 2019 medium office prototype building models can be downloaded from the DOE Building Energy Codes Program Prototype Building Models website (https://www.energycodes.gov/prototype-building-models). There is a ZIP file that includes EnergyPlus Input Data Files (IDF) for 19 climate locations. Please refer to Table 3 from the website link above, *TMY3 Weather Files* for climate information for thermal zones and their representative cities.

Model issues

EnergyPlus version

Once IDFs are downloaded, the original version of the EnergyPlus IDF is 9.0. It is strongly recommended to upgrade the version to EnergyPlus 9.5 or above. Thermal performance metric calculations were corrected in EnergyPlus version 9.5. Also, this version added resilience metric outputs from the simulation results. The resilience output includes thermal resilience metrics of standard effective temperature hours. Refer to the section *23.5.1.3 Standard Effective Temperature Hours*[1] from *EnergyPlus 9.5 Engineering Reference*[2].

HVAC system type

HVAC systems in the current prototype models

The ASHRAE 90.1-2019 medium office prototype building model has three floors, and each floor has one core and four perimeter thermal zones. The model has three packaged air conditioning units that include gas furnace for heating and direct expansion (DX) cooling coil systems serving each floor. Each zone has variable air volume (terminal) box air distribution system with damper and electric reheat coil. The packaged air conditioning systems supply air to VAV terminal boxes with temperature 12.8-15.6 °C depending on outdoor air temperature. The amount of air to each VAV box varies to match the heat balance of each zone, and dampers adjust the airflow at each zone. This supply air is usually for space cooling only. VAV boxes are set to provide a minimum amount of air, even if that amount exceeds cooling requirements. Then, the terminal electric heating coil after the central cooling coil reheats to the desired supply temperature for each zone. While this maintains air turnovers and minimum outdoor air ventilation rates, if dehumidification is required, the supply air may be overcooled and reheat may be required in VAV terminal boxes, resulting in simultaneous heating and cooling.

Suggested HVAC systems

To overcome these overcooling and reheat issues, it is suggested to have a simple HVAC system type as implemented in the pre-1980 medium office DOE reference building models. The medium office has gas furnace heating systems serving each zone and DX cooling systems serving each

[1] https://bigladdersoftware.com/epx/docs/9-5/engineering-reference/resilience-metrics.html#set-hour
[2] U.S. Department of Energy. EnergyPlus Version 9.5.0 Documentation Engineering Reference 2021. Available from: https://bigladdersoftware.com/epx/docs/9-5/engineering-reference/index.html

zone[3]. This will have 15 gas furnaces and DX cooling coils that will be always available to meet the heating and cooling setpoint temperature for each zone.

How to replace HVAC system type in EnergyPlus IDFs

To modify the HVAC system type in ASHRAE 90.1 2019 prototype model, the following HVAC system related EnergyPlus objects need to be modified. It needs careful attention to update these objects to match HVAC system names and assign system nodes accordingly. There is no clear guidance how to update IDFs, but it is suggested to use a text editor and string editing script. For example, using *Notepad++* text editor, *Multiline Find and Replace* interface from *ToolBucket*[4] plugin is useful for text block edit. Python os library (Miscellaneous operating system interfaces)[5] is useful when editing text blocks for multiple IDFs.

- AirTerminal:SingleDuct:VAV:Reheat
- ZoneHVAC:EquipmentList
- Fan:VariableVolume
- Coil:Cooling:DX:TwoSpeed
- Coil:Heating:Electric
- Coil:Heating:Fuel
- Controller:OutdoorAir
- Controller:MechanicalVentilation,
- AirLoopHVAC:ControllerList
- AirLoopHVAC
- AirLoopHVAC:OutdoorAirSystem:EquipmentList
- AirLoopHVAC:OutdoorAirSystem
- OutdoorAir:Mixer
- AirLoopHVAC:ZoneSplitter
- AirLoopHVAC:SupplyPath
- AirLoopHVAC:ZoneMixer
- AirLoopHVAC:ReturnPlenum
- AirLoopHVAC:ReturnPath
- Branch
- BranchList
- NodeList
- OutdoorAir:Node
- OutdoorAir:NodeList
- EnergyManagementSystem:Sensor
- EnergyManagementSystem:Actuator
- EnergyManagementSystem:ProgramCallingManager
- EnergyManagementSystem:Program
- AvailabilityManagerAssignmentList
- SetpointManager:OutdoorAirReset
- SetpointManager:MixedAir,

HVAC system sizing from autosize to fixed capacity

The prototype model HVAC system is auto sized, which EnergyPlus determines the cooling and heating system capacity from the sizing simulations. Annex 80 passive cooling technologies

[3] Deru M, Field K, Studer D, Benne K, Griffith B, Torcellini P, et al. U. S. Department of Energy Commercial Reference Building Models of the National Building Stock. 2011. Available from: http://www.nrel.gov/docs/fy11osti/46861.pdf
[4] https://phdesign.com.au/npptoolbucket
[5] https://docs.python.org/3/library/os.html

reduce the cooling energy needs. If HVAC systems are auto sized, the capacity of cooling and heating systems will be different with and without passive cooling technologies. This will make that the energy saving or thermal comfort improvement are not from pure passive cooling technologies but from compound effect from the cooling technologies combined with the HVAC system sizing changes. This should not be happened when analyzing the passive cooling technologies performance evaluation. Thus, the HVAC capacities in heating furnaces and cooling coils should be determined in the baseline model, and these fixed capacities should be used throughout the passive cooling technology performance evaluation.

Single-family home

Where to download the IECC 2018 models

IECC 2018 single-family home prototype building models can be downloaded from the DOE Building Energy Codes Program Prototype Building Models website (https://www.energycodes.gov/prototype-building-models). Table 4 from the above website link, *Residential Prototype Building Models by Climate Zone* guides you to download a ZIP file that includes EnergyPlus IDFs for various HVAC system types. Please refer to Table 5 from the above website link, *TMY3 Weather Files for Residential Buildings* for climate information of thermal zones and their representative cities from the above website link.

Modeling issues

EnergyPlus version

The single-family home prototype model IDFs were built in EnergyPlus 9.5. As EnergyPlus version 9.5 or above is recommended, there is no need to upgrade the version.

Thermal zones

The prototype home is a two-story building with one thermal zone covering both bottom and top floor living spaces. For the Annex 80 modeling and simulation, it is suggested to update the single thermal zone to two thermal zones that separate the bottom and top floor living space.

The following EnergyPlus objects need to be updated to make the baseline model two zones so that envelop surfaces, internal heat gain components, and ventilation requirements are assigned accordingly.

- Zone
- BuildingSurface:Detailed
- InternalMass
- People
- Lights
- ElectricEquipment
- ZoneVentilation:DesignFlowRate

HVAC systems

HVAC system type related objects update

Single-family prototype building energy models are available with various heating system types including oil furnace, gas furnace, electric resistance furnace, and heat pump. Depending on the HVAC system type selected for modeling and simulation, EnergyPlus objects related to HVAC system connecting thermal zones and distribution system nodes need to be updated carefully.

HVAC system sizing from autosize to fixed capacity

“Autosize” input in HVAC system capacity input should be updated with the fixed capacity as determined from the baseline simulation. Please see the medium office HVAC sizing issue section for more details.

It needs careful attention to update thermal zone and HVAC related objects accordingly for two the bottom and top floor zones. Again, there is no clear guidance how to update IDFs, but it is suggested to use a text editor and string editing script.

ISSN 1901-726X
DCE Technical Report No. 306