Fundamentals of Building Performance Modeling

Version 2.0

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Foreword

Welcome to Version 2.0 of the **Fundamentals of Building Performance Modeling** Handbook. This handbook provides a comprehensive overview of Building Performance Modeling (BPM) and Simulation, a critical discipline for designing, operating, and optimizing energy-efficient and sustainable buildings. The BPM Handbook describes the technical fundamental concepts associated with building science, operational systems, and whole-building performance.

☑ For Students

The BPM Handbook requires a basic knowledge of thermodynamics and heat transfer. If you are learning about architecture, energy systems, or HVAC engineering, this Handbook will help you. Where appropriate, we have included common AEC industry abbreviations, formulae, and concepts to act as a continuous reminder. We have also included recommendations for your CV/resume.

☑ For Educators

The BPM Handbook is meant to act as a technical teaching aid. We have discovered that over 50% of building performance modeling questions have nothing to do with modeling, but rather are questions about building physics and flows of heat, light, air, and water. The Handbook is rich with additional free references and videos for the student who wishes to learn more about a specific feature of buildings or who is competing in an industry student competition.

☑ For Professionals

The BPM Handbook recognizes the continuous learning curve with respect to buildings and building systems. Whether your current employment requires HVAC design, BEM analysis, or meeting the local energy code requirements, this Handbook aims to maintain relevance with building technologies and modeling methods.

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These materials were prepared to be used in conjunction with various international educational programs and are not intended to provide legal advice or establish legal standards of reasonable behavior. Universities are welcome to include this Handbook as part of a syllabus reference or curriculum material. The information in this document is believed to accurately represent the technologies and building performance parameters described herein and is meant to clarify and illustrate typical situations, which must be appropriately adapted to individual circumstances. Neither IES Ltd. nor any of its employees (1) makes any written or oral warranty, expressed or implied; (2) assumes any legal liability or responsibility for the accuracy or completeness of any information, apparatus, product, process, method, or policy contained herein. No part of this Student Handbook may be reproduced without written permission, except in the case of brief quotations embodied in articles and reviews.

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About Building Performance Modeling

Building Performance Modeling (BPM) is a process that involves creating virtual representations of buildings by utilizing computational physics-based tools to predict how a building will perform under various conditions, enabling informed decisions throughout the building's lifecycle. Themes of BPM fundamentals described in this handbook include:

- ☑ **Heat Transfer and Psychrometrics**
- ☑ **Heating, Ventilation, and Air-Conditioning** (HVAC)
- ☑ **Climate and Weather Analysis**
- ☑ **Decarbonization and Electrification**
- ☑ **Occupant Thermal Comfort Modeling**
- ☑ **Building Energy Modeling**
- ☑ **Envelope and Construction Materials**
- ☑ **Renewable Energy Technology**
- ☑ **Daylight Simulation and Lighting Calculations**
- ☑ **Indoor Air Quality and Airflow Simulation**
- ☑ **Heating and Cooling Load Calculations**
- ☑ **Water Modeling**

Key Benefits of Building Performance Modeling include:

- **Duty of Care:** obligation to ensure that a building design meets a standard of care that protects the health, safety, and interests of the building owner, occupants, and the material items in the building.
- **Energy Savings:** Identifying opportunities to reduce energy usage.
- **Cost Reduction:** Optimizing operational costs and minimizing life-cycle expenses.
- **Improved Comfort:** Ensuring optimal thermal and visual comfort for occupants.
- **Environmental Impact:** Reducing greenhouse gas emissions and carbon footprint.
- **Code Compliance:** Verifying adherence to energy codes and standards.
- **Risk Mitigation:** Identifying potential performance issues before construction.

Techniques, Concepts, and Methods of Building Performance Modeling include:

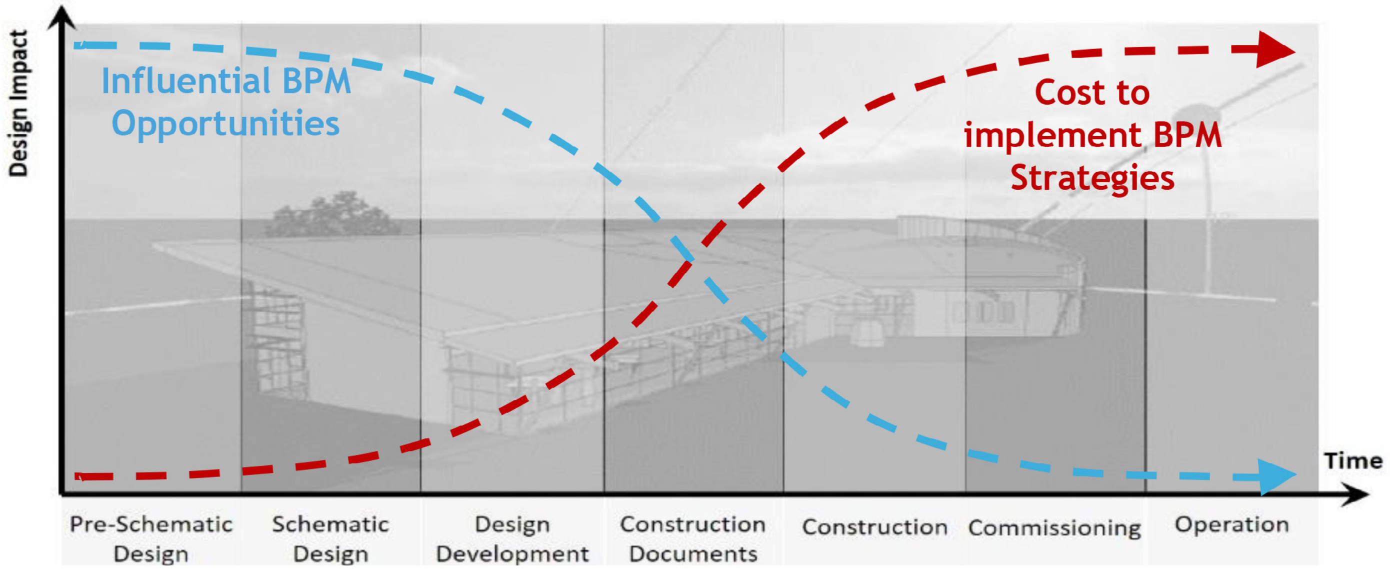
- **Steady-state calculations** refer to the analysis of a system when its variables are unchanging over time.
- **Dynamic thermal Simulation** is a method used to model a building's thermal behavior over time, accounting for factors like occupancy schedules, solar, and building thermal mass. This technique helps assess energy consumption, comfort levels, and compliance with building energy regulations.
- **Nodal network modeling** is a method used to analyze and simulate the behavior of interconnected systems, where components are represented as nodes and their relationships as links.
- **Ideal system modeling** involves creating simplified representations of complex systems to understand their behavior and interactions effectively. An example would be a perfectly constant room temperature.
- **Raytracing** is a computer graphics technique used to simulate how light interacts with objects to create realistic images and calculate the distribution of luminous flux by determining the trajectories of rays.
- **Perfect mixing** in stirred tank modeling refers to the theoretical condition where the composition of the mixture is uniform throughout the entire domain, e.g., a room, allowing for consistent and predictable outcomes. This concept simplifies calculations and enhances the process efficiency of BPM.
- **Computational Fluid Dynamics (CFD)** simulates air flow and thermal comfort in greater detail, unlike the perfect mixing analogy. A temperature gradient is achievable in a room with this method.

Abbreviations and Acronyms

AAHP – Air-to-Air Heat Pump
ACB – Active Chilled Beam
ACE – Air Change Effectiveness
ACH – Air Changes per Hour
AHJ – Authority Having Jurisdiction
AHU – Air Handling Unit
APACHE – Application for Air Conditioning & Heating Engineers
ASE – Annual Sunlight Exposure
AQI – Air Quality Index
ASHRAE – American Society of Heating, Refrigerating & Air-Conditioning Engineers
ASHP – Air-Source Heat Pump
AWHP – Air-to-Water Heat Pump
BEM – Building Energy Modeling
BIM – Building Information Modeling
BHP – Brake Horsepower
BPM – Building Performance Modeling
BREEAM – Building Research Establishment Environmental Assessment Method
Btu – British Thermal Unit
CAV – Constant Air Volume
CBDM – Climate-Based Daylight Modeling
CFM – Cubic Feet per Minute
CFD – Computational Fluid Dynamics
CHW – Chilled Water
CIBSE – Chartered Institute of Building Services Engineers
Clo – Clothing Level
CO2e – Carbon Dioxide Equivalent
COP – Coefficient of Performance
CT – Cooling Tower
CW – Condenser Water
DBT – Dry Bulb Temperature
DEC – Direct Evaporative Cooler
DHW – Domestic Hot Water
DOAS – Dedicated Outdoor Air System
DSY – Design Summer Year
DV – Displacement Ventilation
EA – Exhaust Air
ECAi – Equivalent Clean Airflow
EER – Energy Efficiency Ratio
EF – Energy Factor
EIR – Energy Input Ratio
EPD – Equipment Power Density (plug load)
ERV – Energy Recovery Ventilator
EUI – Energy Use Intensity (kBtu/ft^2/year or kWh/m^2/year)
EWC – Electric Water-cooled Chiller
FCU – Fan-coil Unit
GHG – Greenhouse Gas Emissions
GPM – Gallons per Minute
GSHP – Ground Source Heat Pump
HPWH – Heat Pump Water Heater
HRC/HPC – Heat Recovery/Heat Pump Chiller
HRV – Heat Recovery Ventilator
HSPF – Heating Seasonal Performance Factor
HVAC&R – Heating, Ventilation, Air Conditioning & Refrigeration
HX – Heat Exchanger
IAQ – Indoor Air Quality
IBPSA – International Building Performance & Simulation Association
IDDE – Indirect/Direct Evaporative Cooler
IEC – Indirect Evaporative Cooler
IES – Integrated Environmental Solutions Ltd.
.ies – Illumination Engineering Society (Photometric Data File)
IPLV – Integrated Part Load Value
IWEC – International Weather for Energy Calculations
kW – Kilowatt, unit of Power or Load
kWh – Kilowatt Hour, unit of Energy
LEED – Leadership in Energy and Environmental Design
LCA – Life-Cycle Assessments
LPD – Lighting Power Density (W/ft^2, W/m^2)
MA – Mixed Air
MAU/MUA – Make-up Air Unit/Make-up Air
MBH – Thousand Btu per Hour
Met – Metabolic Rate
MERV – Minimum Efficiency Reporting Value
OA/OSA – Outdoor (Ventilation) Air
OPR – Owner Project Requirements
PM – Particulate Matter
PMV – Predicted Mean Vote
PPD – Percent People Dissatisfied (%)
PSZ – Packaged Single Zone HVAC unit
PTAC – Packaged Terminal Air Conditioner
PTHP – Packaged Terminal Heat Pump
PV – Photovoltaics
RA – Return Air
RCP – Representative Concentration Pathway
RPM – Revolutions Per Minute
RTU – Rooftop Unit
R-value – Thermal Resistance (h*ft^2*°F/Btu) [(m^2*K)/W]
SA – Supply Air
SDA – Spatial Daylight Autonomy (%)
SEER – Seasonal Energy Efficiency Ratio
SHGC – Solar Heat Gain Coefficient
SHW – Solar Hot Water or Service Hot Water
SWEE – Sanitary Wastewater Energy Exchanger
TDH – Total Design Head (Pressure)
TES – Thermal Energy Storage
TMY – Typical Meteorological Year
Ton (cooling) – 12,000 Btu/hr
TRY – Test Reference Year
TSP – Total Static Pressure
TU – Terminal Unit
TVOC – Total Volatile Organic Compounds
UDI – Useful Daylight Illuminance
UEF – Uniform Energy Factor
UFAD – Underfloor Air Distribution System
U-Value – Heat Transfer Coefficient (Btu/h*ft^2*°F) [W/(m^2*K)]
VAV – Variable Air Volume
VRF/VRV – Variable Refrigerant Flow/ Variable Refrigerant Volume
VSD – Variable Speed Drive
WAHP – Water-to-Air Heat Pump
WBT – Wet Bulb Temperature
WBLCA – Whole-Building Life-Cycle Assessments
WSHP – Water Source Heat Pump
WSE – Waterside Economizer
WWHP – Water-to-Water Heat Pump
WWR – Window-to-Wall Ratio
ΔT – Temperature Differential
ρ – Density (kg/m^3, lb/ft^3)

The Integrated Design Process of BPM

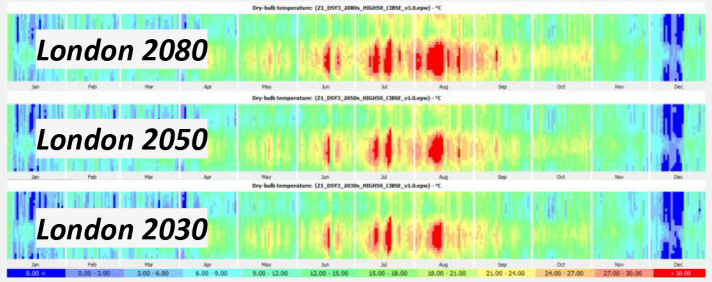
During early design phases of construction projects, analysis from BPM can have the most impact on the final performance of the building. As such, BPM is an **iterative process** that requires **knowledge** of building physics and technical **skills** to analyze the predicted performance of the building, or building systems, using physics-based modeling software tools to simulate various design scenarios. This proactive style of design and construction requires many 'what-if' scenarios to be considered using BPM, often during a collaborative charette involving all members of the design team (architect, mechanical, etc.). The building Owner's Project Requirements (OPR) should be defined during this early stage of design, which may include an energy usage target or green-building rating.

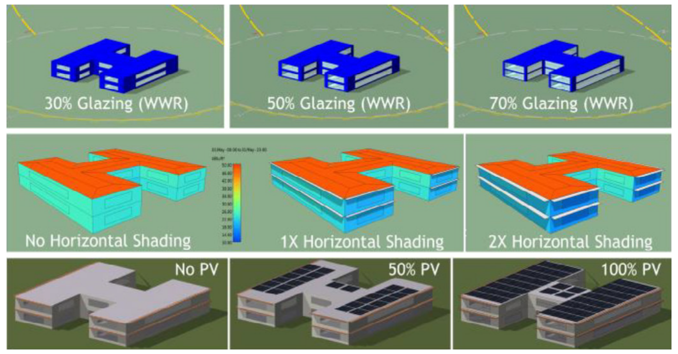


Building Performance Modeling and simulation analysis are frequently applied at various stages during the design, construction, and operation processes for both new buildings and existing buildings.

BPM categories for a project's design phases may include:

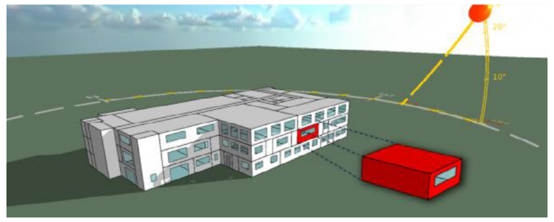
Climate Analysis includes a review of local climatic information for the project. This commonly includes analysis of design weather, typical annual climate data, and perhaps future morphed climate data. Climate risks and design opportunities may be identified with data analysis of temperatures, humidity, wind, solar, daylight, and precipitation.

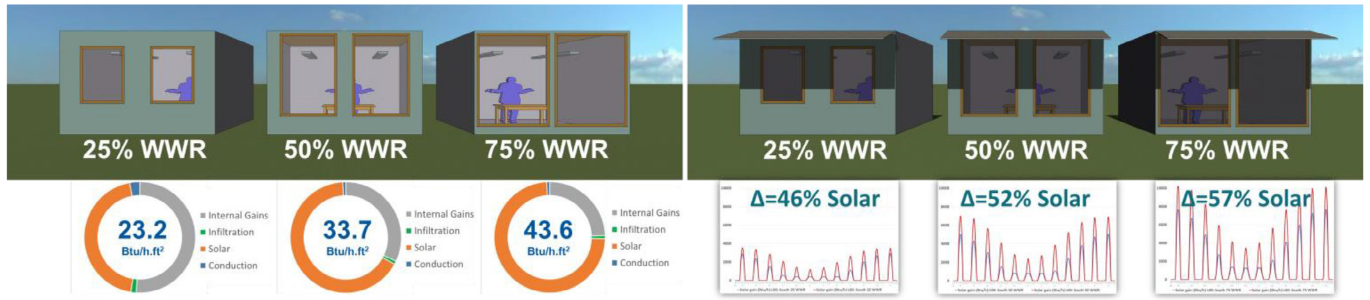




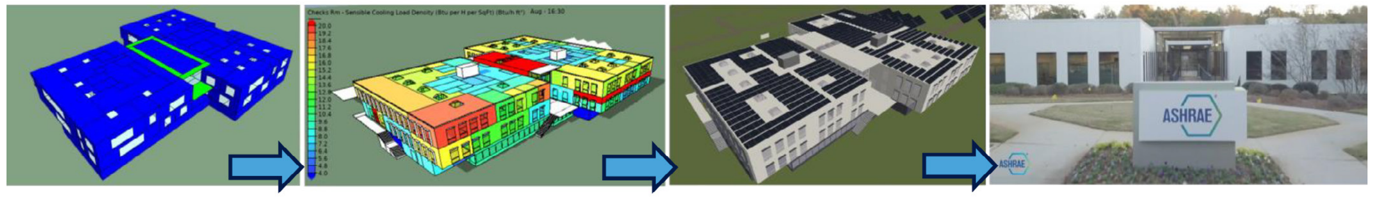
Conceptual/Schematic Design Modeling occurs during the early Schematic Design (SD) stage and includes analysis of architectural layouts & forms, building orientation, PV areas, and window-to-wall % glazing, etc. **Parametric simulation** can be especially useful during these earlier stages of design, whereby thousands of permutations can be considered and compared interactively by using a parallel coordinate chart.

Simple-box Façade Modeling (or Shoe-Box modeling) includes simulation of fenestration design, shading options, glazing specification, envelope materials & types. A whole-building model is not necessary to inform the design optimization of the façade and can be analyzed in isolation, per orientation, for loads, daylight, energy, comfort, and more.





Load Reduction Modeling includes calculating the peak heating & cooling loads for rooms and thermal zones under design conditions. It includes simulation-based analysis of the peak demand reduction for an energy end-use. The ASHRAE Headquarters building model is a good example of progressing a model from Schematic Design, to Loads optimization, a Building Energy Model, and then finally to Operation.



HVAC System Selection Modeling includes the annual energy evaluation of heating, cooling, humidification, dehumidification, conditioning of ventilation air, heat recovery, HVAC controls, and systems optimization. Heating of Domestic Hot Water, or Service Hot Water, is also included, since the heating systems may be integrated with the space heating systems design.

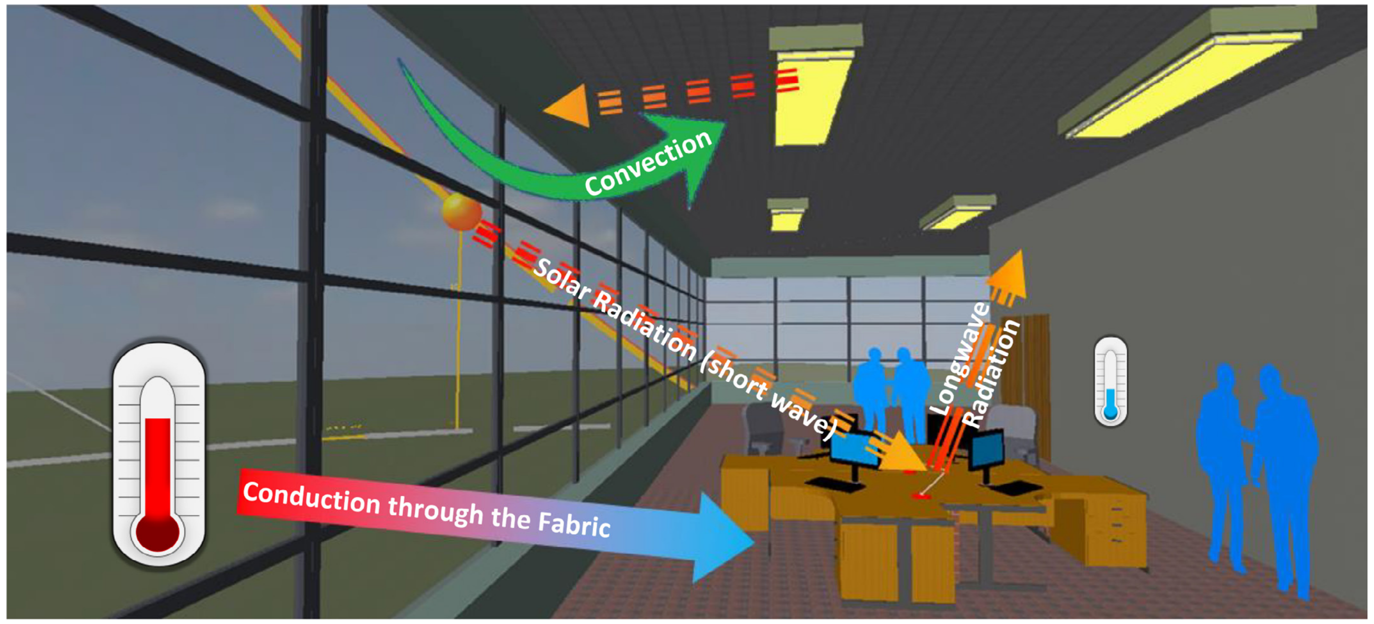
Design Refinement & Optimization Modeling may be used to refine and optimize a system or control sequence. At this phase of design, a project performance goal might be the target outcome before the end of the Construction Document (CD) phase. A Value-Engineering analysis may commonly occur during the construction document phase when unforeseen first-cost or capital expenditure savings are being reconsidered.

Code Compliance Modeling is frequently a requirement for the local Authority Having Jurisdiction to approve the construction and provide a permit for the building. Modeling for a Building Code or Standard is required. Compliance modeling is frequently coupled with **Green-Building Certification** modeling for certification with organizations such as LEED, BREEAM, WELL, etc.

Existing Building Operational Modeling is used to optimize the performance of an existing building. Access to metered data and actual weather data is critical to successful optimization recommendations. Operational analysis may be useful for evaluating whole building model improvements, or for an isolated system within the building, for example, a campus-level chilled water plant.

Fundamentals of Building Heat Transfer

Heat is the primary form of energy used (and wasted) in buildings. How heat is used (or moved) in a building is often the primary source of its energy consumption and carbon footprint. With some exceptions, heating and cooling a building is responsible for more than half of most buildings' energy consumption and energy cost. To maintain a constant deep tissue temperature of 37.2°C (99°F), our bodies must exchange heat with the environment by **conduction, convection, evaporation, and radiation**. Various interactive heat exchanges occur in a typical conditioned space of a building.



- **Conductive** heat flow through the building **fabric** (walls, glazing, etc.) is influenced by the difference between indoor and outdoor temperatures, indoor air movement, and external wind.
- **Convective** heat transfer due to air **infiltration** and air exfiltration is mostly an uncontrolled flow of air through cracks and gaps in the building fabric. This is influenced by indoor and outdoor temperatures, air buoyancy, wind, number of windows and other openings (e.g., louvers), building height, and quality of construction.
- **Forced Convective heat** from Ventilation Air or from Supply Air is frequently conditioned by HVAC system components (e.g., coils) and transported by HVAC equipment (e.g., ducts) due to pressurization (e.g., from fans).
- **Direct and Diffuse Solar Radiation** (short-wave) passes through glazing and is absorbed by materials inside. Re-radiated **long-wave radiation** is mostly trapped inside. Ground reflected **radiation** is also a factor.
- **Transient (non-steady-state)** heat flow may be **stored** thermal energy, which is **absorbed** into and rejected from the building fabric's thermal mass. **Conduction, convection & radiation** are all influential dynamic factors.
- **Internal Heat Gains** (e.g., plug loads): **Convective and radiant** heat gains from electric and process equipment.
- **Occupant Heat Gains: Convective and radiant heat** transfer mechanisms by **sensible and latent** modes. Heat transfer is dependent on the person's clothing, activity, and metabolic rate.
- **Lighting Gains: Radiative and convective** heat gain may be controlled by illuminance and occupancy sensors.
- Heat energy moves **from hot objects to cold objects**, attempting temperature equilibrium. For buildings, the desired air temperature and relative humidity in a space must consider all sources of heat and sinks of heat.
- **Adiabatic** heat transfer is a thermodynamic process that occurs without the addition or removal of heat. This is rare in buildings. An exception might include **evaporative** cooling, which maintains constant enthalpy (h).
- **HVAC Systems** can provide sensible and latent heat for space conditioning, depending on the system type.

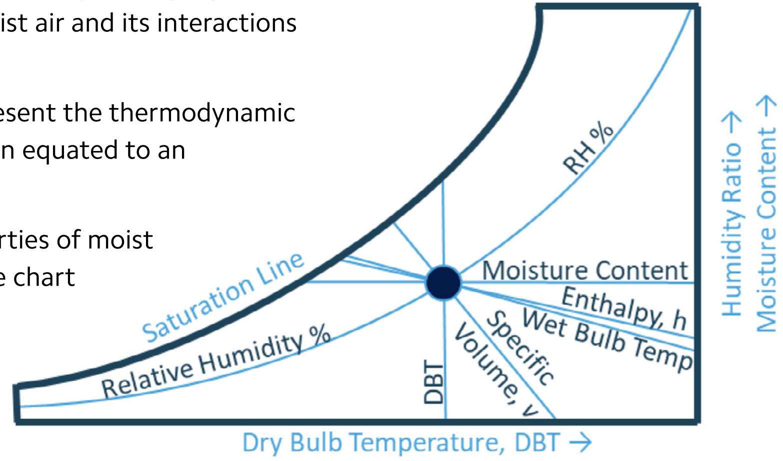
Psychrometrics

Psychrometrics is the study of the physical and thermodynamic **properties** of gas-vapor mixtures, particularly focusing on moist air and its interactions with temperature and humidity.

A **Psychrometric Chart** is used to graphically represent the thermodynamic properties of moist air at a constant pressure, often equated to an elevation relative to sea level.

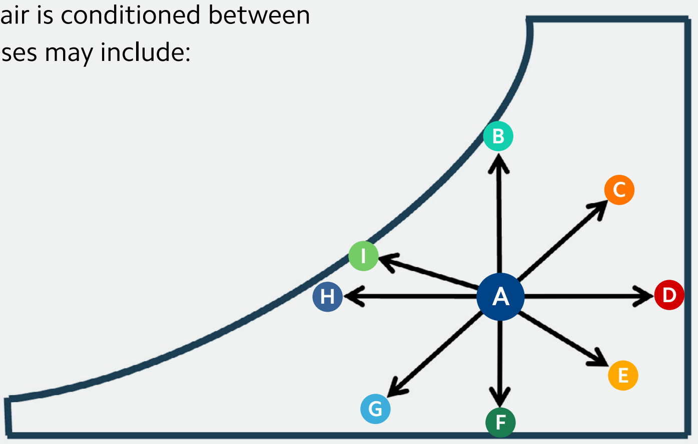
Interrelationships between thermodynamic properties of moist air at various conditions may be established on the chart when a minimum of two air properties are known.

Detailed Psychrometric Charts are available in Appendix A.



Psychrometric **Processes** may be established as air is conditioned between two psychrometric states. Psychrometric processes may include:

- A-to-B = Humidification
- A-to-C = Heating & Humidification
- A-to-D = Sensible Heating
- A-to-E = Chemical Dehumidification
- A-to-F = Dehumidification
- A-to-G = Cooling & Dehumidification
- A-to-H = Sensible Cooling
- A-to-I = Evaporative Cooling



Simple Psychrometric Equations:

☑ **Sensible Heat (QS):**

- Q_S (Btu/h) = **cfm*1.094*ΔT**, where T = Dry Bulb Temperature °F.
- Q_S (kW) = **L/sec*1.2*1.02*ΔT**, where T = Dry Bulb Temperature °C.

☑ **Latent Heat (QL):**

- Q_L (Btu/h) = **cfm*4840*ΔW**, where W = humidity ratio lb/lb.
- Q_L (Btu/h) = **cfm*0.68*Δgrains**, where 7,000 grains = 1 lb. H_2O.
- Q_L (kW) = **L/sec*3.0*ΔW**, where W = moisture concentration g/kg.

☑ **Total Heat (QT):**

- Q_T (Btu/h) = **cfm*4.5*Δh**, where h = Enthalpy Btu/lb.
- Q_T (kW) = **cfm*1.2*1.02*Δh**, where h = Enthalpy kJ/kg.

Properties of Air at Sea Level:

Density, ρ

- 1.2 kg/m³.
- 0.075 lb/ft³.

Specific Heat Capacity (c_p)

- 1.019 kJ/kg·K
- 0.243546845124 Btu/(lb·°F)

Properties of Water:

Density, ρ

- 1,000 kg/m³.
- 62.4 lb/ft³.

Specific Heat Capacity (c_p)

- 4.200 kJ/kg·K
- 1.0 Btu/(lb·°F)

Climate and Design Weather

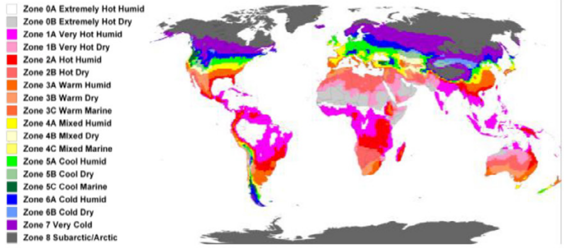
Weather refers to short-term (minutes to months) changes in the atmosphere, with respect to its effects upon life and human activities. It is often referred to in terms of temperature, humidity, precipitation, cloudiness, brightness, visibility, wind, and atmospheric pressure, as in high and low pressure.

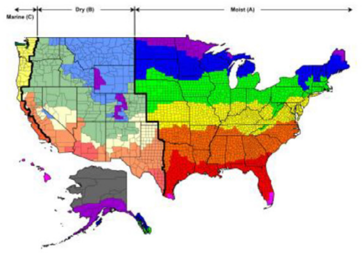
Climate refers to the long-term (e.g., 30 years) pattern of weather in a particular geographical region. Think of Climate as an average pattern of weather for a region. Weather is what we get in the moment; climate is what we can expect over time.

ASHRAE Standard 169 has classified **Climate Zones** and **Moisture Zones** for Building Design Standards.

Climate Zones (CZ):
0, 1, 2, 3, 4, 5, 6, 7, 8

Moisture Zones:
(A) Humid
(B) Dry
(C) Marine





Design Day Weather data includes **288** hours for cooling loads, represented by 24 hours for 1 design day, and for each of the 12 months. Plus, one quasi-steady-state design condition for heating loads. This data is used to calculate:

- ✓ Peak heating and cooling loads for rooms and zones, with associated design airflows.
- ✓ Peak **coincident** HVAC system capacities and flow rates.

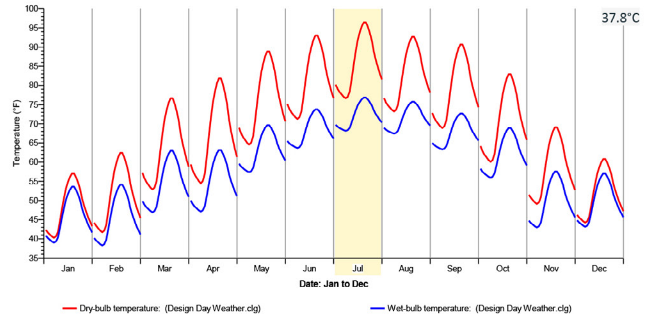
Design Day Data for Mechanical Design is typically presented in two formats: (1) Data table, and (2) Graphical.

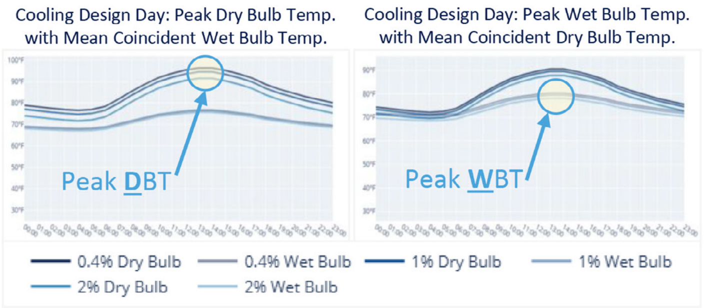
Heating Design Condition	99.6 %	99.0 %
Dry Bulb Temperature DBT (°F)	-1.66°F	3.2°F
Dry Bulb Temperature DBT (°C)	-18.7°C	-16°C

Monthly Climatic Design Conditions should be used for peak cooling loads calculations.

The **Annual Design Conditions** should be **avoided** for peak cooling loads calculations.

Cooling Design Condition	Month of Peak	0.4 %	1 %	2 %
Peak Dry Bulb Temp | MC Wet Bulb (°F)	July	96.4°F | 76.8°F	94.6°F | 76.4°F	91.9°F | 75.7°F
Peak Wet Bulb Temp | MC Dry Bulb (°F)	July	80.2°F | 90.5°F	79.4°F | 89.5°F	78.1°F | 87.8°F
Peak Dry Bulb Temp | MC Wet Bulb (°C)	July	35.8°C | 24.9°C	34.8°C | 24.7°C	33.1°C | 24.3°C
Peak Wet Bulb Temp | MC Dry Bulb (°C)	July	26.8°C | 32.5°C	26.3°C | 31.9°C	25.6°C | 31.0°C



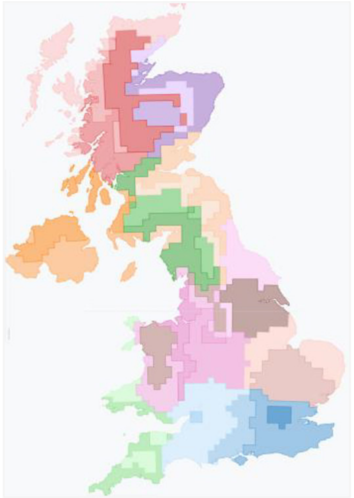

Cooling Design Day: Peak Dry Bulb Temp. with Mean Coincident Wet Bulb Temp.

Cooling Design Day: Peak Wet Bulb Temp. with Mean Coincident Dry Bulb Temp.

Annual Hourly Weather Data

Annual Hourly Weather Datasets typically account for all **8,760** Hours per year for a range of variables. This dataset is commonly referred to as a **weather file** and is used to estimate the operational performance of buildings for energy, carbon, cost, etc. Common formats include Typical Meteorological Year **(TMY)**, International Weather for Energy Calculations **(IWEC)**, Canadian Weather for Energy Calculations **(CWEC)**, Test Reference Years **(TRYs)** are used to conduct operational energy assessments. Other types include Actual Meteorological Year **(AMY)** weather files by Athenium, which are used for model calibration since they represent actual recorded data, and future weather files by WeatherShift, which morph weather for various future climate scenarios, or Representative Concentration Pathways **(RCPs)** to project future greenhouse gas concentrations.

CIBSE provides Test Reference Years **(TRYs)** and Design Summer Years **(DSYs)** for **28 UK Zones** that are representative of the climate conditions in the U.K.

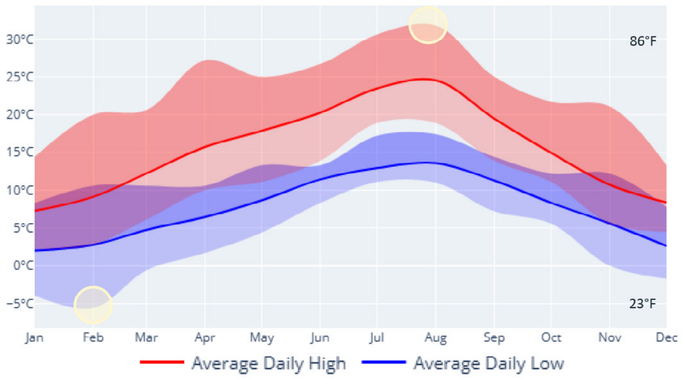


DSYs are years with various hot weather events and should be used to conduct overheating risk assessments. There are three types of DSY files available (DSY1, 2, and 3) representing different hot weather events:

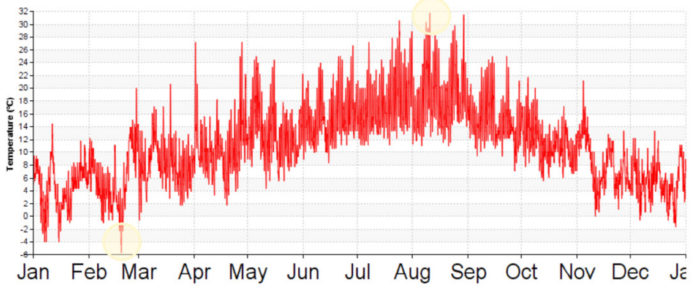
- **DSY1:** moderate year containing heat events for a 7-year period.
- **DSY2:** the year containing the most intense heat events.
- **DSY3:** the year containing the longest heat events.

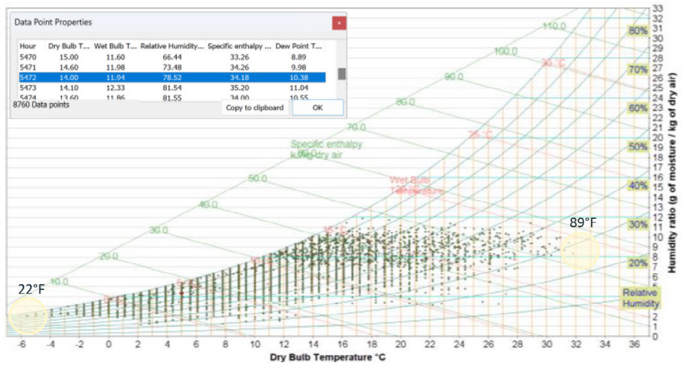
Weather data is available for three future time periods: the 2030s (2019–2039), 2050s (2039–2059), and 2080s (2069–2089). Each time period includes different emission scenarios: High scenario (RCP 8.5) for 2030s, Medium (RCP 4.5) and High for the 2050s, and Low (RCP 2.6), Medium, and High for 2080s.

Annual Hourly Temperatures can be graphically shown in a range of formats and charts in IESVE Software.



Daily high temperatures and daily low temperatures by month are shown to demonstrate the range of conditions for a given period. In this chart, the mean, maximum, and minimum temperatures are shown for the daily high and low of each month. In this example, the hottest temperature of the year is 31.8°C (89.2°F) and occurs in August, while the coldest temperature of the year is -5.6°C (22°F), which occurs in February.




Data Point Properties

Hour	Dry Bulb T...	Wet Bulb T...	Relative Humidity...	Specific enthalpy ...	Dew Point T...
5470	15.00	11.60	66.44	33.26	8.89
5471	14.60	11.98	73.48	34.26	9.98
5472	14.00	11.94	78.52	34.18	10.38
5473	14.10	12.33	81.54	35.20	11.04
5474	13.60	11.86	81.55	34.00	10.55

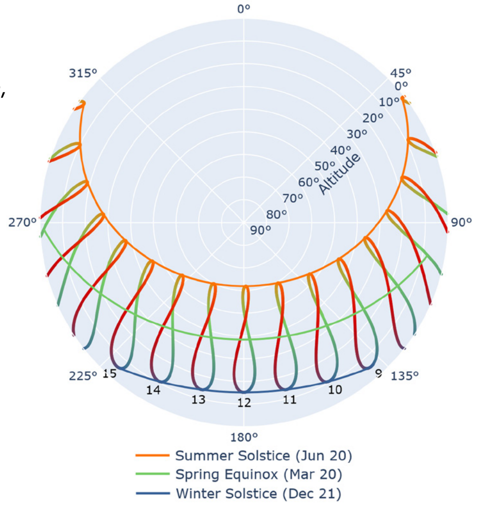
8760 Data points

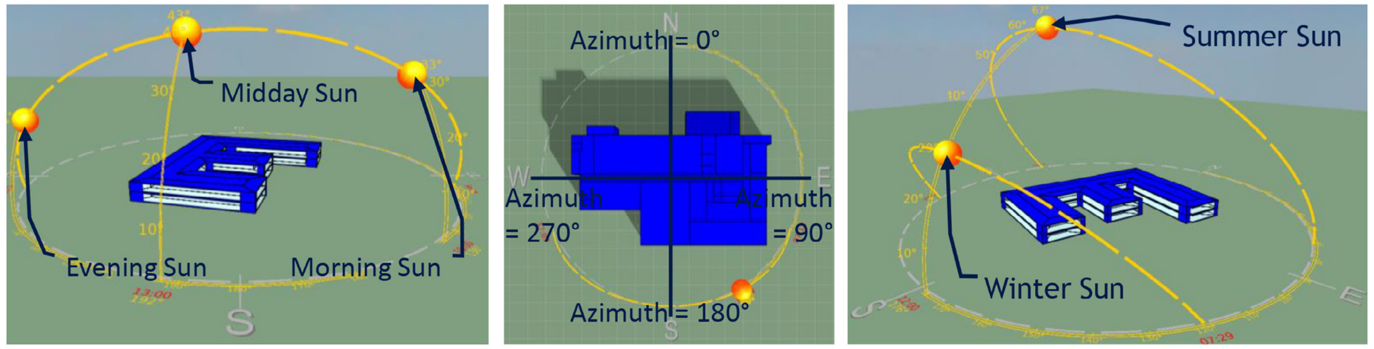
Weather Files are available from iesve.com/support/weatherfiles

Solar

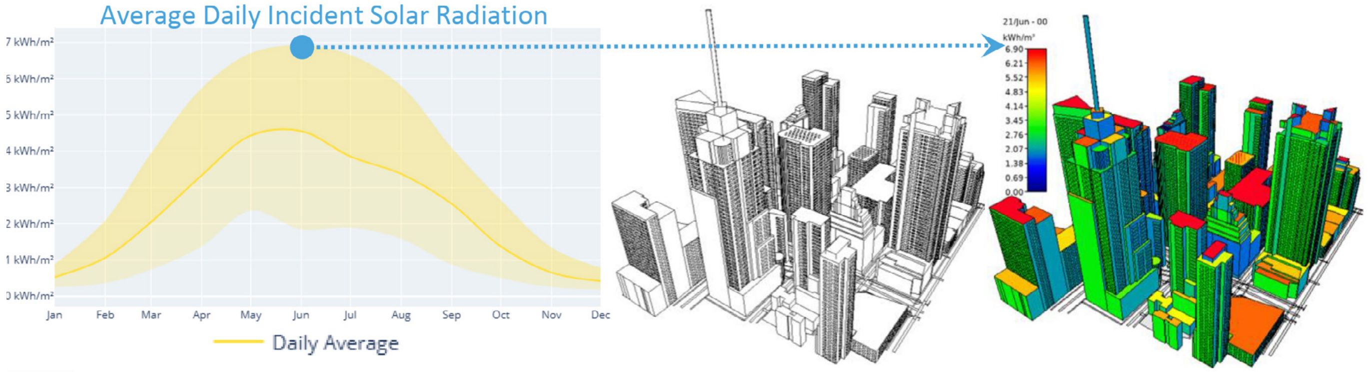
Solar Path charts allow visual analysis of the sun's relative position across the sky throughout the year. The sun's position is described by the **altitude** angle, or the angle between the sun and the horizon, and the **azimuth** angle, or the angle clockwise from true north. The solar path chart shows the **analemma** for each hour, which appears as **figure-eight loops** in the graph. For this Northern hemisphere example, there are 14 hours of Summer sun during the longest day in June, and the altitude angle at noon is 75.6°. On the shortest day in December, there are only 8 hours of Winter sun, and the altitude angle at noon is 29.0°. Model analysis of solar positions relative to the building can influence the design of:

- ☑ Passive solar heating.
- ☑ Solar PV panel layouts.
- ☑ Façade design to limit unwanted direct solar radiation.





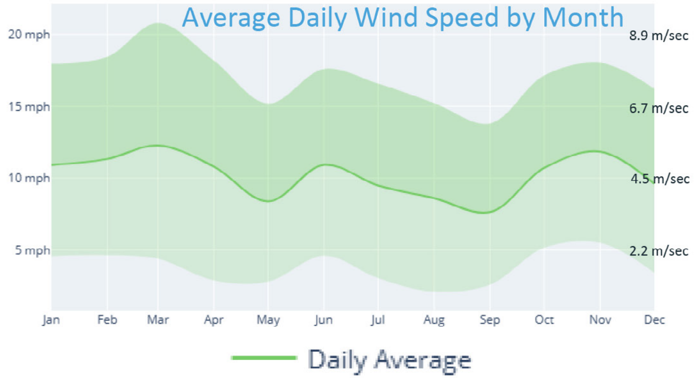
Incident solar radiation refers to the total amount of solar energy that reaches the Earth's surface at a specific location over a defined period. The 24-hour solar energy values shown reflect the mean, maximum, and minimum for each month. In the example below for New York City, USA, the highest radiation month is June, while the month is December. The maximum daily solar radiation for the year is 6.9 kWh/m², occurring on June 29. Solar radiation analysis of climatic data without the context of shading from building self-shading and adjacent buildings, or other topographical obstructions, is critical for a meaningful solar analysis, as shown by the spatially-aware solar radiation city model. See animation

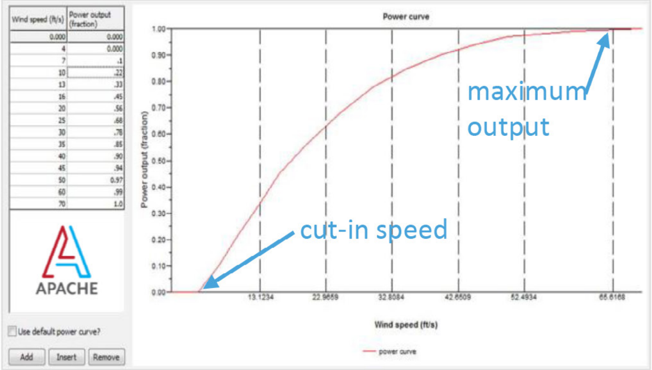


Wind

The effects of wind can be evaluated in a few ways, given the overall context of operational performance.

Wind Energy can generate limited on-site electricity due to the requirement of consistent wind speed on-site. Annual wind data is available in the Climate Assessment report. A wind turbine will include a '**cut-in speed**', as shown in the power curve. The power curve also shows a **maximum output**, whereby it cannot produce any additional electricity.

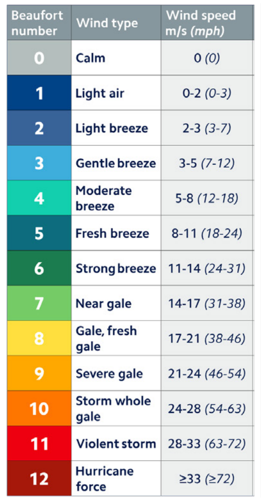




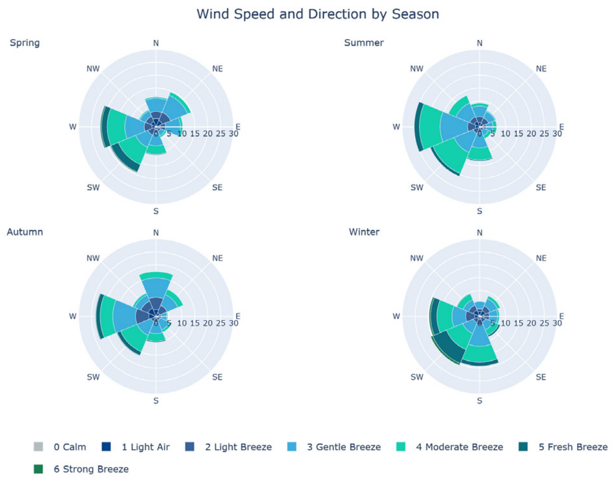
Wind speed (ft/s)	Power output (fraction)
0.000	0.000
4	0.000
7	.1
10	.22
13	.33
16	.45
20	.56
25	.68
30	.78
35	.85
40	.90
45	.94
50	0.97
60	.99
70	1.0

☐ Use default power curve?

The Chart above reflects the daily mean, maximum, and minimum **wind speeds**, averaged over each month.

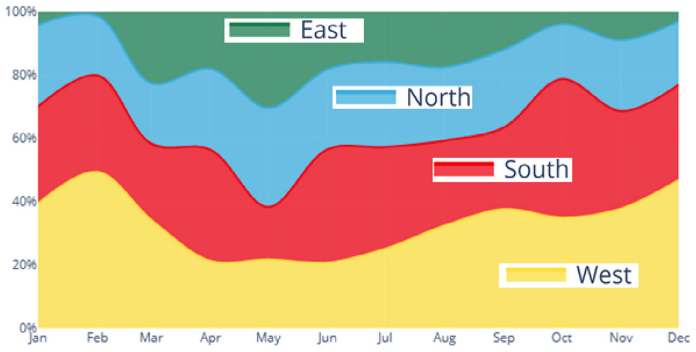


Beaufort number	Wind type	Wind speed m/s *(mph)*
0	Calm	0 *(0)*
1	Light air	0-2 *(0-3)*
2	Light breeze	2-3 *(3-7)*
3	Gentle breeze	3-5 *(7-12)*
4	Moderate breeze	5-8 *(12-18)*
5	Fresh breeze	8-11 *(18-24)*
6	Strong breeze	11-14 *(24-31)*
7	Near gale	14-17 *(31-38)*
8	Gale, fresh gale	17-21 *(38-46)*
9	Severe gale	21-24 *(46-54)*
10	Storm whole gale	24-28 *(54-63)*
11	Violent storm	28-33 *(63-72)*
12	Hurricane force	≥33 *(≥72)*



The **Beaufort scale** is a system that measures wind strength based on observed conditions on land or at sea, ranging from **0 (calm) to 12 (hurricane)**. These **four seasonal wind rose** patterns illustrate wind strength and direction. The radial axis represents frequency, or the percentage of time spent in each strength category during each season. These graphs can be used for architectural consideration of pedestrian comfort and natural ventilation during shoulder seasons.

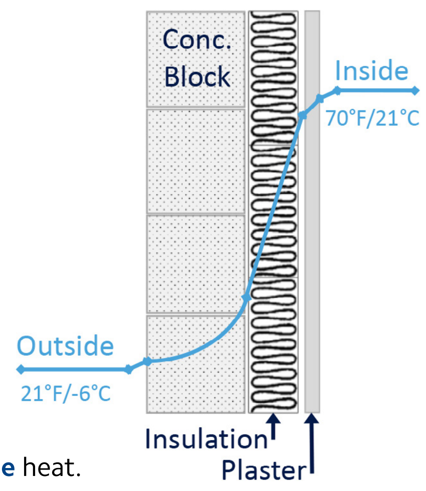
This **Wind Direction** chart at the project site indicates the direction from which the wind is blowing, and each direction is displayed as a percentage of time that the wind blows from that direction each month. In this example, the wind blows from the west for the majority of the year.



East North South West

Building Constructions and Assemblies

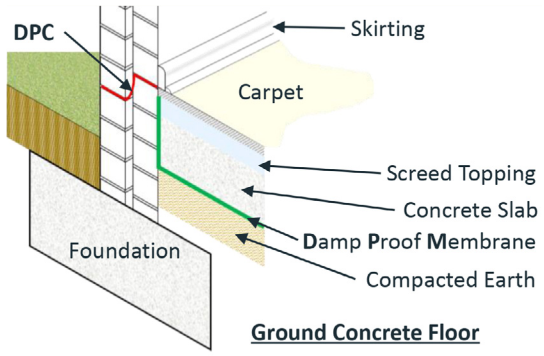
The **thermal** performance of the **Building Envelope** (roof, walls, floor, glazing) plays a significant role in heat flows, and therefore influences the HVAC system size and building energy use. An important balance of thermal performance must consider thermal inefficiencies such as glazing, in order to provide better visual performance, daylight and views for the occupants. The envelope functions as the barrier between the indoor and outdoor environment. The overall heat transfer coefficient of an envelope assembly is represented by a calculated **U-value** or **U-factor**.



- **U-value** = Heat Transfer Coefficient of an assembly, including for all layers
  (Btu/h*ft²*Degree F) or [W/(m²*K)]. $U = (1/R_{TOTAL})$.
- R_{TOTAL} = Total thermal resistance of all assembly layers, including air resistance
  (h*ft²*Degree F/Btu) or [(m²*K)/W]. $R_{TOTAL} = (1/U)$.
  $R_{TOTAL} = (R_{OUTSIDE\ AIR} + R_{MATERIAL\ \#1} + R_{MATERIAL\ \#2} + R_{MATERIAL\ \#3} + \ldots + R_{INSIDE\ AIR})$
- **R** = Thermal resistance of heat flow for a material. $R = L / k$, where:
  L = Thickness of a Material (inches) [mm]
  k = Thermal Conductivity of a Material (Btu.in/h.ft2.°F) [W/(m*K)].
- **Density (ρ)** – the mass per unit volume (lb/ft³) [kg/m³]
- **Specific Heat Capacity (c_p)** – amount of heat that must be added to one unit of mass to raise the temperature one unit (Btu/lb.°F) [J/(kg.K)]
- **Thermal mass** – ability of a material (or assembly) to **absorb, store, and release** heat. Note the **non-linear temperature profile** through the concrete block layer.
- **Total Envelope Heat Transfer (Q):** Q = Heat due to Clear Field (Q_0) + Heat due to Thermal Bridging Anomalies
- **Envelope Clear Field Heat Transfer (Q_0):** Q_0 = U-value * Area of Assembly * ($Temp._{OUTSIDE} - Temp._{INSIDE}$)
- **Envelope Thermal Bridging Heat Transfer (Q_{TB}):** $Q_{TB} = \sum(\psi * L) + \sum(\chi * N)$, where:
  L = Length of Linear Thermal Bridge; and **ψ** is the Psi-factor.
  N = Number of Point Thermal Bridges, and **χ** is the Chi-factor.
- **Solar reflective index (SRI)** – indicator of the ability of a roof to return solar energy to the atmosphere
- **Emissivity** – effectiveness in emitting energy as thermal radiation.
- **Infiltration Sensible Heat Transfer** due to air leakage: $Q_S = CFM * c_p * (Temp._{OUTSIDE} - Temp._{INSIDE})$, where:
  $CFM = (ACH * Volume) / 60$, making as assumption of ACH due to infiltration. E.g. between 0.05 – 0.25.
  Air tightness limits may be given for an entire assembly, e.g. 0.04 cfm/ft² under a specified pressure differential.
- Characteristic Dimension (B’) is an approximation used to calculate the building ground-contact heat transfer.
  Characteristic Dimension (B’) = [Building Area / (0.5* Building Perimeter)]
- **Vapor Resistivity** – measure of material’s ability to resist permeation of water vapor $(perm.in)^{-1}$ [GN.s/(kg.m)]

Moisture performance: Condensation will occur and form on a surface when the temperature of the **surface** is below or equal to the dew point temperature of the air surrounding the surface.

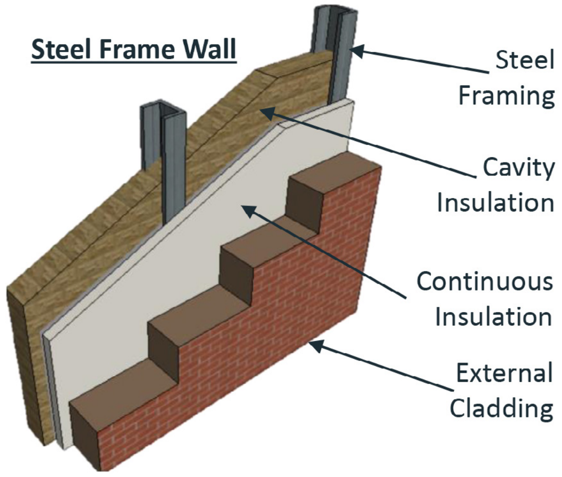
Condensation will occur **interstitially** if the vapor pressure is equal to or greater than the saturated vapor pressure within a construction. Horizontal Vapor Barriers, like a DPC (Damp-Proof Course) within a wall, will prevent rising damp from the ground, while DPM (Damp-Proof Membrane) is a sheet or coating used as a continuous layer to stop moisture penetration from below a floor or through foundation walls.



Thermal Bridging

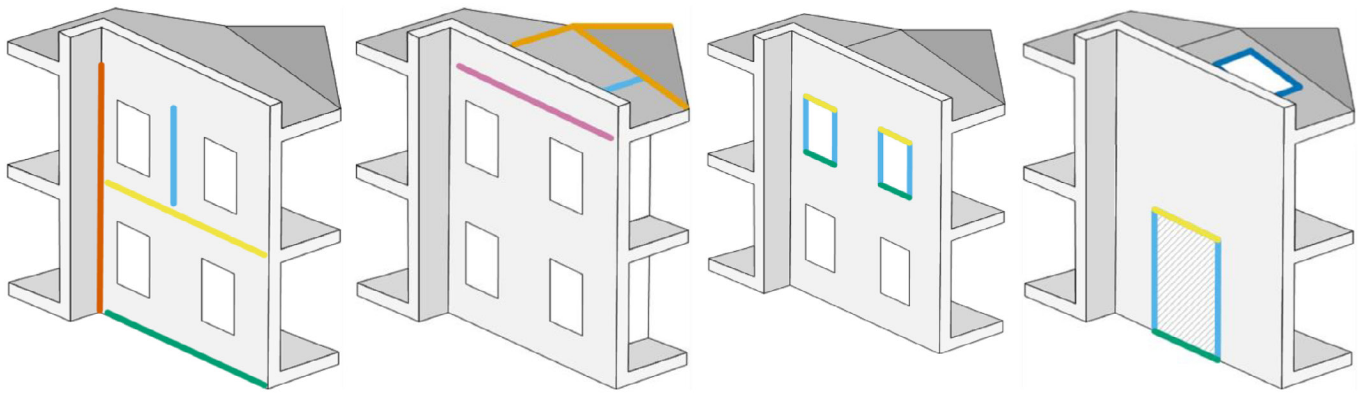
Thermal Bridging occurs when heat moves across an object that is more conductive than the materials around it. This causes the assembly R-value to be de-rated, as heat will bypass insulation, to follow the path of least resistance, thereby increasing the rate of heat transfer.

There are different types of thermal bridges.



Clear-field Thermal Bridges represent elements of a building envelope assembly that are distributed over the area of the assembly; for example, studs, webs, and face shells of masonry units, ties, tracks, plates, girts, and purlins for metal building envelopes, and fasteners. A clear-field thermal bridge is typically represented over a **repetitive** area as a **Composite Layer**, which may have multiple paths of heat transfer in parallel. For example, 80% cavity insulation and 20% for metal or wood framing stud/header. Heat Loss per area may be referred to as **U₀**. Other non-repeating bridges can be considered as ‘random’ categories, such as area bridges, linear bridges or point bridges.

Point Thermal Bridges represent a discreet element that penetrate the insulation in the building envelope; e.g., a beam penetrating a wall, a column penetrating a roof or floor. The cross-sectional area of the point thermal bridge is measured at the outer surface of the outermost layer of insulation that is penetrated by the element. The **Chi-factor**, or **χ** is the thermal transmittance of a point thermal bridge in units of Btu/(h·°F) or [W/K].

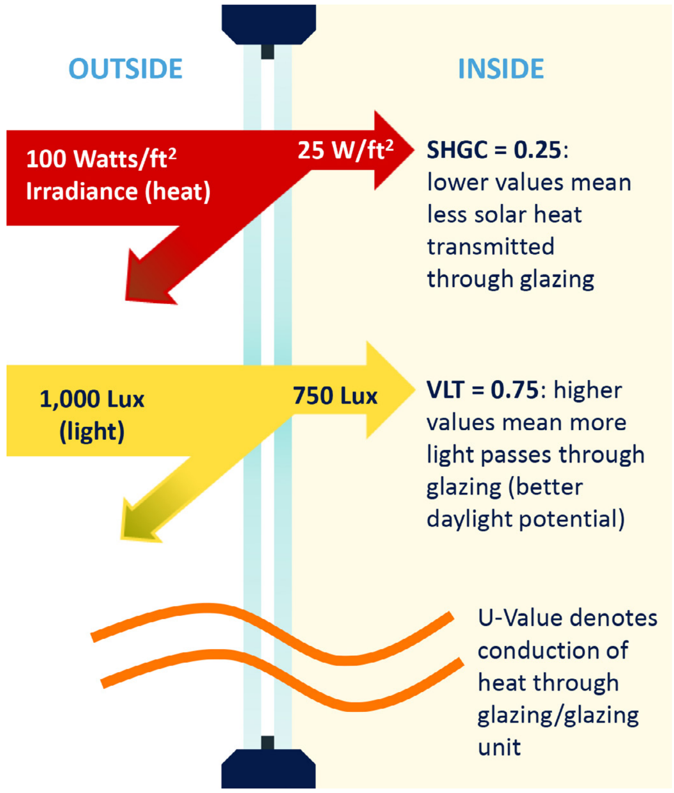


Linear Thermal Bridges represent a length-based element (horizontal, vertical, or diagonal) that penetrates the insulation in the building envelope and with length measured along the exterior surface of the building envelope; e.g., edges of floors, balconies, columns and beams in the plane of an assembly, parapets, roof-wall floor intersections, wall corners, fenestration interfaces, roof transitions, shelf angles, fenestration transitions at lintel, jamb or sill, and similar conditions not otherwise defined as a clear-field thermal bridge or point thermal bridge. The **Psi-factor** or **ψ** is the thermal transmittance per unit length of a linear thermal bridge in units of Btu/(h·ft·°F) or (W/[m·K). Note that some Psi-factors (ψ) lengths are defined differently for an internal plane versus an external plane. Refer to various Compliance Codes & Standards as appropriate: ISO 14683, UK Part L/SAP, AECB, ASHRAE Standard 90.1, and RP 1365.

A simpler (non-Psi) Linear Thermal Bridge transmittance y-value coefficient may be selected in units of Btu/(h·ft²·°F) or (W/[m²·K). This approach is better suited for early-phase design, when more detailed Psi values may not yet be known.

Fenestrations – Glazing Units

Fenestrations may include glazing constructions (windows, skylights or rooflights, glass doors) and other openings such as louvers and doors. Insulating Glass Units (**IGUs**) consist of two or more glass panes separated by a space to reduce heat transfer across the window, while maximizing useful natural daylight into the building. The occupants also benefit from the biophilic access of views to the environment outside and access to ventilation air if the window is openable. Commonly specified IGU metrics include U-Value, SHGC or SC, VLT, leakage & cavity gas.



Solar Heat Gain Coefficient (SHGC) is a measure of how effectively glass transmits solar heat. A lower SHGC value means a lower portion of solar **heat** is transferred through the glazing.

- Generally, lower SHGC values are desirable in hot sunny climates e.g., 0.25, and higher SHGC values are desired in cold climates for passive solar heating, e.g., 0.65.
- **Shading Coefficient (SC)** – replaced by SHGC in the USA but still used in some international locations. SHGC = (SC * 0.87)

Visible Light Transmittance (VLT) or Visible Transmittance (VT) measures how much **light** in the visible spectrum passes through the glazing. Typical VLT values range from 30% for darker, tinted or coated glass with higher reflectivity, to 70% for clearer glass. **Red, Green, Blue Transmissivity** values can be derived from a VLT value.

Light to Solar Gain Ratio (LSG) is the ratio of VLT to SHGC. A high LSG ratio indicates better daylight potential. However, this must be balanced against the overall SHGC, for the space and climate.

LSG = VT (0.75) / SHGC (0.25) = 3.0

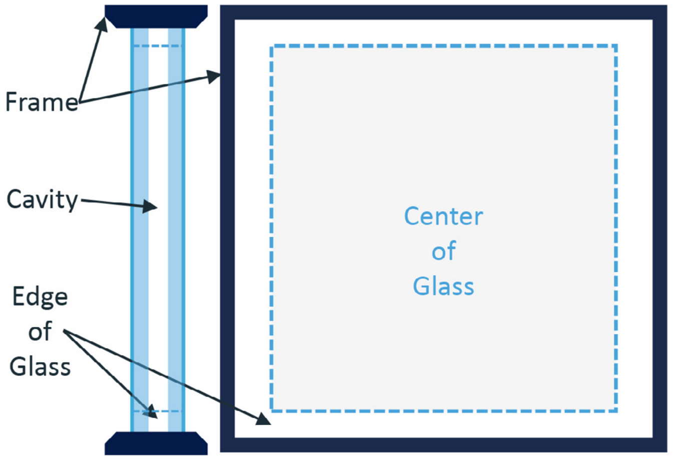
Center of Glass (CoG) U-Value is the U-Value, or U-Factor, of glazing measuring only the glass itself.

Typical U-Values range from 1.14 W/m².K (0.20 Btu/h.ft².°F) to 2.83 W/m².K (0.50 Btu/h.ft².°F).

Assembly U-Value is the U-Value of glazing, including the effects of the frame and mullions. Typically, the assembly U-value is higher than the CoG U-value.

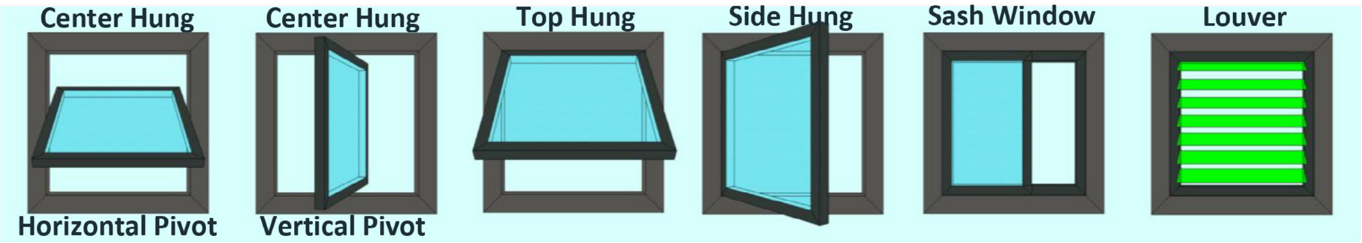
Frame materials can be wood, PCV, alumium, steel, or other metal, some with a thermal break.

Cavity gases of the IGU can be argon (most common), CO_2, Xenon, or Krypton since they are all less conductive than air and improve overall performance.

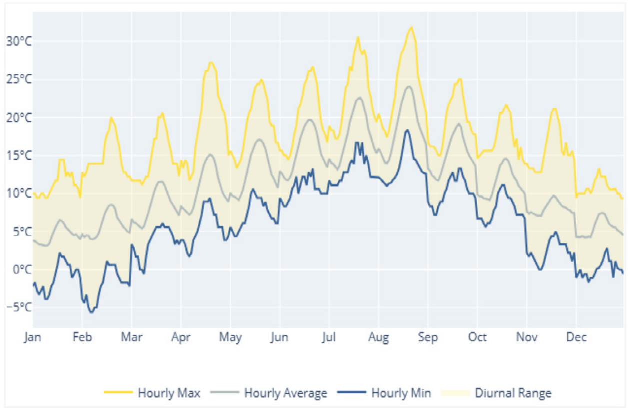


Fenestrations – Window Operation

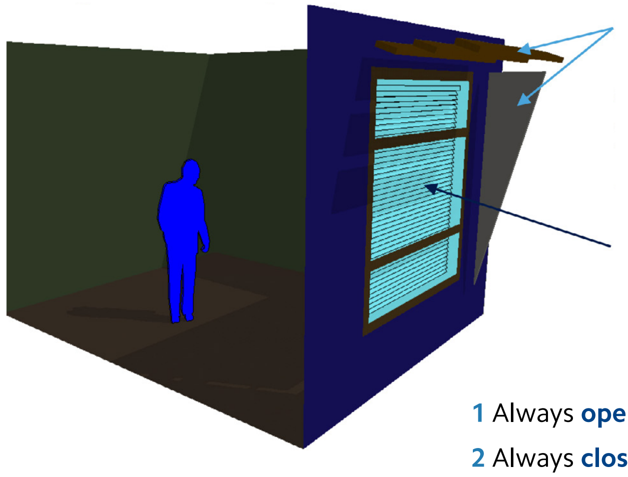
Building occupants can have a profound impact on window performance through their operation of window management devices, such as blinds, shades, or variable transmission glass. **Natural ventilation** is the intentional flow of air through openings such as (1) Windows, skylights, doors; (2) Louvers or dampers; (3) Trickle' vents, other penetrations, and it is driven by natural and/or artificially produced pressure differentials. Windows include crack lengths at the perimeter and effective seals. The effective opening area of a window should not be confused with the structural opening area. The **equivalent orifice area** of the window is a function of the opening area/angles, window type, and proportional dimensions, for which there are many variations.



Other important factors for optimum window performance include (1) Exposure Type, (2) Crack Flow Coefficient & Length, and (3) Window Controls. The window opening control can be via an automated actuator, or it can be assumed to be operated by the building occupant, possibly being notified by a **red-light / green-light** window display. The controls can be set after an understanding of the space function, setpoints, and external conditions. A climate study of the **diurnal temperature ranges** is particularly critical to understand temperature variation over a single day and evaluate nighttime pre-cooling strategies.



The overall performance of the glazing unit is also a function of other dynamic features, such as external shading, electrochromic glazing and internal blinds.



Shading can be motorized or permanently fixed. Horizontal shading is appropriate for limiting solar gains from high solar angles. E.g., summer at noon for a south-facing window (northern hemisphere). Vertical shading is more appropriate for east or west exposures to limit some solar gains at periods of lower solar angles. However, this is more challenging.

Blinds can also be motorized or operated manually when appropriate to limit excessive glare or direct solar beam, causing occupant discomfort. Daylight simulations can consider blinds in three modes.

1 Always **open** – no impact on glazing VLT.
2 Always **closed** – e.g., VLT reduces to ~10 – 37%.
3 Blinds **operational** – switching hourly between open & closed.

Hourly daylight simulation uses an hourly TMY weather file and is primarily concerned with occupied periods.

Daylighting

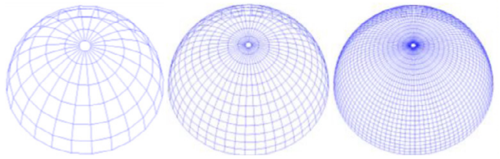
Useful daylight in buildings can be used to reduce energy consumption by reducing the number of hours electric lighting systems are energized, which in turn reduces the sensible lighting heat gains and reduces mechanical cooling demands. Views to outdoors and exposure to natural daylight offer health & wellness benefits to building occupants. A good daylight design can be achieved by optimizing the vertical & horizontal fenestration layouts, utilizing a high-VLT glazing specification, and giving consideration to the external dynamic sky conditions.

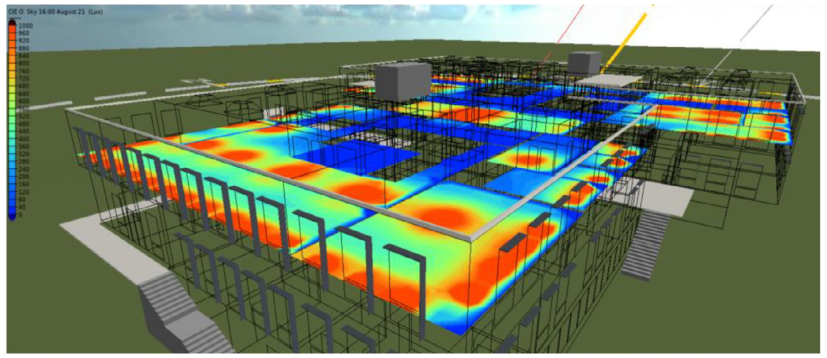
0.0001 lux	0.001 lux	0.01 lux	0.1 lux	1-10 lux	100-1,000 lux	100-100,000 lux	10,000-100,000 lux	100,000+ lux
Dark Cloudy Night	Clear Night No Moon	Young Moon	Full Moon	Street Lighting	Home/Office Lighting	Daytime Overcast Sky	Sunny with some clouds	Sunny sky mid-day

Units for Light: 1 Lux = 0.0929 Foot.candle (fc) and 1 fc = 10.7639 lux. 1 Fc = 1 lumen per ft².

For dynamic climate-based daylight modeling **(CBDM)**, a Perez sky resolution may split the sky hemisphere into sky patches of varying complexity.

145 patches | 577 patches | 2,305 patches

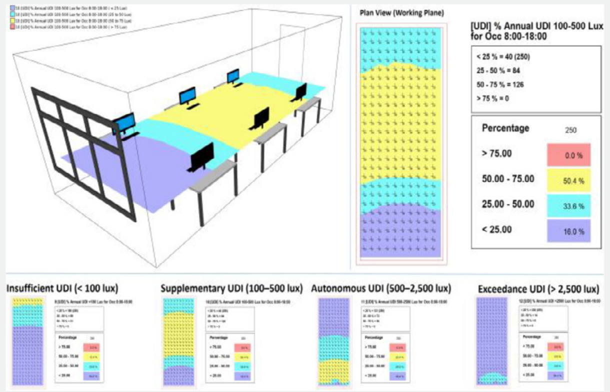




Sky conditions and **exterior obstructions** (trees, shades, blinds, overhangs, adjacent structures) will impact indoor daylight effectiveness and unwanted glare. These factors must be included in the daylight model prediction.

Properties of materials (reflectance, specularity, color, transmittance, etc.) should be included to accurately account for modeled daylight performance and designed electric lighting effectiveness.

Important Daylight Metrics:



Daylight Factor (DF %) is the ratio of the illuminance at a point on a plane in a room due to the light received from a sky of assumed or known luminance distribution, to that on a horizontal plane due to an unobstructed hemisphere of this sky.

Useful Daylight Illuminance (UDI) is the annual occurrence of illuminances that is within a "useful" range for occupants. Examples of UDI ranges are shown as:

(1) Insufficient <100 lux; **(2)** Supplementary 100-500 lux;

(3) Autonomous 500–2,500 lux; **(4)** Exceedance > 2,500 lux.

Spatial Daylight Autonomy (sDA) is the annual sufficiency of daylight levels in a space. sDA examines the percentage of an analysis area (e.g., working plane) that meets a minimum illuminance level (e.g., 300 lux) for a specified fraction of the operating hours per year (e.g., 50% of the annual operational hours).

Additional Resources:

- Definitions of Metrics, including Annual Sunlight Exposure (ASE) and Daylight Glare Probability (DGP).
- Daylight modeling Tutorial; Daylight Simulation, Glare-Modeling, and Lighting Energy Calculations.

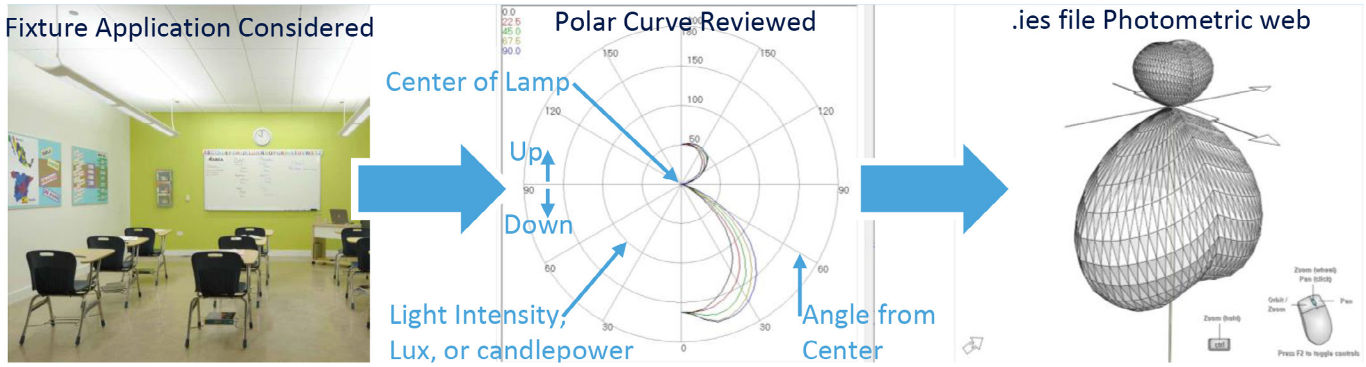
Electric Lighting

A **Luminaire** is a lighting fixture. E.g., a Recessed lighting fixture or a Direct/Indirect Pendant Lighting Fixture.
A **Lamp** is a component of a luminaire (or light fixture), sometimes referred to as the bulb.
Different types of lamp technology may be rated in terms of **Luminous Efficacy**. For example:

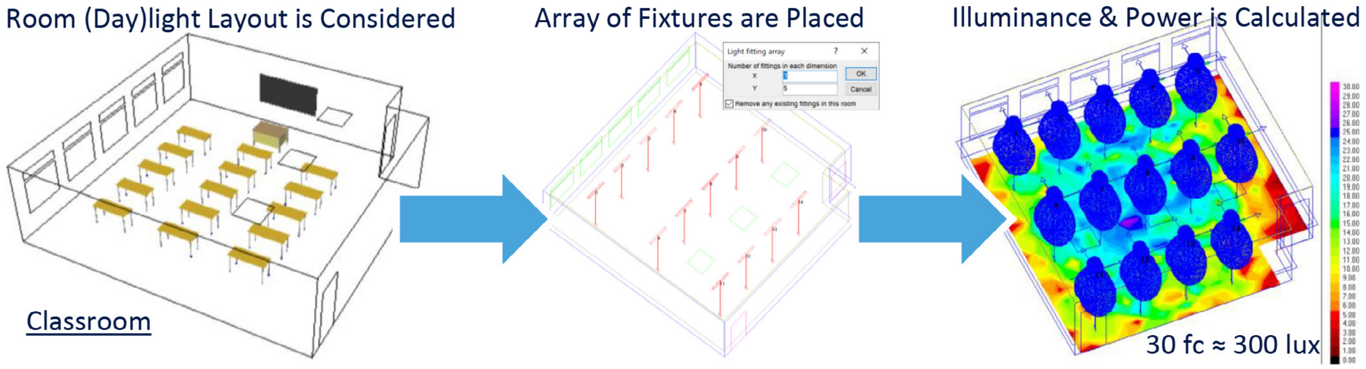
- L.E.D. technology is the most energy efficient, with luminous efficacy of ~100-200+ lumens per watt.
- Fluorescent lamps (~90 lumens/watt) or incandescent lamps (~15 lumens/watt) are less efficient.
- Fluorescent lamps also require a ballast control device to restrict the amount of electric current to it.

Lighting manufacturers will often provide **luminous intensity distribution curves** for their light fixtures or lamps. These are sometimes referred to as **Polar Curves**, which are a graphical representation of the light output (or luminous intensity) from a lamp/luminaire.

A digital version of a Polar Curve is frequently available as an **.ies file**, viewed as a Photometric web below.



Lighting System design is frequently based on the **Point-to-Point Method (or Lumen Method)** to calculate the horizontal illuminance (lux) on a **work plane** (e.g., desk) in a space, and the **uniformity** of light distribution.



Typical recommended lighting levels and **Lighting Power Density (LPD)** for some space types are shown below.

Room Function	Lighting Levels		Lighting Power Density (LPD)*	
	(Foot Candles)	(Lux)	(Watts per ft²)	(Watts per m²)
Classroom – General	30-50 FC	300-500 lux	0.71	7.64
Corridor – General	5-10 FC	50-100 lux	0.41	4.41
Kitchen / Food Prep	30-75 FC	300-750 lux	1.09	11.73
Laboratory (Professional)	75-120 FC	750-1200 lux	1.33	14.32
Office – Open Plan	30-50 FC	300-500 lux	0.61	6.57

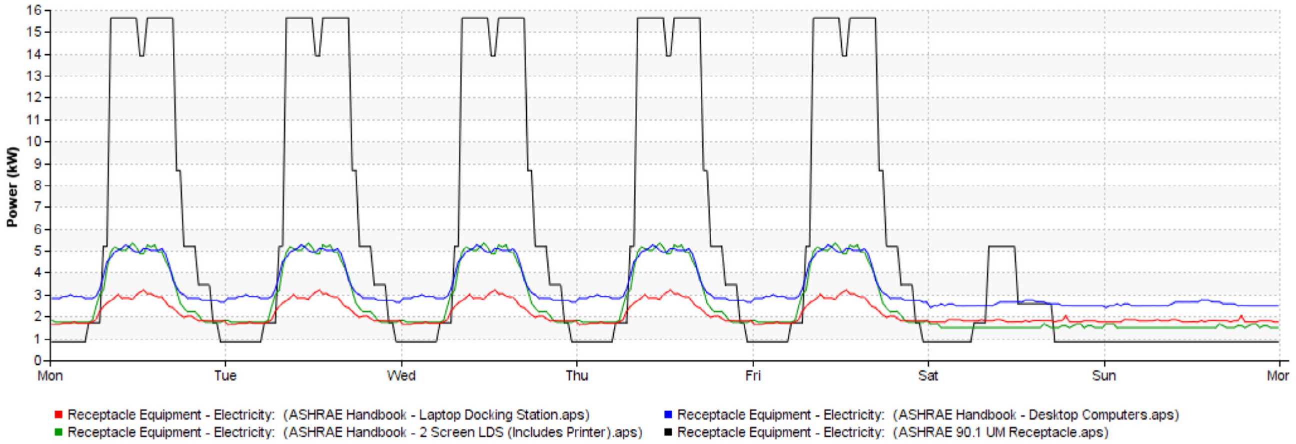
* Lighting Power also generates heat to the space.

Plug Loads and Other Energy End Uses

Most spaces typically have equipment that is plugged into receptacles (e.g., plug sockets in a wall) that use electricity and produce heat as a byproduct. They are commonly referred to as **plug loads**, equipment heat gains, **receptacle** loads, or small power, and examples include computers, televisions, audio equipment, printers, etc. A database of energy-efficient equipment is available via Energy Star. Most frequently, equipment heat gains are input by space type in Watts, Watts/ft², or (W/m²). It is important to study the predicted operational heat gain activity for a typical occupied weekday separately from weekends or holidays. There can also be some seasonal variation. E.g., a school's summer holidays.

Typical Application	Equipment Power Density	
	Sensible W/ft²	Sensible W/m²
Theater	0.5	5.4
Office	1.5	16.1
Office	1.5	16.1
Retail Sales	0.5	5.4
Factory	1.0	10.7
Nightclub/Gym	0.5	5.4
Factory Workshop	1.0	10.7
Classroom	1.0	10.7

A vigilant use of traditional ASHRAE Standard 90.1 User Manual profiles for internal heat gains is recommended since ASHRAE Research Project 1742 monitored modern office equipment power draw and sub-hourly usage as shown below. For example, a 2-screen laptop docking station (LDS) per occupant will result in a predicted 52% reduction when compared to an ASHRAE 90.1 baseline model with 90.1 User Manual profiles.



Vertical Transportation: Multi-story buildings, especially high-rise multi-story buildings, require elevators and escalators to efficiently transport occupants between floors. In addition to the equipment rooms, these systems can require pressurization fans. Note that escalators may operate continuously if no occupancy sensors exist, whereas elevators typically use energy during times of high occupant movement. E.g., morning, lunch, and evening times in an office building.

Exterior Lighting systems for buildings may be mounted on the external façade and within the site boundary. Examples include parking lighting, walkway lighting, retail entrances, and lighting for secure ATM areas.

Process Energy examples may include manufacturing processes in a factory.

Other Process Energy examples include snow melt systems, pump energy for water fountain features, and Electric Vehicle (EV) charging stations.

Refrigeration Systems include refrigerators, freezers, and ice-making equipment.

Commercial Kitchens are typically very energy-intensive due to cooking energy demand from kitchen equipment (fryers, refrigeration, freezers, ovens, etc.); kitchen exhaust hoods and associated make-up air. Cooking byproducts (steam, grease & odors) require thorough consideration for air pressurization and filtration. **Induction stoves** can be ~three times more efficient than gas stoves and ~5-10% more efficient than conventional electric stoves.

Occupant Heat Gains

Internal heat gains from people and other internal sources (lighting, plug load appliances, motors, or process equipment) may contribute to the majority of sources for cooling loads in buildings, particularly as buildings continue to improve upon the construction assemblies and materials in buildings.

Occupant heat gains are a function of varying states of activity, or Met rates, whereby occupants emit **sensible** heat, **latent** heat, and moisture. The impact of occupant heat gains on space cooling loads is affected by the thermal storage characteristics of the space and building because heat gains from occupants are both convective and radiant.

Heat Gain Type	Heat Gain Split (100% Total)	
	Radiative	Convective
Occupant – e.g., office	60%	40%
Plug Load Equipment	10% - 80%	20% - 90%
Lighting	Lighting Varies – e.g., 78% for an LED fixture	Varies – e.g., lighting may be plenum recessed

In each occupied space, a person adds both sensible and latent heat to the space depending on their activity level, metabolic rate, and age. Occupant heat gains are either calculated per person or accounted for by occupant density, e.g., occupant density per floor area.

Level of Activity (values from ASHRAE)	Typical Application	Heat Gain (per/person)			
		Sensible (Btu/h)	Latent (Btu/h)	Sensible (Watts)	Latent (Watts)
Seated at rest	Theater	225	105	66	30
Seated, light work	Office	245	155	72	45
Moderate office work	Office	250	200	73	60
Standing, walking slowly	Retail Sales	250	250	73	73
Light bench work	Factory	275	475	80	140
Athletics/Dancing	Nightclub/Gym	350-550	545-870	100-161	160-255
Heavy work	Factory Workshop	635	965	185	283
Children	Classroom	150	105	45	30

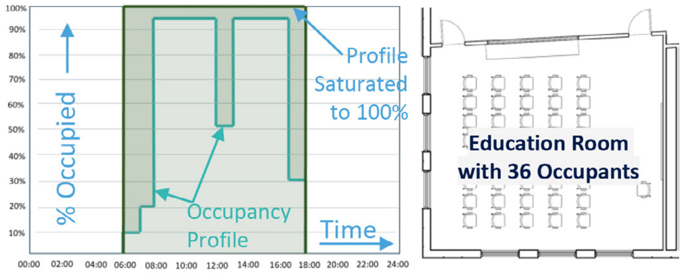
The number of occupants in a space may be determined by two approaches:

(1) By furniture layouts or program tables.

(2) Typical Occupancy Density per floor area

See typical Occupancy Density values below:

Occupant Category	Occupant Density	
	# per 1,000 ft²	# per 100 m²
Classroom (age 5 – 8)	20	
Classroom (age 9+)	25	
Lecture Hall	150 (fixed seats)	
Bank Lobby	15	
Retail Mall	40	
Library	10	
Office	5	
Entertainment Spectator Area	150	



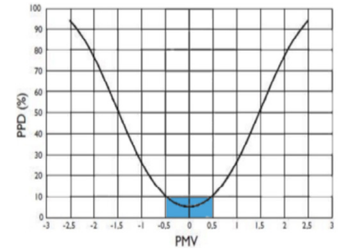
Occupant Profiles and Diversity factors should be considered independently and not equivalent for multiple use cases. For example:

- Design day cooling loads: 100% occupied, no diversity.
- Central VAV-AHU system sizing: ~90% diversity
- Operational modeling: Dynamic Occupancy Profiles.

Human Thermal Environmental Conditions

Dynamic factors that influence indoor thermal comfort for occupants include:
- **Personal** factors include the person's activity, or **metabolic rate**, and their **clothing levels**.
- **Thermal environmental** factors include **air speed, humidity, thermal radiation**, and **temperature**.
- **Nonthermal environmental** factors include air quality, acoustics, and natural illumination or other factors that may affect comfort or health.

Common Dynamic Thermal Comfort Calculation Methods include:
1. Analytical Comfort Zone Method uses Fanger's **7-point PMV-PPD** scale.
   - **PMV:** Predicted Mean Vote. Acceptable limits are **-0.5 to +0.5**.
   - **PPD:** Percentage People Dissatisfied. Acceptable limits are **<10%**.
2. Graphic Comfort Zone Method
3. Elevated Air Speed Comfort Zone.



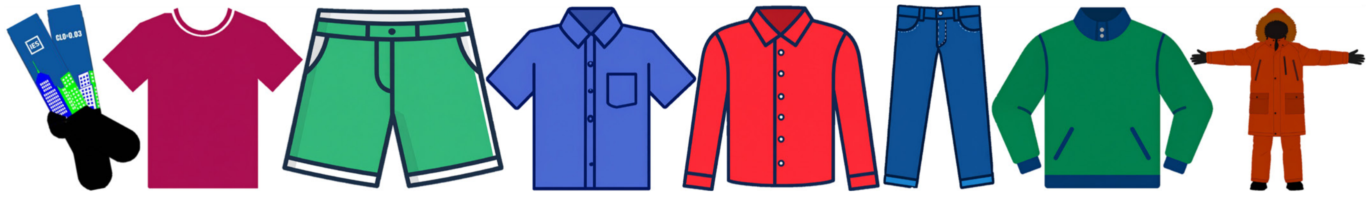
-3	-2	-1	0	+1	+2	+3
Cold	Cool	Slightly Cool	Neutral	Slightly Warm	Warm	Hot

Metabolic rate (Met) is the rate of transformation of chemical energy into heat and mechanical work by metabolic activities of an individual, per unit of skin surface area, expressed in units of Met, which is the energy produced per unit skin surface area of an average person seated at rest. Met varies depending on occupant behavior, such as:

0.7	1.0	1.4	1.7	2.0	3.0	4.0	4.8	7.0
Sleeping	Seated at rest	Sedentary work, standing	Very light work, walking	Walking, Medium light work	Steady medium work	Heavy work, exercise	Sport, very heavy work	Exercise, Heavy sport

1 Met = 58.2 W/m^2 (18.4 Btu/h·ft^2)	1 Clo = 0.88.ft^{2}h°F/Btu = 0.155.m^2°C/W

Clothing Level (Clo) is used to express thermal insulation provided by clothing and varies depending on season, culture, and gender. Clo values per garment are additive for an overall total Clo value. A seated person may be affected by the chair's Clo materials, and Clo levels should **not** be considered as static variables. Typical Clo values:

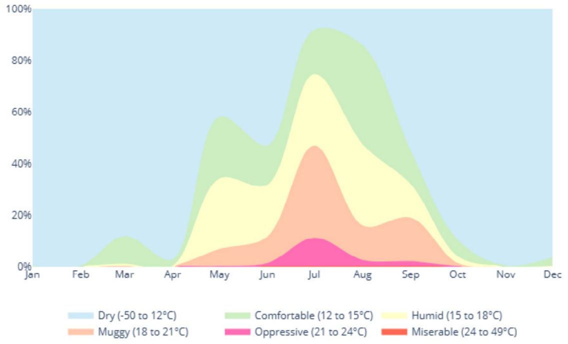


0.03	0.08	0.08	0.19	0.34	0.15-0.24	0.13-0.22	1.3-1.5
Socks	T-shirt	Shorts	Short-sleeved Dress Shirt	Long-sleeved Flannel Shirt	Trousers	Sweater / Jumper	Full Winter Outfit

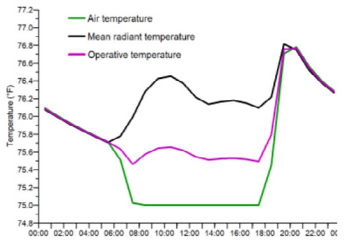
Air Speed is the rate of air movement at a point without regard to direction.
- 20-50 fpm (0.1-0.25 m/sec) is common.
- 20-240 fpm (0.1-1.2 m/sec) is common with local control of elevated air speed.
  - Desk fans, or local ceiling fans may be used for local air speed control.

Occupant Thermal Comfort and Overheating

The Indoor design conditions for air temperature and Relative Humidity (%) can depend upon the space function, activity, occupied period, and season. **Humidity** levels can be a function of the **dew point temperature**, which is the temperature at which air must be cooled to reach 100% relative humidity, causing water vapor to condense into liquid water. Outdoor Humidity Comfort Levels can be displayed as a percentage of time spent in each comfort band during each month. In this example, the most humid month is July, and the least humid month is January.

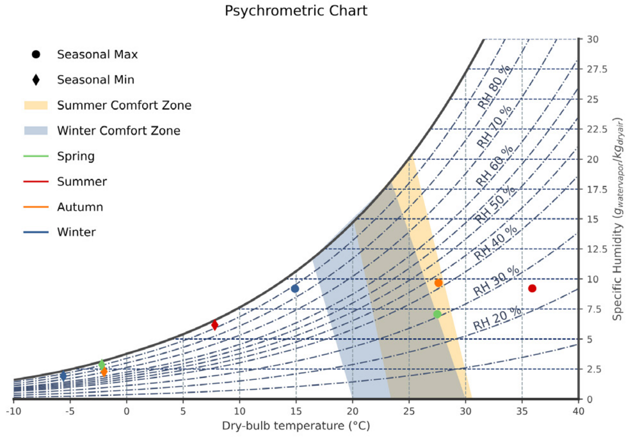


The **Thermal radiation** field around a person may be nonuniform due to hot and/or cold surfaces and direct solar radiation. This radiant temperature asymmetry may cause local discomfort, or high % PPD, and reduce the thermal comfort acceptability of the space. **Mean Radiant Temperature (MRT)** is a measure of the average temperature of the surfaces that surround a particular point, with which it will exchange thermal radiation. **Operative Temperature** is the ~average of the MRT and **Air Temperature**.



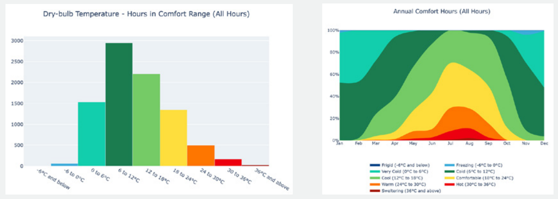
- **PMV:** 70-76°F, 21-24°C
- **Adaptive:** 64-86°F, 18-30°C

The example Psychrometric Chart shows the seasonal average peaks for daily high and low temperatures, plotted against coincident humidity using the ASHRAE Standard 55 **Graphic Comfort Zone Method** for Summer and Winter seasons. Assumptions for the seasonal Comfort Zones:
- **Summer:** 0.5 Clo, Mean Radiant Temperature 25°C (77°F)
- **Winter:** 1.0 Clo, Mean Radiant Temperature 20°C (68°F)
- **Both:** 1.2 Met, 0.09 m/sec (0.3 ft/s) - unnoticeably still.



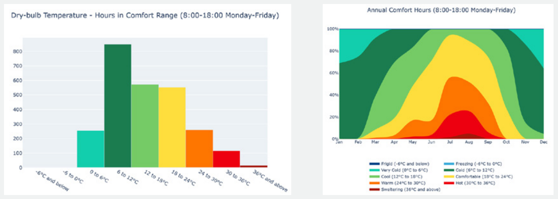
Overheating assessments are a critical part of a resilient building design, accounting for heatwave risks or power outages. CIBSE TM52, TM59, Part O, and LEED have all cited these concerns and provide design guidance to limit the risk of overheating and categorize thermal comfort methodologies into various criteria.

All Hours (8,760 Hours)



Outdoor DBT Ranges (°C) Annual Comfort Hours

Occupied Hours (Monday-Friday, 08:00-18:00)



Outdoor DBT Ranges (°C) Annual Comfort Hours

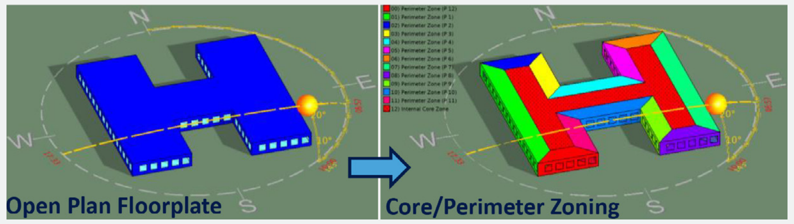
Ranges of outdoor air temperatures are binned into comfort categories. For the **Comfortable** range of 18-24°C (64.4-75°F), 930 hours of Comfort for the entire year reduces to 550 hours when the Occupied period is considered. Levels of **Annual Comfort Hours** are displayed as a percentage of time spent in each comfort band for each month using a sensory scale. This can help to inform seasonal and time-of-day design strategies.

Thermal Zoning for HVAC Design

A Thermal Zone for HVAC design is a space or group of spaces within a building with heating, humidity, or cooling requirements that are **sufficiently similar** so that desired conditions (e.g., same design temperature) can be maintained throughout using a single control device (e.g., thermostat or temperature sensor). Being 'sufficiently similar' is an ambiguous term, so the act of zoning can be considered an imperfect **art** as much as a science. There are numerous design principles that should be considered for an effective zoning strategy, and there will likely be advantages and disadvantages to any zoning strategy. This is the nature of zoning design.

There are likely advantages and disadvantages to any zoning strategy. For example, **a Simple Zoning** approach can be to allocate one thermostat and terminal device to each room – i.e., each room is an independent zone.

Simple Zoning Approach	
Advantages	**Disadvantages**
Dedicated control for each enclosed room or open plan area	Perimeter regions of large open plan spaces not effectively conditioned
Low probability of Unmet Load Hours	Higher first cost

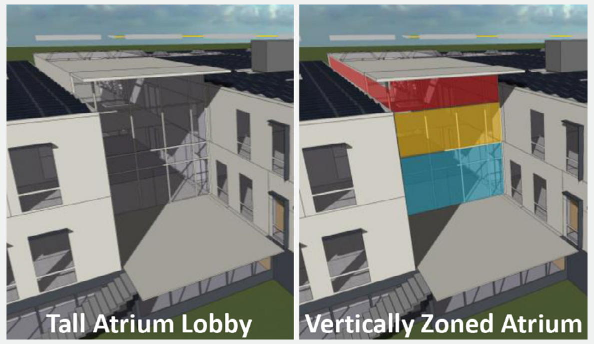


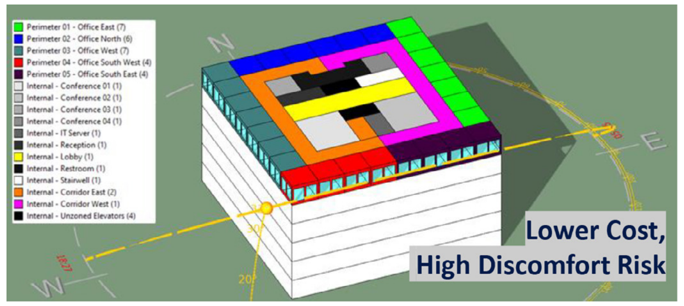
Core and Perimeter Zoning approaches should be applied to large open-plan spaces with multiple exposures at varying orientations. External perimeter zones should be ~15 ft (4.5 meters) or 1.5 times the floor-to-ceiling height.

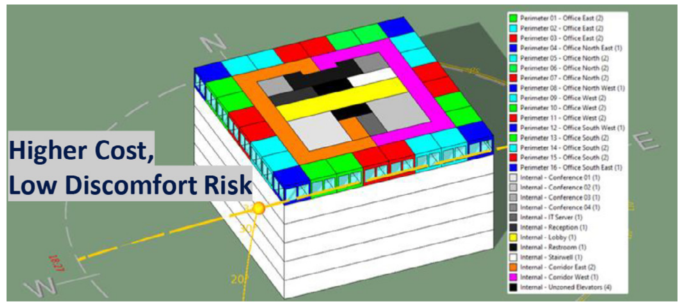
Alternate zoning considerations may include **grouping** enclosed rooms into zones with similar space functions, load patterns, solar exposure, similar load density, ventilation requirements, exhaust air requirements, and **dividing** open plan areas if the perimeter and interior have different load densities. Other zoning considerations include infiltration (e.g., retail entrance lobby), corner spaces with multiple exposures, ground contact spaces (e.g., basements), unconditioned spaces, occupant comfort (e.g., a CEO/director office), cost, and convenience.

The atrium example (right) demonstrates a vertical zoning approach whereby the **lower occupied zone**, **middle stratified zone**, and **upper stratified zone** are created independently. Convective heat will rise from the lower occupied zone, and radiative heat from above will be directed to the lower occupied zone.

The intermediate floor plate example (below) demonstrates two different zoning approaches. The lower-right option would be considered a standard design that considers both thermal comfort with capital cost.





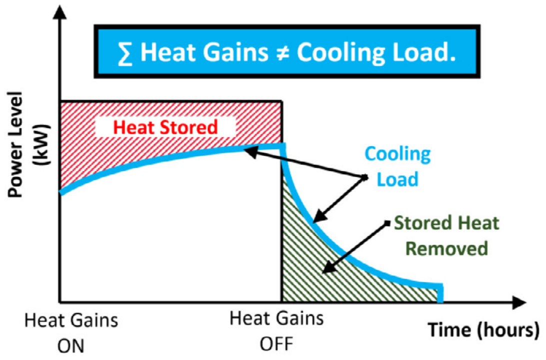


Heating and Cooling Loads Calculations

Calculating Heating Loads and Cooling Loads for rooms and thermal/HVAC zones is required to determine the amount of heat that must be added or removed to the spaces in order to maintain design setpoints in those spaces at the time of peak design conditions.

Unless there are other requirements (e.g., primary ACH), room & zone loads calculations are normally the basis of HVAC emitter sizing for the room & zone. These loads will influence the sizes and capacities of airflow diffusers, radiators, reheat coils, VAV boxes, pipes, ducts, heat pumps, boiler, chiller, etc. There are two popular load calculation methods used in industry:

- ☑ **The ASHRAE Heat Balance Method**
- ☑ **The CIBSE Admittance Method**

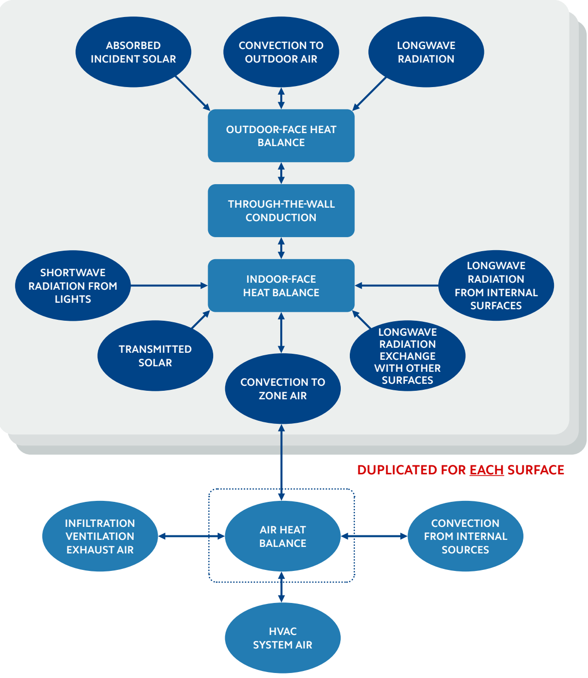


A **heating load** is quasi-steady-state, and predominant factors influencing the load include fabric conduction and infiltration heat losses. Solar gain should be excluded. The most important concepts to understand for how **cooling loads** are calculated include:

- There is a time value associated with the calculation.
- The cooling load is **not** equivalent to the sum of heat gains since a zone has thermal mass, and a heat gain has a split between convective and radiative heat.

Typical requirements for Heating and Cooling Loads Calculations that utilize a **Heat Balance Method** include:

- Design Weather Data and Indoor Design Conditions
- Hourly solar radiation through fenestrations for **all** building room surfaces and optional accounting for blinds or shades.
- Opaque envelope components with thermal mass effects
- Sensible and latent heat gains from infiltration
- Hourly Internal Heat Gains; including **hourly** sensible & latent heat gains, convective & radiative apportionments, number of occupants & activity levels, diversity load factors, and (recessed) lighting heat gain to a ceiling plenum.
- Heating Load including infiltration, cold processes (e.g., refrigerated cases), and the **optional** inclusion of internal heat gains, excluding solar heat.
- System Cooling and Heating Loads; including ventilation, duct leakage, fan & pump energy, heat transfer through pipes & ducts, diversity of occupants/equipment/lighting, and psychrometric processes for reheat, dehumidification, humidification, air-mixing & airside heat-recovery (e.g. ERV).



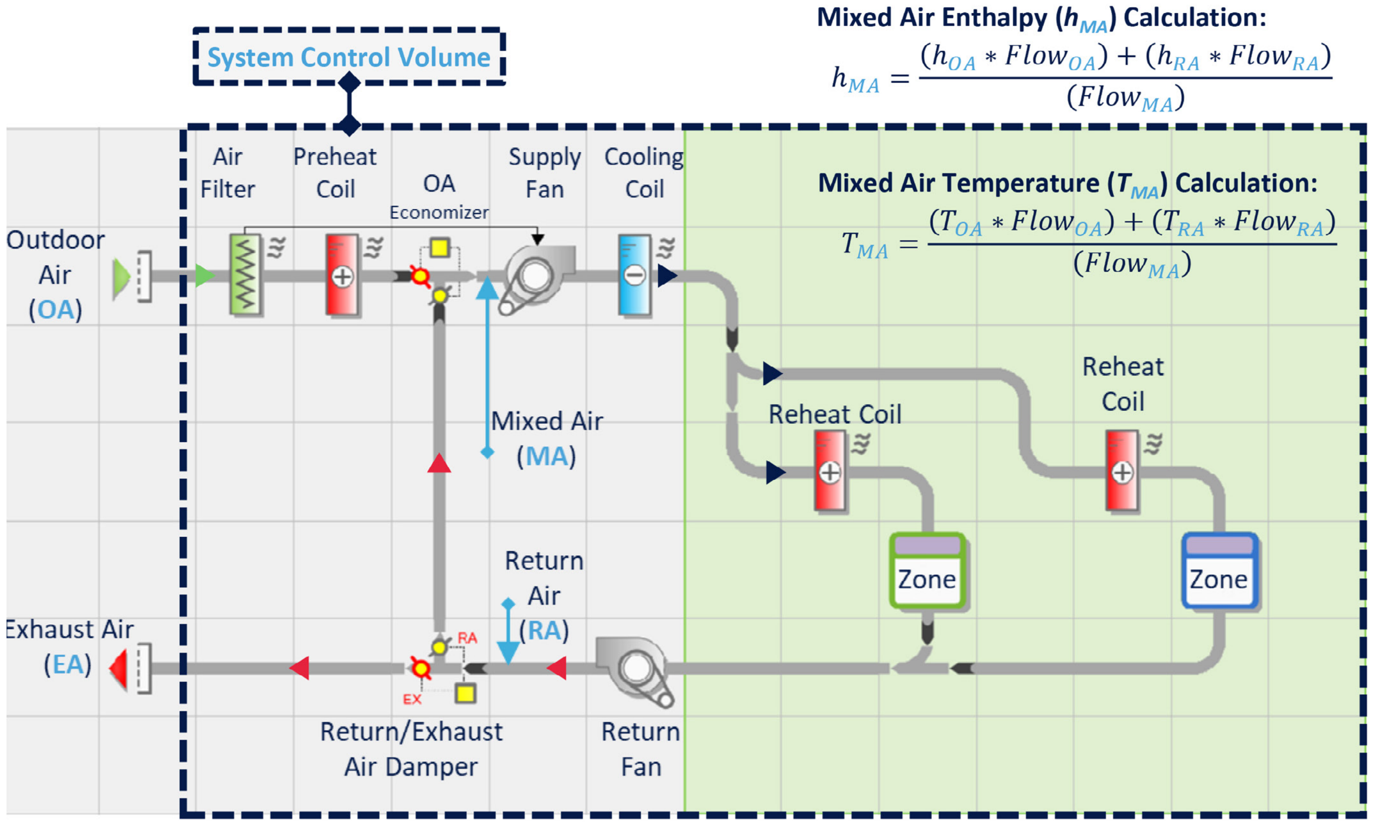
A Design Engineer should consider the following factors when performing load calculations.

- ASHRAE Design day weather data is updated every four years with the latest external design conditions.
- Safety/oversizing factors for peak loads range between 10-15%, after heat gains may be set to 100% on 24/7.
- Peak cooling loads don't always occur during the hottest summer day/time.
- Heat gains/losses from ventilation are frequently handled by the HVAC system (not room/zone). E.g. DOAS.
- Compare calculated loads results against appropriate rules-of-thumb.

Ventilation Air Systems

Outdoor air, or ventilation air, that flows through a building is often used to **dilute and remove** indoor air contaminants. The common relevant phrase in industry is **The Solution to Pollution is Dilution!** Ventilation is the intentional introduction of air from the outside into a building, often via an AHU and ducted distribution system. Ventilation is divided into natural ventilation and forced ventilation. **Forced ventilation** is the intentional movement of air into and out of a building using fans and intake & exhaust vents; it is also called **mechanical ventilation**.

Unlike the heating and cooling loads calculations for rooms and thermal zones, the system loads include the ventilation contribution, sometimes referred to as a **ventilation load**. This ventilation portion of the overall system-level load is defined as the net heat and moisture flux between outdoor air entering the system and exhaust air leaving the system. Therefore, the load is system-dependent and must consider the **System Control Volume** for that specific system type.



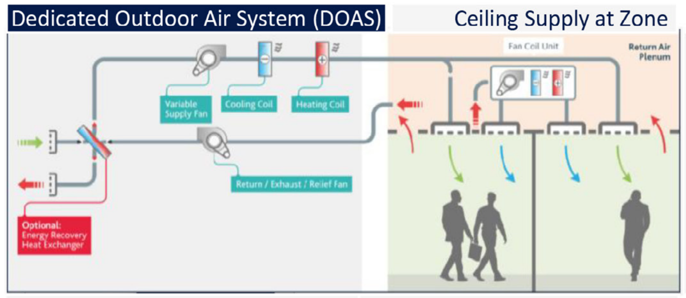
Mixed Air Enthalpy (h_{MA}) Calculation:

$$h_{MA} = \frac{(h_{OA} * Flow_{OA}) + (h_{RA} * Flow_{RA})}{(Flow_{MA})}$$

Mixed Air Temperature (T_{MA}) Calculation:

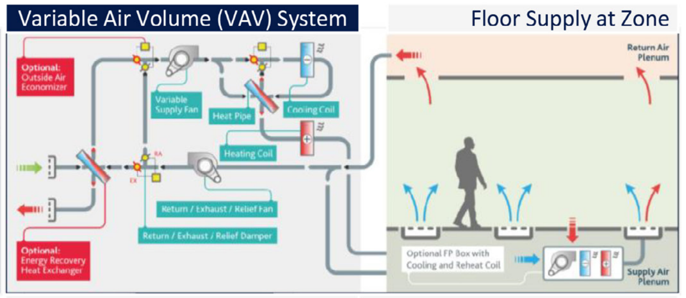
$$T_{MA} = \frac{(T_{OA} * Flow_{OA}) + (T_{RA} * Flow_{RA})}{(Flow_{MA})}$$

Zone Air Distribution Effectiveness (E_Z) is the ratio of the change of contaminant concentration between the air supply and air exhaust to the change of contaminant concentration between the air supply and the breathing zone.



Heating E_Z = 0.8

Cooling E_Z = 1.0



Heating E_Z = 0.7

Cooling E_Z = 1.2

Indoor Air Quality

Humans require good Indoor Air Quality (IAQ) for health, wellness, and productivity. IAQ refers to the types and concentrations of airborne contaminants found in buildings. There are three widely accepted approaches to improving IAQ in buildings.

1. **Source Control** – remove and minimize airborne contaminants. E.g., filtration of Particulate Matter (**PM**).
2. **Ventilation** – provide clean outdoor air to dilute & remove contaminants indoors.
3. **Air Cleaning** – use technology to remove contaminants from outdoor and indoor air. E.g., sorbents.

Forced mechanical ventilation has the greatest potential for control of air exchange when the system is properly designed, installed, and operated. It should provide acceptable IAQ when **ASHRAE Standard 62.1** requirements are followed. Several alternative procedures may satisfy the requirements of this ASHRAE Standard:

1. **Ventilation Rate Procedure (VRP)** – outdoor rates based on space type, occupancy level & floor area.
2. **Indoor Air Quality Procedure (IAQP)** – maintaining concentrations of design Total Volatile Organic Compounds (TVOC) & $PM_{2.5}$, **requiring post-occupancy verification**.
3. **Natural Ventilation Procedure (NVP)** – outdoor air provided through openings

The Ventilation Rate Procedure (VRP) is the most commonly used ventilation calculation method and states that IAQ is assumed to be acceptable if both:

A. The concentrations of **six pollutants** in the incoming outdoor air meet the national ambient air quality standards. E.g., **CO**, **O_3**, **$PM_{2.5}$**, **NO_2**, **sulfur oxides** (**SO_2**, **SO_3**), **and Lead** (**Pb**).
B. The outdoor air (OA) supply rates meet or exceed values provided in a table, depending on the space type. The minimum outdoor air supply will maintain an indoor **CO_2** concentration below 0.1% (1,000 parts per million), assuming a typical **CO_2** generation rate per occupant. For example, the office minimum OA ventilation requirement is: **OA = 5 cfm/person + 0.06 cfm/ft²; or [OA = 2.5 L/s/person + 0.3 L/s/m²]**

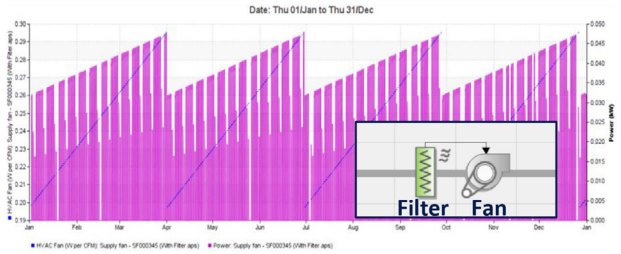
Space Function	CFM/Person	L/sec-Person	CFM/ft²	L/sec-Meter²	ECAi CFM/Person	ECAi L/sec-Person
Classroom	10	5	0.18	0.9	40	20
Office	5	2.5	0.06	0.3	30	15
Retail	7.5	3.8	0.12	0.6	40	20
Warehouse	10	5	0.06	0.3	20	10

ASHRAE Standard 170 provides guidance for healthcare and laboratory spaces, typically specified with primary, ventilation and exhaust rates, by Air Changes per Hour (ACH); and ASHRAE Standard 241 specifies Minimum Equivalent Clean Airflow (ECAi) per Person in a Breathing Zone when in IRMM infection risk management mode.

Filtration

Air filters improve the quality of the airstream by removing contaminants. **ASHRAE Standard 52.2** rates filters using Minimum Efficiency Reporting Values (**MERV**), from 1 to 16.

- **MERV 6** should be placed upstream of the first coil to maintain coil cleanliness for optimum heat transfer.
- **MERV 13** can remove any aerosol contaminant, but not with 100% certainty.
- **MERV 17 and higher** are for **High Efficiency Particulate Air (HEPA)** filters, which can be +99.97% efficient at 0.3 μm diameter.



Filters require regular cleaning or replacement. Increased static pressure from soiled air filters results in a worsening energy penalty on the fan, as shown by the 4-spike saw-tooth graph, representing the 90-day clean-to-dirty filter cycle.

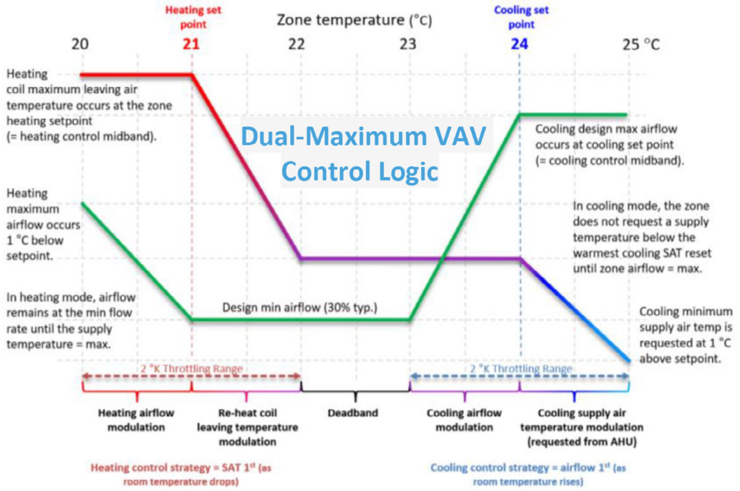
Airside Controls

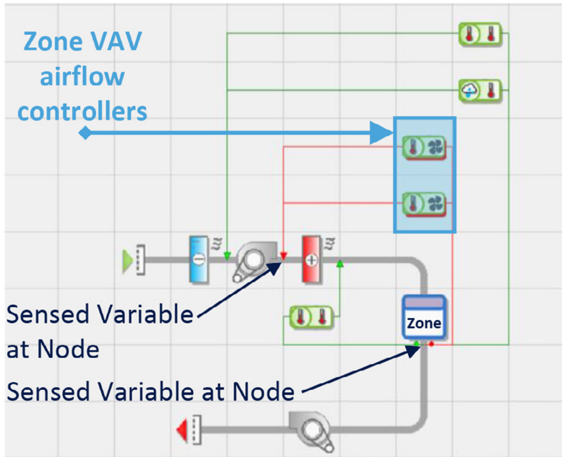
Controls for airside HVAC systems manage the flow, quality, and condition of air within a building's HVAC system schematic or airside network. The simulated model controls ensure that the appropriate volume of conditioned air is delivered to different spaces, maintaining thermal comfort and optimizing for energy efficiency.

Model-Network control logic includes On/Off, Proportional, Independent, Dependent, and Independent-differential. The logical control types typically include '**AND**', '**OR**', and '**Bias**' connections.

Controlled & sensed model variables can include Air Flow Rate, Dry-bulb Temperature, Relative Humidity, Wet-bulb Temperature, Dewpoint Temperature, Percent Flow, Heat Transfer, Moisture Input, and Enthalpy.

Zone thermostatic controls are recommended to provide a temperature range of at least 5°F, within which the supply of conditioned air and/or heat to a zone is shut off or reduced to a minimum. E.g., 69–76°F (18–24°C). One of the more common applications of airside controls is **dual-maximum VAV** (Variable Air Volume) control logic, whereby the controls will manage HVAC airflow by adjusting the volume of air supplied to different zones based on demand. Dual-maximum refers to efficient temperature control of two different maximum flow rates: **(1) cooling**, and **(2) heating**, while maintaining comfort and ventilation requirements in various spaces.





Air Network with Dual-Max VAV Control Logic

Further reading and tutorial video about BPM controls: Fundamentals of ApacheHVAC Airside Controls.

Affinity Laws, for Fans and Pumps:

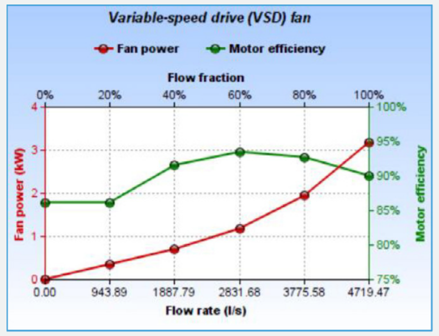
☑ **Law #1: Speed (N) is directly related to flow (Q) and diameter:**
- $CFM_2 / CFM_1 = (RPM_2 / RPM_1)$ … replace GPM for pumps.
- $CFM_2 / CFM_1 = (Diameter_2 / Diameter_1)$

☑ **Law #2: Pressure (P) changes as the square of the flow (or speed):**
- $P_2 / P_1 = (CFM_2 / CFM_1)^2$
- $P_2 / P_1 = (RPM_2 / RPM_1)^2$

☑ **Law #3: Power (BHP) varies as the cube of the flow (or speed):**
- $BHP_2 / BHP_1 = (RPM_2 / RPM_1)^3$
- $BHP_2 / BHP_1 = (CFM_2 / CFM_1)^3$

Pump Power, BHP = (Flow*Pressure) / (Efficiency of Pump)

Pump Motor Power = (Flow*Pressure) / (Efficiency of Pump)*(Efficiency of Pump Motor)

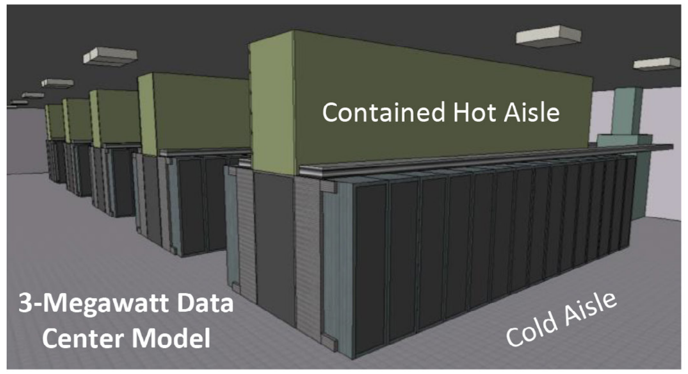


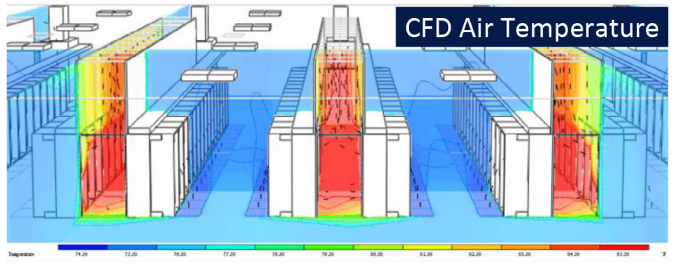
CFD Airflow Simulation

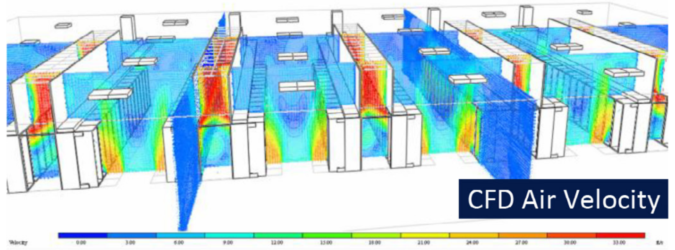
Computational Fluid Dynamics (CFD) simulates how a fluid, like air, moves in and around objects – including buildings, spaces within buildings, and pedestrian areas outside buildings. Sophisticated CFD software is necessary for modeling detailed air temperature gradients, air velocities, pressure, water vapor, age of air, air change effectiveness (ACE), carbon dioxide (CO_2), carbon monoxide (CO), and occupant comfort simulation (PPD, PMV, Operative Temperature). There is a wide range of building-specific applications for CFD.

Data Center equipment generates significant heat which frequently requires airflow management strategies to enhance operational efficiency, reduce costs, extend equipment lifespan, and reduce environmental impact.

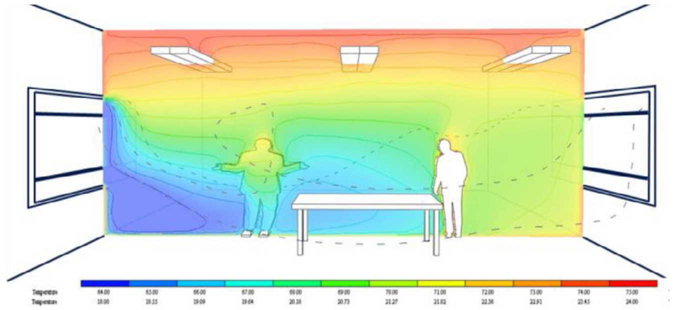
Containment of heat in air in data centers improves cooling efficiency by separating cold air from hot air. In this hot aisle containment strategy example, cold air is provided through perforated floor tiles.



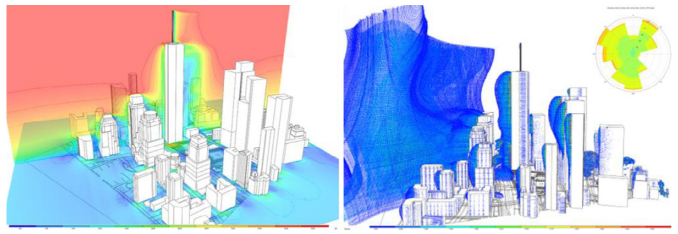




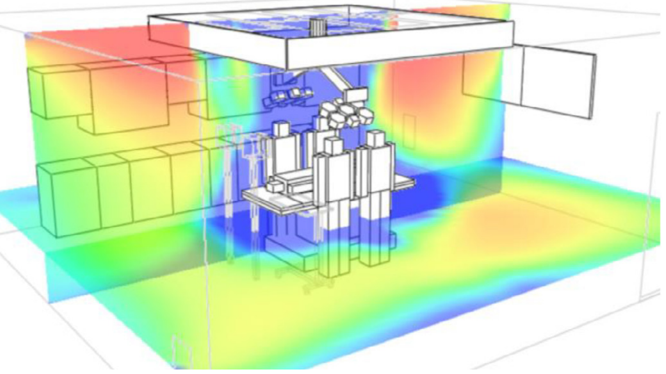
Natural Ventilation CFD simulation is used to evaluate occupant thermal comfort from passive strategies. This can be useful for assessments of overheating and providing increased ventilation air.



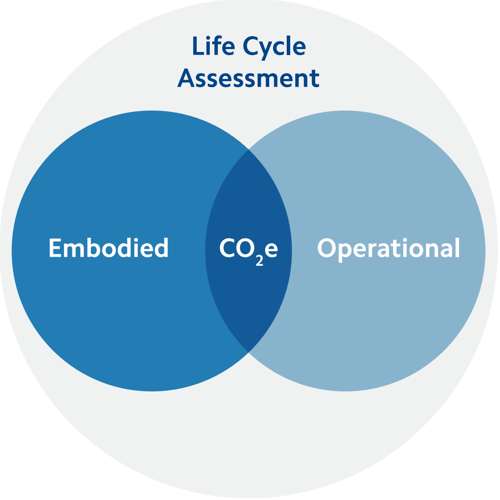
External CFD simulation is used to evaluate wind studies, pressure, and pedestrian comfort.



Contaminant control CFD simulation evaluation is used to evaluate Particle Tracking and the Local Mean Age of Air (LMA), or 'Age of Air' for short. The mean age of air is the average time the air has spent in a space, accumulating unwanted contaminants. In the example, the Operating Room (OR) has a requirement of 20 Air Changes per Hour (ACH); i.e., the room air is to be changed every 3 minutes. This hospital Operating Room CFD simulation is used to evaluate the laminar-flow supply diffusers, room pressurization, equipment, and occupant safety.



Decarbonization



Building decarbonization encompasses the entire life cycle of buildings, including the building design, construction, operation, and end of life. Construction, energy use, fuel use, and refrigerants are the primary sources of **greenhouse gas emissions (GHG)**, generated within a building site boundary. **CO_2e** is used as an **equivalent GHG** in a common unit, and is reported as **$kgCO_2/ft^2$/year** or **$kgCO_2/m^2$/year**. Buildings are responsible for 33% of GHG globally. A building's Life-Cycle Assessment **(LCA)** incorporates embodied carbon and material impacts into performance assessments and considers operational carbon emissions. Strategies for reducing a building's CO_2e include:

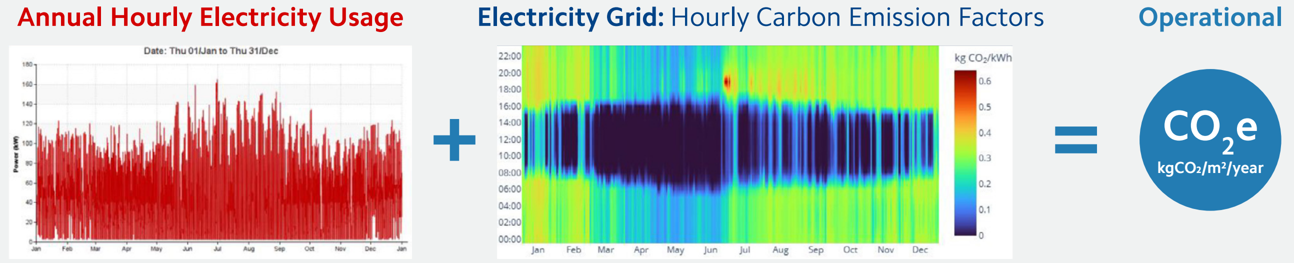
- Reduce or remove building energy use through energy efficiency and energy conservation
- Reduce or remove building embodied carbon
- Eliminate refrigerant releases, minimize leakage, and use low-global-warming-potential (low-GWP) refrigerants
- Energy-efficient electrification of the building's energy demands
- Design buildings to optimize grid flexibility and incorporate energy storage technology
- Provide on-site renewable energy that meets the demand of the building and site, including EV charging
- Decarbonize the electrical grid by considering demand response and the seasonal & hourly stresses of the grid

Whole-building life-cycle assessments (WBLCA) are being incorporated into Building Codes, Standards, and Rating systems to reduce embodied and operational GHG emissions related to buildings and their HVAC&R systems.

- Building performance standards (BPS) are being adopted as a policy tool for existing building decarbonization.
- Common operational metrics include carbon, energy, and cost, but there are many more used in industry.

Operational Carbon refers to the greenhouse gas emissions produced during the sub-hourly actions of a building and its systems, such as HVAC, lighting, water heating, etc. The equation to calculate the operational carbon of a building or site is simple.

[(Hourly Energy Usage, by Fuel) + (Utility Grid Carbon Emission Factor by Fuel)] / Area = CO_2e

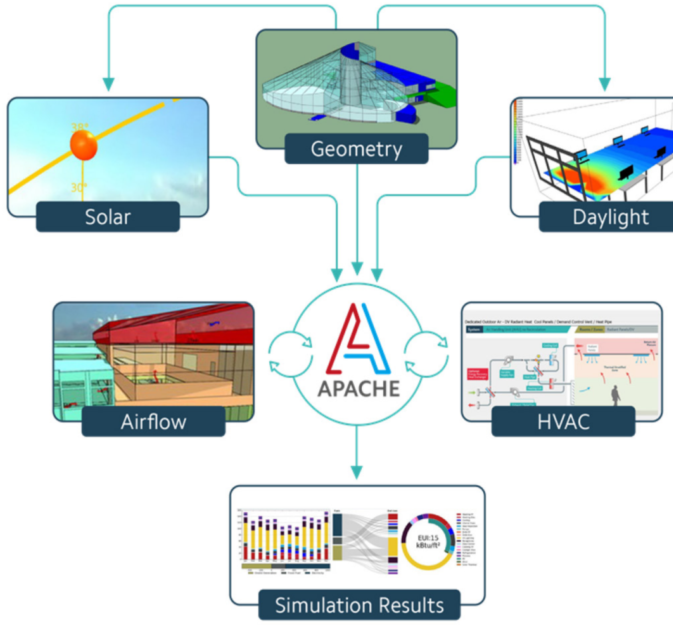


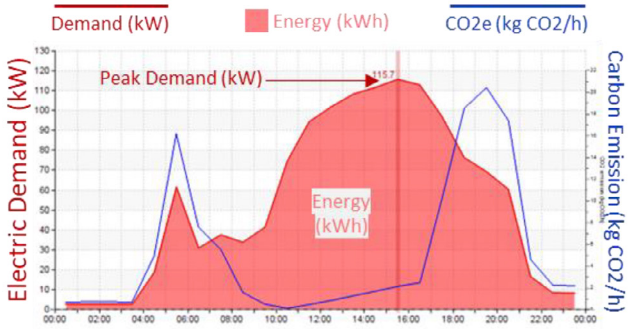
Hourly electrical grid emission factors are generally considered in two different ways: average and marginal, depending on the use case. In the example above, the local utility's Emission Factors for electricity show lower CO_2 factors annually during the day when ample PV electricity generation occurs. Annual average US factors are shown (right), though they do not benefit energy storage strategies.

Fuel	CO_2e emissions factor (100-year), kg/MWh
Propane or LPG	275
Coal	352
Natural Gas	214

Building Energy Modeling

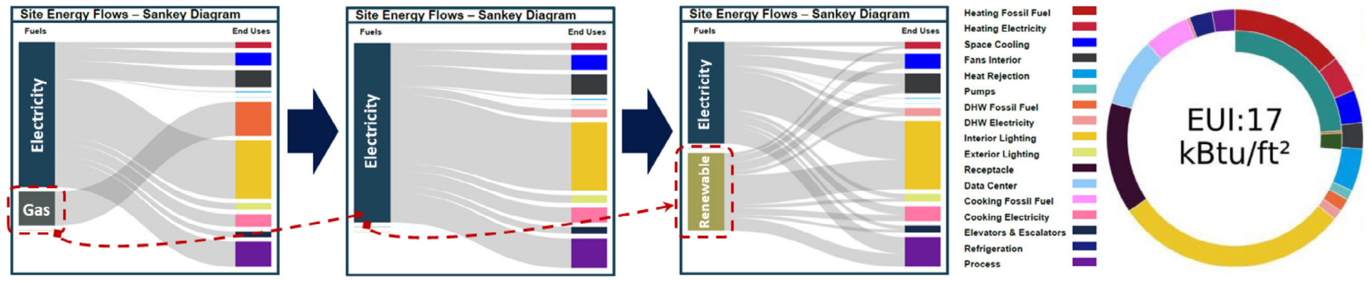
Building Energy Modeling (BEM) is a process that involves creating virtual representations of buildings by utilizing physics-based simulation software tools to predict how a building will perform under various conditions, use & generate energy, enabling informed decisions throughout the building's lifecycle. BEM is used for building design, regulatory energy code compliance, and energy efficiency improvements, by simulating sub-hourly performance, allowing for comparative cost-effective strategies to optimize for site energy use, source energy use, operational utility cost, carbon emissions, or other BEM-related energy metrics as required by the project. Seasonal and Time-Of-Use energy costs can be determined by applying Utility Tariffs (OpenEI tutorial).





While annual energy performance is typically reported as Energy Use Intensity (**EUI**), in units of kBtu/ft²/year or kWh/m²/year for all 8,760 hours per year, it is important to understand the sub-hourly relationships between **demand, or load (kW), energy (kWh)**, and associated fuel-dependent **Carbon Emission (kg CO_2/h)**.

A **Zero Net Energy (ZNE)** building is one in which the sum of all energy that is delivered to the property is less than the sum of all energy that is exported from the property. A ZNE building is not possible without incorporating some renewable energy technology. **Net Site Energy = [Energy Used – Energy Produced]**. The harmony between energy supply and demand on site for ZNE promotes **Electrification**.



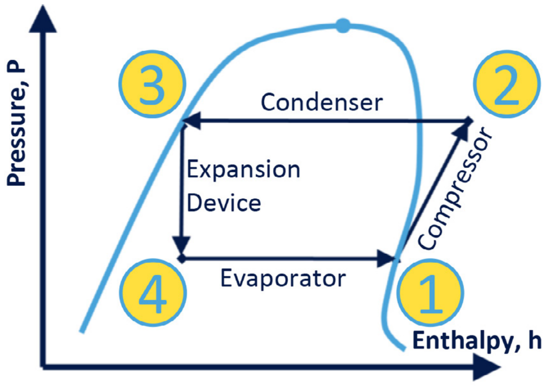
Renewable Energy Technology installed at the building site will generate electricity, and the most common type is Solar Photovoltaic (PV) technology, including Monocrystalline Silicon (η=21%), and Polycrystalline Silicon (η=17%). Building-integrated PV panels should be placed on a model to capture additional benefits of solar shading, which can reduce unwanted cooling loads.

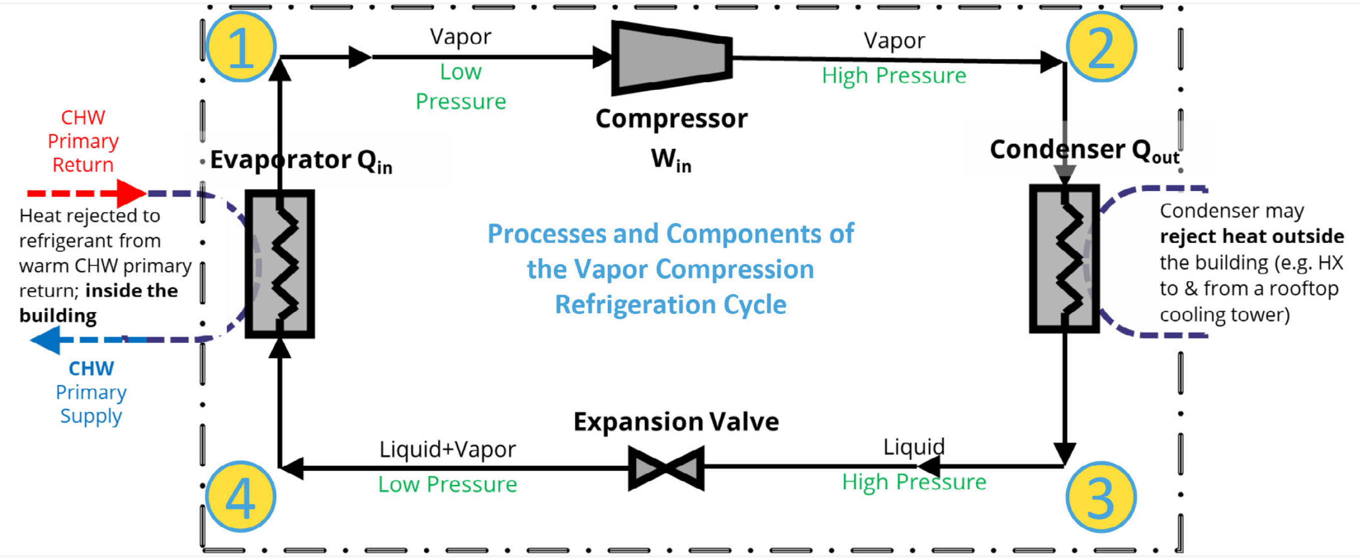
Time-independent **energy storage** is possible thermally from a water tank or electrically by charging/discharging a battery at the building, which may be charged from PV electricity production. Battery discharge can be controlled to meet general electricity building demands, optimized Time-Of-Use (TOU) control, or Demand Response (DR), which can be triggered from a utility provider signal to trim peak electricity demand on the grid.

Refrigeration

The Refrigeration cycle, or **Vapor Compression Refrigeration Cycle**, is a set of closed-loop processes that moves heat from a source to a sink, using a refrigerant fluid. There are four key components of the Vapor Compression Refrigeration Cycle, as shown in the Pressure-Enthalpy diagram and component diagram.

1. **Compressor:** converts low-pressure vapor into high-pressure vapor
2. **Condenser:** reject heat by converting high-pressure vapor into high-pressure liquid; e.g., via forced air, or a Condenser Water (CW) loop
3. **Expansion device:** convert high-pressure liquid into a low-pressure liquid+vapor mixture
4. **Evaporator:** converts a low-pressure liquid+vapor mixture into a low-pressure vapor. This provides the cooling, which may be called upon from a cooling coil.





Closed Loop System Boundary – Example, Chiller (non-absorption)

Refrigerants:

There are several applications of the Refrigeration Cycle in buildings and HVAC system design, including chillers, DX split systems, VRF, and heat pumps. Important factors when considering the refrigerant include:

- Low-to-zero **Ozone Depletion Potential (ODP)**
- Low-to-zero **Global Warming Potential (GWP)** by limiting greenhouse gas leakage into the atmosphere.
- Low Flammability (**A1-A2L class**) and toxicity
- Energy efficiency; heat pump with higher **COP**
- F-gas Regulations against Hydrofluorocarbons (**HFC**)

Coefficient of Performance (cop)

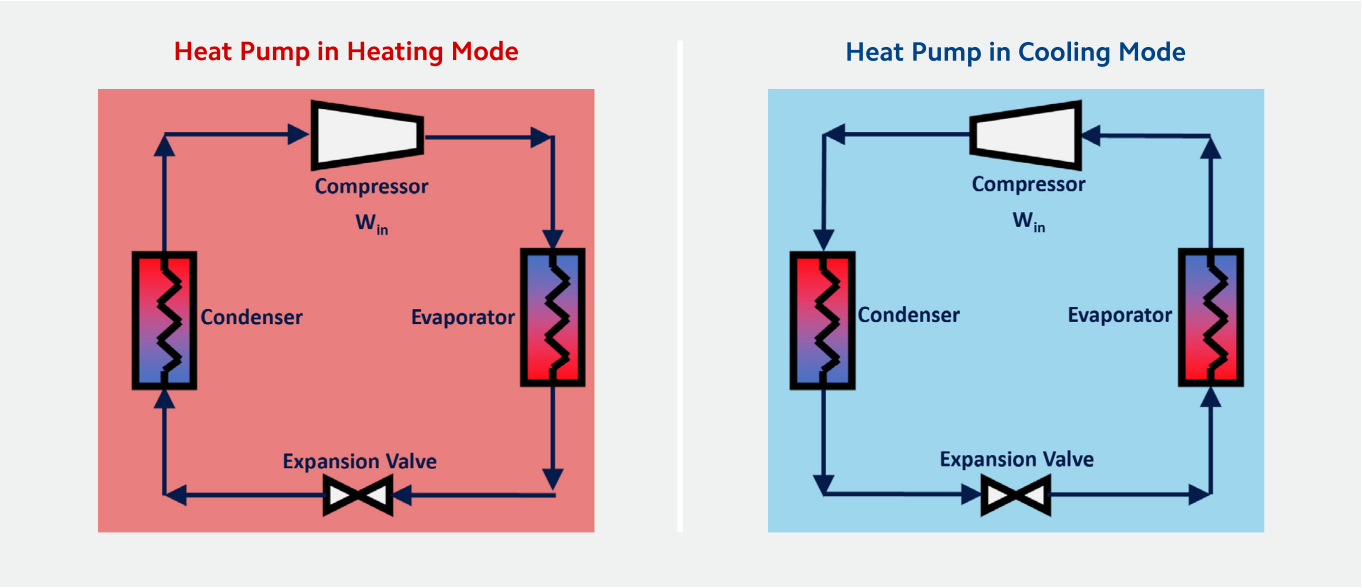
COP = (Refrigeration.output / Work.input)

- $(h_1 - h_4) / (h_2 - h_1)$ …
- Example: (114 – 30) / (140 – 114) = 3.2

- Reducing the Compressor Lift, or ΔP, from 1 to 2, reduces the work and saves energy.
- Reducing a condenser water setpoint or increasing the chilled water setpoint reduces the Lift.
- 1 COP = (EER / 3.412) = [3.517 / (kW/Ton)]
- 1 Ton Refrigeration = 12,000 BTU/hr = 3.517 kW

Heat Pumps

Heat Pumps are mechanical systems that can provide heating or cooling using a reversible refrigeration cycle since the refrigerant out of the compressor can flow in two directions, depending on the desired mode of operation, heating or cooling. Unlike electric resistance heating, which will provide 1 unit of heat output for 1 unit of power input, a heat pump (HP) can provide 2 – 6 times the heat output for 1 unit of power input.



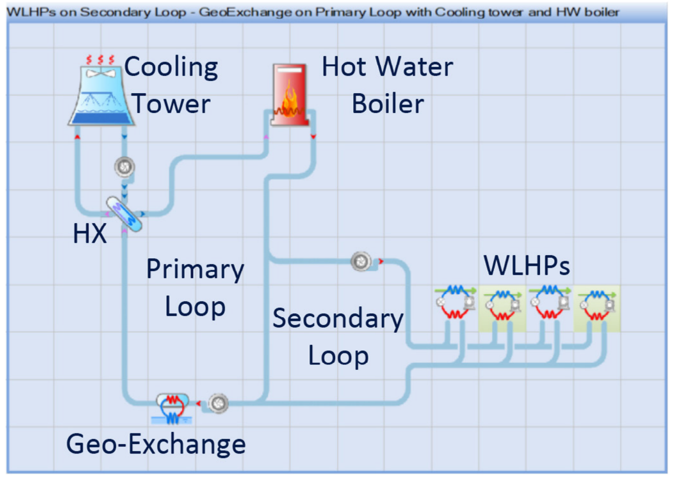
Efficiency rating may use COP, EIR, EER, SEER, SEER2, ISMRE2, HSPF, HSPF2, EF, or UEF, depending on the type.

Air Source Heat Pumps (ASHP) can be air-to-air (AAHP), or air-to-water (AWHP) and the variants include:

- **AAHP:** Ductless Mini Split, Packaged Terminal Heat Pump (PTHP) and Variable Refrigerant Flow (VRF) System.
- **AS-VRF** systems use refrigerant as a distribution fluid to move heat between a variable-speed compressor unit & the indoor fan coil unit(s) to heat or cool an individual zone in a building. Heat recovery from one zone to another is possible with a branch circuit distribution box if simultaneous heating & cooling demand exists.
- **AWHP:** Hot water for space heating is complimented well with low-temperature systems, e.g. radiant.
- **HPWH:** Water Heaters for DHW/service purposes can be coupled with a hot water tank.
- **Defrost** cycles are required when outdoor coil is operating below ambient dew point and it is below freezing.

Water Source Heat Pumps (WSHP) can be water-to-air (WAHP) or water-to-water (WWHP). Variants include:

- **WAHP:** common for individual zone control demand.
- **WWHP:** common application suitable for many occupancies, building types, and DHW configurations.
- **GSHP:** can use the ground/groundwater, lakes, or ponds as heat sources or heat sinks using the same WSHP equipment. The tempered loop shown uses conventional WSHPs maintaining between 13°C (55°F) & 38°C (100°F) using boilers & cooling towers.
- **WS-VRF,** as HP above, with heat recovery of indoor units. VRF may include Heat Recovery modes.
- **Heat Recovery Chiller** for simultaneous heat/cooling.



Heating Systems and Equipment

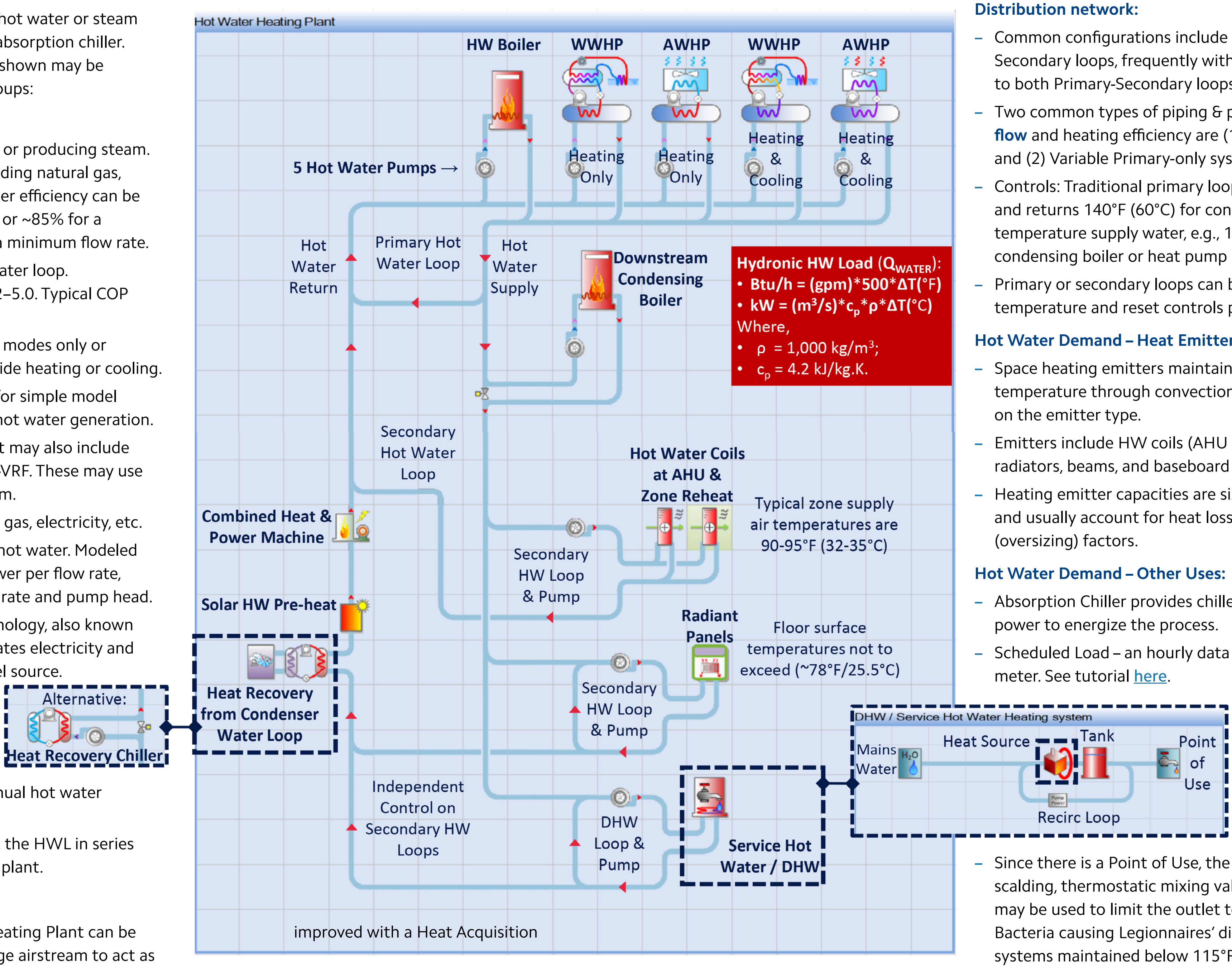
Heating Systems may be used to provide hot water or steam for space heating, service/DHW, or to an absorption chiller. The example hydronic heating schematic shown may be broadly categorized into the following groups:

Heating Plant:

- Boilers generate heat by heating water or producing steam. They can use various fuel sources, including natural gas, oil, propane, biomass, or electricity. Boiler efficiency can be ~95% for a gas-fired condensing boiler, or ~85% for a non-condensing boiler. Boilers require a minimum flow rate.
- Heat pumps transfer heat to the hot water loop. Typical COP of an Air-to-Water HP is ~2–5.0. Typical COP of a Water-to-Water HP is ~4–6.
- AWHPs and WWHPs can have heating modes only or be reversible with functionality to provide heating or cooling.
- Other Heating Plant (part-load curve) for simple model approaches to steam boiler and other hot water generation.
- Non-hydronic space heating equipment may also include gas-fired furnaces, AAHP, or Air Source-VRF. These may use air and refrigerants as a heating medium.
- All heating plants require a fuel source: gas, electricity, etc.
- Pumps are responsible for moving the hot water. Modeled pump energy is often specified as a power per flow rate, though a detailed option includes flow rate and pump head.
- Combined Heat and Power (CHP) technology, also known as cogeneration, simultaneously generates electricity and useful thermal energy from a single fuel source.
- Heat Recovery Chiller (HRC) simultaneously transfers heat to the hot water demand and chilled water demand locations. It is common in building applications with constant annual hot water and cooling demands.
- The Heat Recovery Chiller can pre-heat the HWL in series or in parallel to the existing Hot Water plant.

Heat Recovery:

- The annual average efficiency of the Heating Plant can be improved with a Heat Acquisition Rejection Coil (HARC) placed in a salvage airstream to act as a heat source or sink.
- Condenser water (CW) heat recovery can be used for pre-heat instead of an HRC. A WWHP can be used with the CW.
- Solar hot water preheat systems may be useful on lower temperature HW systems, radiant heating, or DHW as described in this article.



Hydronic HW Load (Q_{WATER}):

- **Btu/h = (gpm)*500*ΔT(°F)**
- **kW = (m³/s)*c_p*ρ*ΔT(°C)**

Where,

- ρ = 1,000 kg/m³;
- c_p = 4.2 kJ/kg.K.

Distribution network:

- Common configurations include a Primary-only HW loop or Primary-Secondary loops, frequently with independent temperature control to both Primary-Secondary loops. All configurations are closed loops.
- Two common types of piping & pumping strategies to manage water **flow** and heating efficiency are (1) Constant Primary-Variable Secondary and (2) Variable Primary-only systems.
- Controls: Traditional primary loops often supply ~160°F (70°C) hot water and returns 140°F (60°C) for conventional HW coil heating. A lower-temperature supply water, e.g., 140°F (60°C), is more suitable for a condensing boiler or heat pump design application.
- Primary or secondary loops can be set up with independent supply water temperature and reset controls per HW load or outdoor temperature.

Hot Water Demand – Heat Emitters:

- Space heating emitters maintain space temperature or supply air temperature through convection, radiation, and conduction, depending on the emitter type.
- Emitters include HW coils (AHU or at zone reheat), heating panels, radiators, beams, and baseboard heaters.
- Heating emitter capacities are sized based on heating load calculations and usually account for heat losses due to distribution and safety (oversizing) factors.

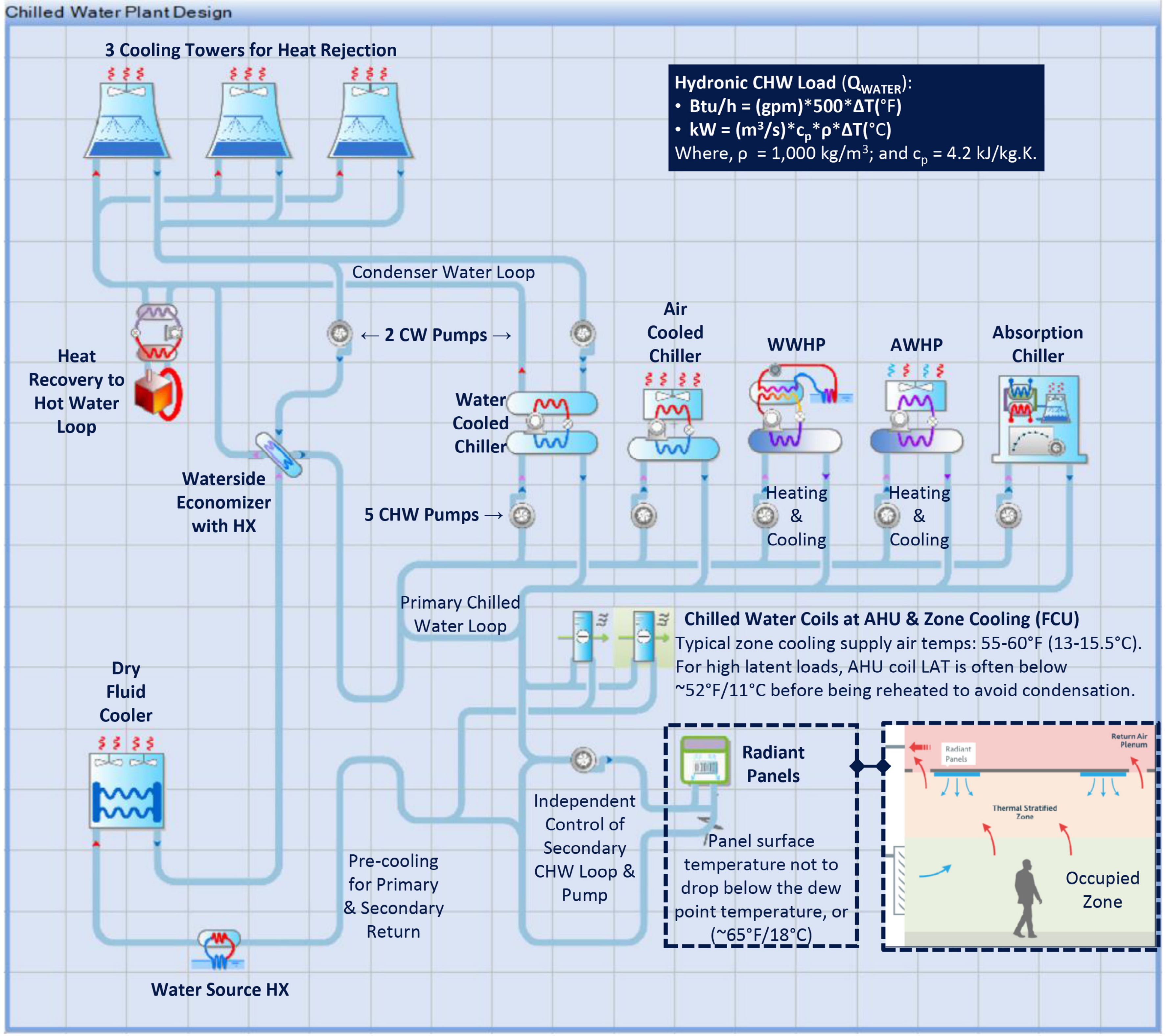
Hot Water Demand – Other Uses:

- Absorption Chiller provides chilled water but uses heat instead of electric power to energize the process.
- Scheduled Load – an hourly data profile, e.g., from an existing building meter. See tutorial here.

Domestic Hot Water (DHW) or Service Hot Water (SHW)

- DHW, or SHW, examples include water heating for showers, cleaning, laundry, handwashing, commercial kitchens, & beauty salons.
- Since there is a Point of Use, the DHW Loop is an Open Loop. To avoid scalding, thermostatic mixing valves for public lavatory faucets/taps may be used to limit the outlet temperature to 110° (43°C). Bacteria causing Legionnaires' disease have been found in DHW systems maintained below 115°F (46°C).

Cooling Systems and Equipment


Chilled Water Plant Design

Hydronic CHW Load (Q_{WATER}):
- **$\text{Btu/h} = (\text{gpm})*500*\Delta T(°F)$**
- **$\text{kW} = (m^3/s)*c_p*\rho*\Delta T(°C)$**

Where, $\rho = 1{,}000\ \text{kg/m}^3$; and $c_p = 4.2\ \text{kJ/kg.K}$.

Chilled Water Coils at AHU & Zone Cooling (FCU)
Typical zone cooling supply air temps: 55-60°F (13-15.5°C). For high latent loads, AHU coil LAT is often below ~52°F/11°C before being reheated to avoid condensation.

Panel surface temperature not to drop below the dew point temperature, or (~65°F/18°C)

Cooling Systems may be used to provide space cooling, dehumidification or process cooling. Tutorials for Airside System setup and Waterside/Plant System detail the process for sizing cooling coils, fans, chillers, pumps, and cooling towers. The example hydronic cooling schematic shown may be broadly categorized into the following:

Cooling Plant:

- Chillers are machines that remove heat from a liquid coolant via a vapor-compression refrigeration (via electric work) or absorption refrigeration (via heat) cycles.
- **Air-cooled chillers** move air across the condenser to reject heat and are constrained by the ambient dry bulb temperature, typically 95°F (35°C) or below, to operate effectively.
- **Water-cooled chillers** use Condenser Water (CW) to reject heat from the condenser.
- **Heat Recovery Chiller** (HRC) simultaneously transfers heat to the chilled water demand and hot water demand locations. Common for healthcare applications.
- Chilled water (CHW) is the common distribution fluid on the delivery side, e.g., to coils.
- Chiller Metrics: EER, COP, EIR, kW/ton, NPLV & IPLV. **IPLV = 0.01A+0.42B+0.45C+0.12D;** where A/B/C/D represent the COP at 100/75/50/25% of the Load, respectively.
- **Heat pumps** transfer heat to the chilled water loop. Typical COP of an Air-to-Water HP is ~2–5.0. Typical COP of a Water-to-Water HP is ~4–6.
- AWHPs and WWHPs can have cooling modes only or be reversible with a heating mode.
- Non-hydronic space cooling equipment may also include AAHP, Air Source-VRF, or evaporative coolers. These may use air, water, and refrigerants as a cooling medium.
- A space circulation fan is not a cooling technology, but it does provide air circulation.

Distribution network:

- Configurations include a Primary-only CHW loop or Primary-Secondary loops, frequently with independent temperature control to both Primary-Secondary loops.
- Pumps are responsible for moving the chilled water (CHW) and Condenser water (CW). Variable speed drives can save pump energy. Controls: Primary loops often supply ~44°F (6.5°C) CHW and can return 54°F (12°C) for conventional CHW coil heating. Higher CHW temperatures are more suitable for a radiant system and heat pump design application.
- CHW reset controls can be per CHW load, coil maximum flow, or outdoor temperatures, dry-bulb or dew-point temperature. Though reset control can be constrained by space dehumidification requirements.

Heat Rejection:

- Condenser water (CW) is the common distribution fluid on the heat-rejection side of a water-cooled chiller, or it can be air for an air-cooled chiller. Condenser water (CW) heat recovery or Heat Recovery Chiller can be used for pre-heating a hot-water loop.
- Common Heat Rejection equipment includes Cooling Towers, Fluid Coolers, water or groundwater heat exchangers. A waterside economizer is used when “free cooling” when environmental conditions are available, so mechanical cooling can be bypassed.

Chilled Water (CHW) Demand Equipment:

- Zone cooling equipment maintains space conditions and can include CHW coils (AHU or at zone), radiant panels, and chilled beams.
- Cooling equipment capacities are sized based on cooling load calculations and usually account for distribution losses and safety (oversizing) factors.
- Scheduled Load – an hourly data profile, see example from an existing building meter.
- Cooling Distribution Unit (CDU) for liquid cooling data-center equipment.

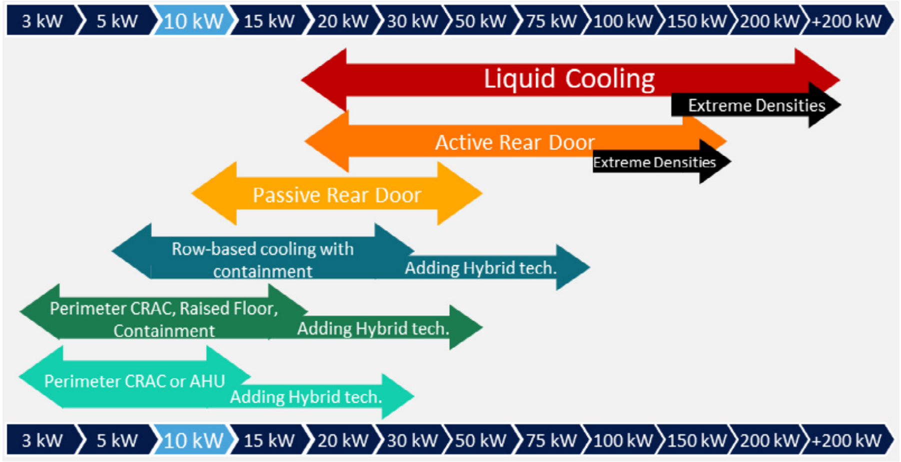
Liquid Cooling and Evaporative Cooling

Liquid Cooling is a rapidly increasing trend for cooling of data center equipment due to the AI-generation graphics processing units (GPUs) having higher thermal density properties than traditional central processing units CPUs. Air-based cooling cannot cool higher-density GPU-based racks efficiently, since the heat generation is too dense. A Liquid Coolant Distribution Unit (CDU) can be used efficiently where higher rack densities occur because liquid is more efficient than air at transferring heat.

Computer Rooms: Most commercial buildings have some on-site IT computer room to house their server/comms equipment. ASHRAE differentiates a computer room from a data hall based on the IT equipment load. An IT load greater than 10 kW is now defined as a Data Center and is often required to comply with ASHRAE Standard 90.4.

Guidance on how various cooling technologies can be considered as the IT rack density increases in the data center is suggested by CDU manufacturers.

- The CDU can maintain temperatures from -20°C to +70°C (-4°F to 158°F).
- The (S-Class liquid) Inlet Fluid Temperature from the CDU is typically a liquid mix of water and propylene glycol.

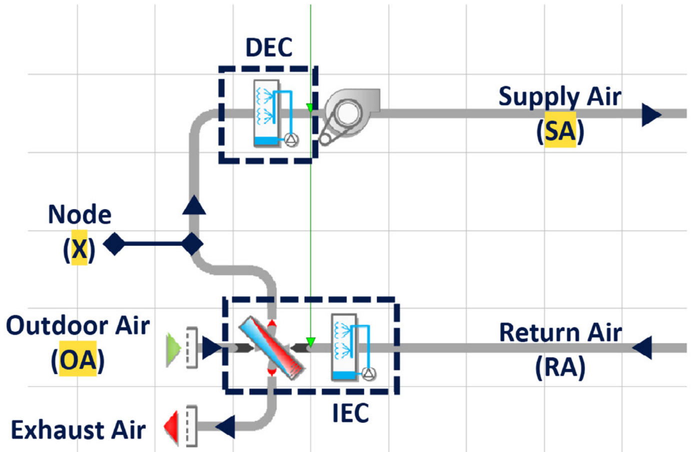


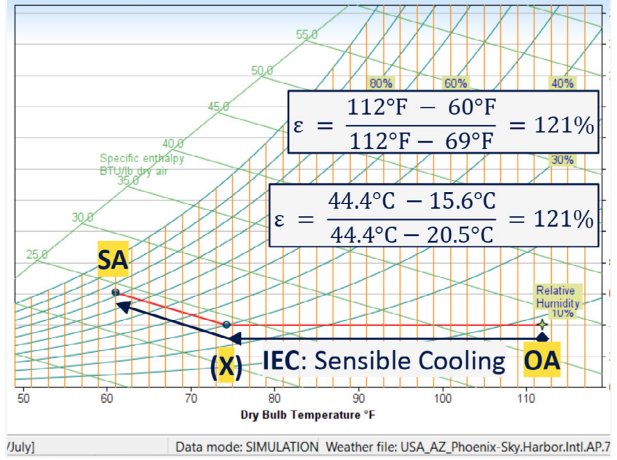
Evaporative Cooling, or evaporative pre-cooling, is an adiabatic **(constant-enthalpy)** energy efficiency option that may avoid or reduce the requirement for a vapor-compression-based cycle that is used in a chiller or heat pump. It can be particularly efficient in hot & dry climates, and for cooling return air with high-density sensible heat gains. There are three common design options:

- **IEC:** Indirect Evaporative Cooling of air not supplied directly to the zone.
- **DEC:** Direct Evaporative Cooling of air directly supplied to the zone.
- **IDEC:** Indirect+Direct Evaporative Cooling is a combination of IEC & DEC.

Wet Bulb Effectiveness (WBE)

$$\varepsilon = \frac{OA_{DBT} - T_{supply\ air}}{OA_{DBT} - OA_{WBT}}$$

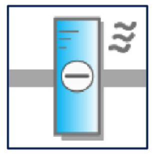




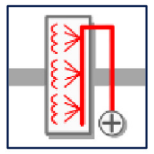
Water-Energy Nexus

The Water-Energy Nexus considers the interrelationship between water and energy. E.g., Power plants consume water for cooling systems, and Water plants consume power for treatment and distribution. Calculating water usage for a building accounts for all water used and recovered inside and outside the building. Aside from DHW demands, HVAC systems can use water and can reclaim water from HVAC processes. HVAC systems can be responsible for up to ~30% of a commercial building's total annual water use.

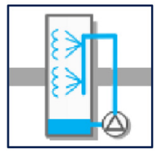
Cooling Coil Condensate Recovery: Latent heat is transferred by moisture in the air to the coil via the process of **condensing** on the surface of the cooling coil.



Steam Humidifiers produce mist by boiling or heating the water, along with increasing the humidity levels in the air. The warm vapors lost to the air requires **makeup** water.



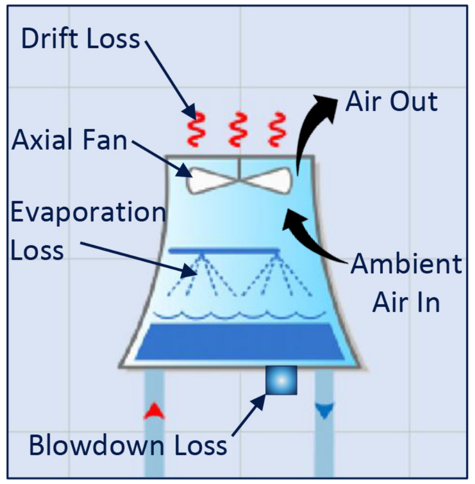
Evaporative Spray Chamber / Wetted Media adds moisture to the air. The air temperature decreases and is humidified, with a constant enthalpy **(adiabatic)** Psychrometric process.



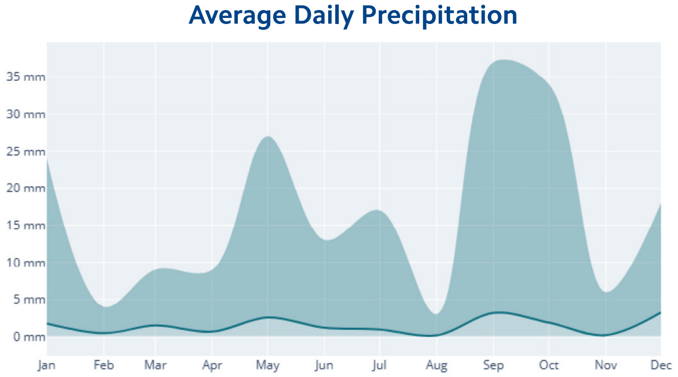
Open Circuit Cooling Tower introduces ambient air into the tower. The condenser water (CW) flows directly over the cooling tower's heat transfer surfaces (or '**fill**'). Varying tower control strategies impacts performance.

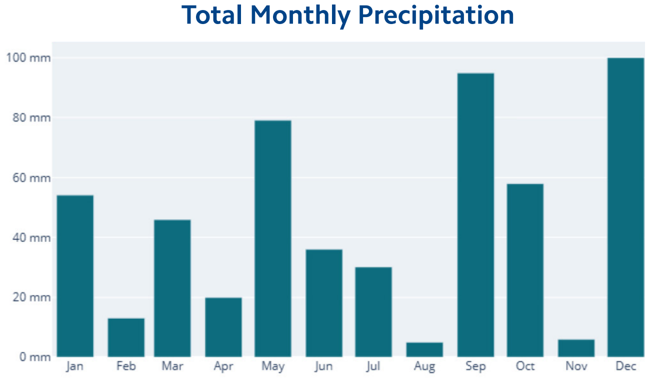
Cooling Tower Makeup water is a function of water losses from:

1. **Evaporation:** Occurs as part of the latent heat removal process.
   - **Evaporation GPM = (Flow GPM * Range °F * 0.001)**
2. **Drift:** Occurs when water droplets are entrained in the air-stream and removed from the tower.
3. **Blowdown:** Occurs when water is drained, or 'blown-down', from the cooling tower basin. The blowdown water has a higher concentration of dissolved solids (after some water was evaporated. When the water concentration of dissolved solids is too high (it becomes hard water) it needs to be diluted so that scaling will not occur in the basin/pipes. The '**Cycles of Concentration**' (CoC) vary by utility water provider and by the seasonal time of year.
   - **Bleed Rate GPM = [Evaporation GPM / (CoC – 1)]**

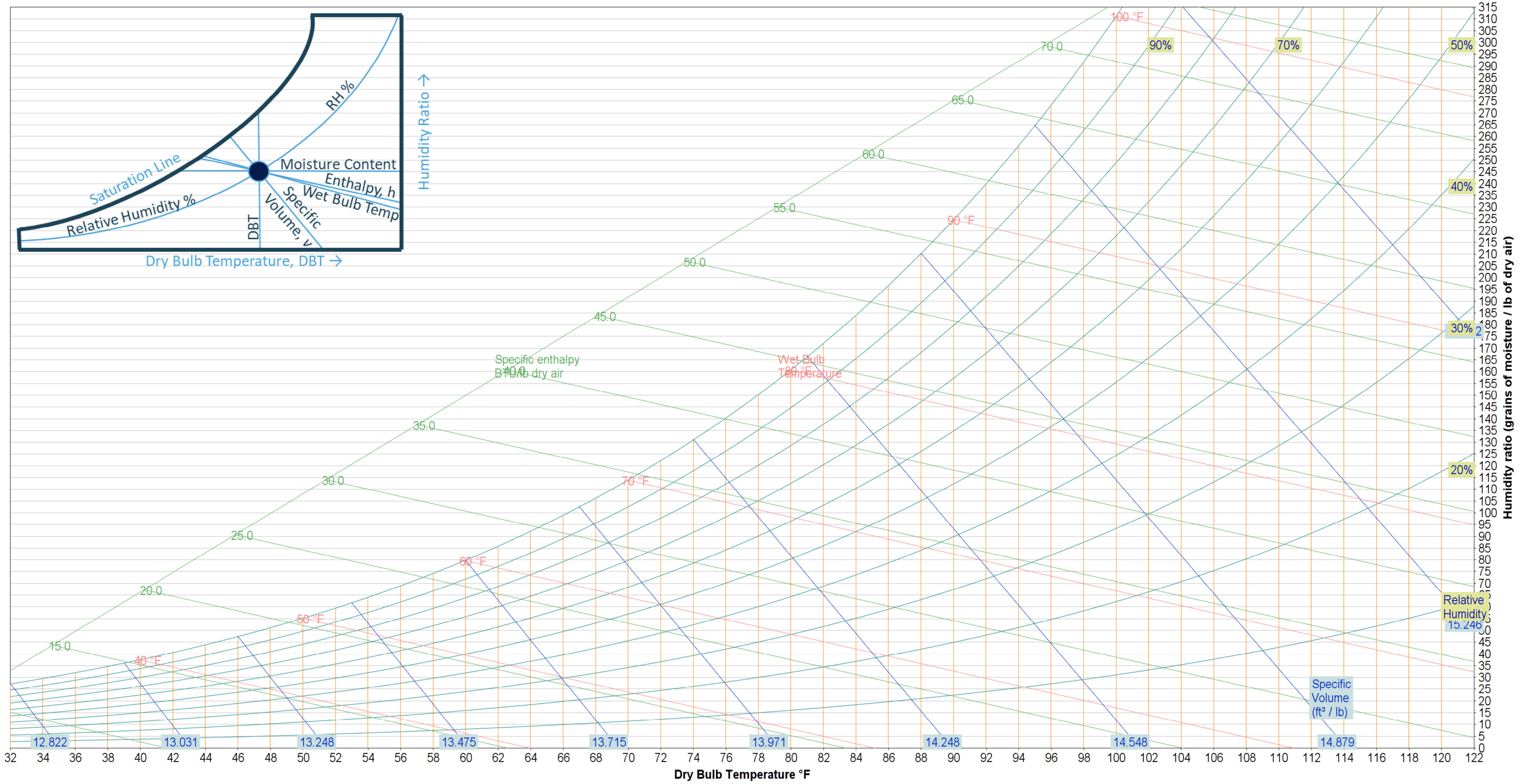


Rainwater harvesting is the collection and storage of rainwater, rather than allowing it to run off. Most commonly, harvested rainwater can be used for non-potable applications such as flushing of toilets, and urinals, and landscape irrigation. Analysis of daily and monthly precipitation from the model's .epw weather file is recommended.
The Average Daily Precipitation chart (left) shows values for the mean, maximum and minimum daily precipitation for each month. The Total Monthly Precipitation chart (right) shows the total accumulated precipitation for each month. For this example, the total precipitation for the year is 542mm.

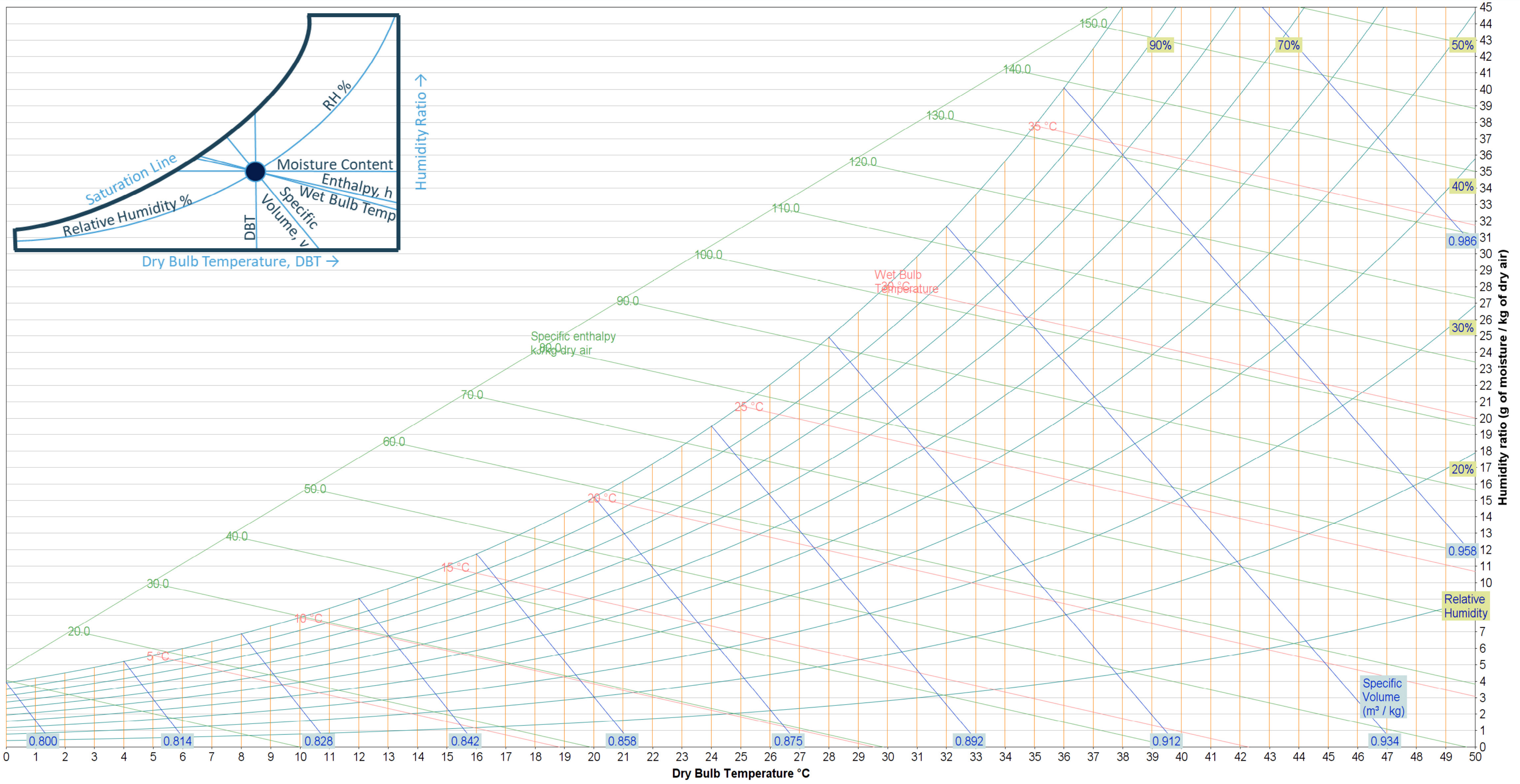

Average Daily Precipitation


Total Monthly Precipitation

Appendix A: Psychrometric Chart (I-P)



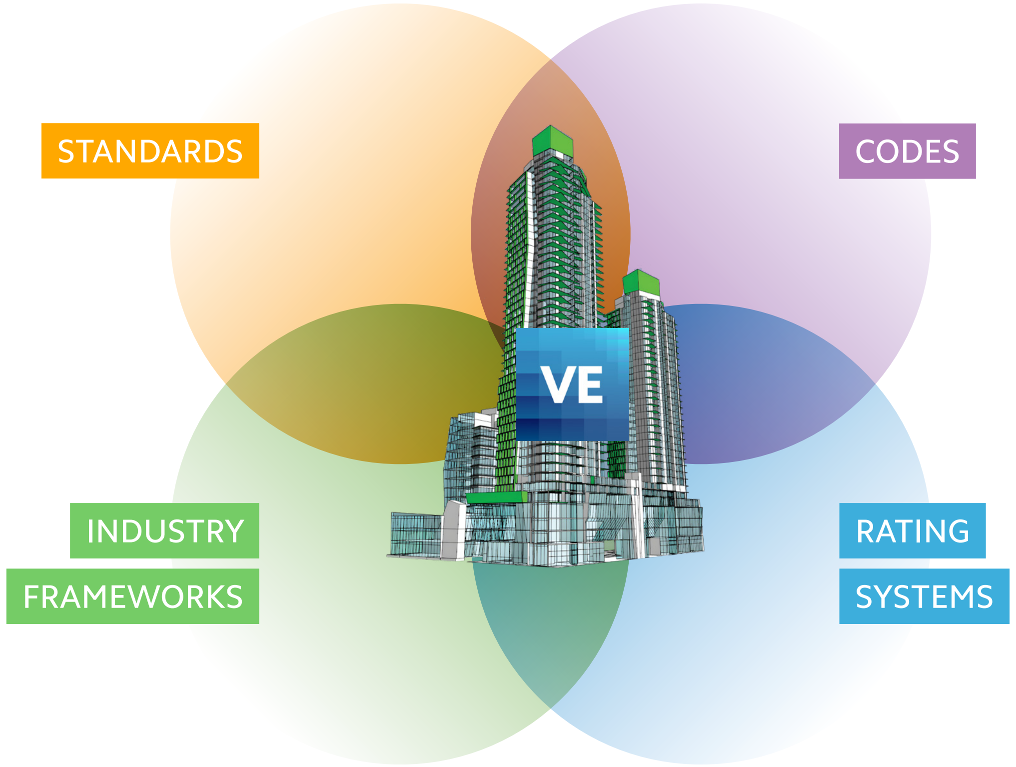
Appendix A: Psychrometric Chart (SI)



Appendix B: Codes, Standards & Ratings

FAQ: How do the regional regulatory Building Codes, Standards, and Green-Building Rating Systems relate to Building Performance Modeling?

Building Codes and Regulations are adopted by the Authority Having Jurisdiction (AHJ), which is a legal enforcement, e.g., at a city planning department. The Building Codes and Regulations often refer to Building Standards (e.g., from ASHRAE) and Manuals (e.g., from CIBSE). The various voluntary green-building rating systems may also refer to Standards and Manuals to score points or credits associated with the rating systems. All of these will have some form of Building Performance Modeling requirements, and they are often interrelated and serve multiple use-cases. There are relevant tutorials available for free on the IES On-Demand Learning platform.



Some relevant use-cases referencing Building Performance Modeling requirements include:

- **LEED** (Leadership in Energy and Environmental Design) requires BEM within the "Energy and Atmosphere" credit category; and within the "Indoor Environmental Quality" credit category for daylight simulation and indoor air quality. See: https://www.usgbc.org/credits.
- **BREEAM** (Building Research Establishment Environmental Assessment Method) has an energy category that is focused heavily on CO_2 emissions to meet minimum code (E.g., Part L Building Regulations).
- The **Living Building Challenge**, created by the International Living Future Institute, is considered the most rigorous green building rating system and is based solely on actual recorded performance. The energy category requires **Zero Net Energy** for 12 months, so energy metering is required. See https://living-future.org/lbc/.
- The **WELL Building Standard** is focused on the Health and Wellness of the building occupant. While WELL has no direct energy impacts, it has many indirect impacts (e.g., outdoor air requirements, daylight, thermal comfort). See https://standard.wellcertified.com/well.
- The **NABERS Building Standard** provides a rating from one to six stars for building efficiency across Energy, Water, Waste, and Indoor environment. See https://www.nabers.gov.au/about/what-nabers.

Appendix C: Sensible Heat Equation Constant

FAQ: Where does the 1.094 constant come from in the Sensible Heat equations, instead of 1.08?

Regarding the value used for sizing HVAC airflows based upon zone loads, the foremost consideration for BPM is consistency with other calculations in IESVE Software. This consistency is satisfied by the **1.094** value as calculated below:

1.2 * 1019 * 0.0004719474 / (0.2930711 * 1.8) = 1.093965

where the figures in this sum are

Standard air density = 1.2 kg/m^3
Standard air specific heat capacity = 1019 J/kgK
1 cfm = 0.0004719474 m^3/s
1 Btu/h = 0.2930711 W
1 F = 1.8 K

HVAC design engineers working in IP units have slightly different conventions for standard values, conversion factors, and minor rounding errors in the standard values. These calculated results show an insignificant difference and are negligible compared to the actual real-world variability of conditions. In fact, the value used by IESVE Software may be a better reflection of what ASHRAE has assumed for generic conditions at sea level.

Starting from the basics:

Air density is a function of local barometric pressure, temperature, and humidity ratio. ASHRAE points out that while pressure and temperature have a significant influence on density, humidity has a very minor or even negligible influence. The ASHRAE Handbook Fundamentals assumes "U.S. Standard Atmosphere" conditions at sea level to be 59°F (15°C) and 14.696 psia (101.325 kPa) dry air.

$$\rho = 2.7 * \text{ppsia} / (\text{TF} + 459.7)$$
$$= 2.7 * 14.696 / (59 + 459.7)$$
$$= 0.76497 \text{ lb/ft3}$$

Outdoor air density at sea level is generally, but not consistently or exactly, assumed for calculations in **ASHRAE Fundamentals to be ~ 0.075 lbm/ft^3** at or near sea level, matching the calculated value above from the "U.S. Standard Atmosphere" conditions at sea level. This is essentially the same as the standard value of 1.2 kg/m^3 used, which converts to **0.0765 lb/ft^3** in IP units. Apart from very minor rounding errors, these are the same number.

Standard air specific heat capacity = 1019 J/kgK converts to 0.2435468451243 Btu/(lb-°F). This is rounded in the typical IP-based HVAC design calcs to either 0.24 Btu/lb-F, yielding a conversion factor of 1.08, or 0.241 for a conversion factor of 1.085 (which is also a rounded value).

60 x 0.075 x 0.24 = 1.08
60 x 0.075 x 0.241 = 1.0845 = 1.085
60 x 0.0765 x 0.24 = 1.102
60 x 0.0765 x 0.241 = 1.106

All of the above suggest that the conversion constant of 1.08 or 1.085 typically used by engineers working in IP units is normally derived from rounded approximate values or rounded from more specific assumed values. In any case, if a few decimal places are preserved from the ASHRAE values for temperature and pressure, the 1.094 factor used for airflow sizing in IESVE Software is more true to the standard ASHRAE values than the rule-of-thumb 1.085, or more commonly 1.08.

Appendix D: Energy Benchmarking

Since BEM is most frequently used as a predictor of building energy use, a good sanity check is to compare the simulated energy results against known benchmarked data, since, like any model, the prediction can be based on assumptions that will affect the results. There are many public benchmark datasets available.

Global Real Estate Assessment Results, 2024 – (GRESB.com)

Site EUI - kWh/m^2	Americas	Asia	Europe	Oceania	Global
Retail Building	242.3	218.4	159.9	226.2	211.5
Office Building	192.5	161.8	154	127.2	171.1
Residential Building	139.3	100.3	120.1	102.5	132.6
Industrial Building	86.5	49.6	77.5	62	77.3

Energy Star Portfolio Manager, USA median - August 2024 (energystar.gov)

Building type	Site EUI (kBtu/ft^2.yr)	Site EUI (kWh/ft^2.yr)	Site EUI (kWh/m^2.yr)
Bank branch	88.3	25.9	278.6
Education, K-12 school	48.5	14.2	153.0
Education, college/university	84.3	24.7	265.9
Convention center	56.1	16.4	177.0
Restaurant, fast food	402.7	118.0	1270.4
Restaurant, sit-down	325.6	95.4	1027.1
Grocery store / Supermarket	196	57.4	618.3
Hospital (general medical & surgical)	234.3	68.7	739.1
Medical office	97.7	28.6	308.2
Hotel	63	18.5	198.7
Multifamily housing	59.6	17.5	188.0
Office (not medical)	52.9	15.5	166.9
Library	71.6	21.0	225.9
Convenience store	350.9	102.8	1106.9
Religious Worship	30.5	8.9	96.2
Fitness / Gym	50.8	14.9	160.3
Stadium	56.2	16.5	177.3
Warehouse - Distribution	22.7	6.7	71.6
Warehouse - Refrigerated	84.1	24.6	265.3
Laboratory Best refer to Laboratory Benchmarking Tool: https://lbt.i2sl.org/buildings/charts	115.3 (50 – 850)	33.8	363.7
Data Center (PUE=Total Energy/IT Energy)	1.82 PUE	1.82 PUE	1.82 PUE

Other useful building benchmarked datasets include:

- **ASHRAE Standard 100** - Energy Efficiency in Existing Buildings (ASHRAE)
- **Commercial Building Energy Consumption Survey** (CBECS) Data – from U.S. Energy Information Administration

UK Energy Benchmarking

UK CIBSE Energy Benchmarking (2021) – 'Good Practice' Class (cibse.org)

Category	Building Type	Fossil Fuels (kWh/m^2.year)	Electricity (kWh/m^2.year)
Catering	Fast Food Restaurant	480	820
Catering	Restaurant with bar	2700	1300
Education	Catering, Restaurant	182	137
Education	Lecture Room	100	67
Education	Science Lab	110	155
Education	Library	71	69
Education	Primary School	85	34
Education	Secondary School	78	39
Entertainment	Theatre	95	83
Entertainment	Cinema	515	135
Hospital	General	216	80
Hospital	Teaching/Specialist	196	111
Hotel	Small	240	80
Hotel	Luxury	300	90
Office	Air Conditioned	114	234
Office - Open Plan	Naturally Ventilated	79	54
Public Building	Fire Station	115	56
Public Building	Church	80	10
Retail	Bank	63	71
Retail	Clothes	65	234
Retail	Distribution Warehouse	103	53
Sports & Recreation	Swimming Pool	264	96
Sports & Recreation	Fitness Centre	201	127

UK RIBA 2030 Climate Challenge Targets (architecture.com)

Building Type	Reference (kWh/m^2.year)	2025 Target (kWh/m^2.year)	2030 Target (kWh/m^2.year)
Office (new build)	90	75	55
School (new build)	75	70	60
Residential / Domestic	60	60	35

Notes

Notes

Find out more

www.iesve.com