Pacific Northwest
NATIONAL LABORATORY

PNNL-32140

# Mechanical Performance Factor Development for HVAC System Performance

## Technical Documentation

October 2021

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U.S. DEPARTMENT OF ENERGY

Prepared for the U.S. Department of Energy
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# Executive Summary

The prescriptive path is likely the most widely used approach for commercial code compliance in the United States. Though easy to implement, the prescriptive approach does not discriminate between high-performing and poorly performing heating, ventilation, air conditioning (HVAC) system configurations that are both minimally compliant. There are many energy-impacting components that go into an HVAC system beyond equipment efficiency. These include ductwork and piping design, accessories such as outside air economizers, controls like demand controlled ventilation, and other optimization strategies. In the prescriptive path, allowance must be made in requirements for worst case situations; for example, the fan power limits are nowhere near the typical case. Selecting the lowest efficiency parts of the prescriptive path results in an overall system efficiency that is pretty low.

In some cases, particular prescriptive requirements are difficult to meet, like outside air economizers in some buildings, expensive energy recovery ventilation, and fan power limits in taller buildings. In the past, trade-offs have required whole building analysis that can be expensive. The HVAC System Performance Rating path allows for trade-offs just within HVAC, so other efficiency improvements can make up for prescriptive measures that are not a good match for a particular project. Once established, the Total System Performance Ratio (TSPR) can even be used as a tool to determine utility cash incentives.

The TSPR is a metric for evaluating overall system efficiency instead of individual component efficiency, a solution that could also eventually facilitate the transition to a 100% performance-based code structure. TSPR is a ratio that compares the annual heating and cooling load of a building to the annual energy consumed by the building's HVAC system. A web-based calculation tool has been developed for determining a building's TSPR. Already incorporated into the 2018 Washington State Energy Code, this approach has also been evaluated by the ASHRAE Standard 90.1 Project Committee and has the potential to provide a comprehensive performance-based approach for HVAC system evaluation and analysis.

This technical documentation provides background on TSPR and support for the mechanical performance factors that are developed each 90.1 edition cycle to be used in the calculation. The current factors are developed for the 2022 edition of 90.1 in combination with addendum AG.

# Acronyms and Abbreviations

| | |
|---|---|
| AFUE | annual fuel utilization efficiency |
| ASHRAE | American Society of Heating, Refrigerating and Air-Conditioning Engineers |
| COP | coefficient of performance |
| DCV | demand control ventilation |
| DOAS | dedicated outdoor air system |
| DOE | U.S. Department of Energy |
| EER | energy efficiency ratio |
| HSPF | heating seasonal performance factor |
| HVAC | heating, ventilation, air conditioning |
| IECC | International Energy Conservation Code |
| LPD | lighting power density |
| MPF | mechanical performance factors |
| OSA | outside air |
| PNNL | Pacific Northwest National Laboratory |
| PTAC | packaged terminal air conditioner |
| PTHP | packaged terminal heat pump |
| P-VAV | packaged variable air volume system |
| SEER | seasonal energy efficiency ratio |
| SP | static pressure |
| TSPR | Total System Performance Ratio |
| VAV | variable air volume |
| VRF | variable refrigerant flow |
| VSD | variable speed drive |
| WLHP | water-loop heat pump |
| WSEC | Washington State Energy Code |
| WWR | window to wall ratio |

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# 1.0 HVAC System Performance

The HVAC System Performance Technical Documentation provides an overview of the Total System Performance Ratio (TSPR) metric and the HVAC System Performance methodology, which is a proposal for ASHRAE Standard 90.1-2019 as an alternative path to mechanical prescriptive requirements. The HVAC System Performance methodology is a discipline performance approach.[1]

The sections below provide an overview of why the transition to performance-based codes is critical to meet the aggressive energy and carbon reduction goals or meet policy objectives for electrification and decarbonization. It lays out the limitations associated with prescriptive path and the advantages and challenges associated with whole building Performance Rating paths. The HVAC System Performance approach integrates the ease of use of the prescriptive path with the flexibility of the Performance Rating path by providing a simple approach that can be used for a system-level analysis. Currently adopted by Washington State Energy Code (WSEC 2018) and under review for adoption as an addendum to ASHRAE Standard 90.1-2019 (ASHRAE 2019), this approach can be adopted through various formats that can be tailored to meet policy objectives, as discussed in Section 1.3.

## 1.1 Case for Performance-Based Codes

Energy codes have traditionally contained *mandatory* and *prescriptive* items and an alternative *performance-based* compliance option. Mandatory measures must be complied unless there is a specific exception noted in the code or standard. Prescriptive paths establish minimum requirements for energy-related characteristics of individual building components such as minimum required R-values of insulation, solar heat gain coefficients of fenestration, occupancy sensors for lighting control, maximum fan power limits, restrictions on window area, and others. Due to this, the prescriptive path can also result in a wide range of performance outcomes, depending on the minimally code compliance option selected (Rosenberg et al. 2015). On the other hand, most whole building Performance Rating paths allow buildings to trade off some prescriptive requirements for improved performance in other building components and systems. The improved building performance is demonstrated through whole building energy simulation.

While easy to use and understand, the prescriptive path limits design flexibility and fails to acknowledge individual building characteristics as well as the interactive considerations that can optimize a building's energy performance with integrated solutions. Because prescriptive requirements are typically established at an individual component level and limited by cost effectiveness requirements, the rate of improvement of each subsequent code has slowed down based on economic considerations and limits of technological feasibility. In some cases, improvements in prescriptive requirements come at the expense of limitations in design flexibility. These are some of reasons that designers choose a Performance Rating path over the prescriptive path to demonstrate compliance.

It is also unlikely that energy codes largely dependent on prescriptive compliance will achieve aggressive savings policy goals. Figure 1 shows the rate of improvement in the prescriptive path of ASHRAE Standards 90 and 90.1 since the first edition in 1975. It shows the rate of future improvement in three

[1] An example of a discipline Performance Rating path is the Building Envelope Trade-Off Compliance Path in the envelope discipline of Standard 90.1 that is supported by Appendix C. There are current proposals under public review in Standard 90.1 for discipline Performance Rating paths for both lighting and HVAC disciplines.

ways: (1) if the Standard continues to improve at the average rate it has since 1975; (2) if the Standard improves at the accelerated rate it has since 2004 (not likely, as described above); and (3) the rate at which the Standard needs to improve if it is to reach net zero energy, considering a reasonable amount of rooftop solar photovoltaics (Franconi et al. 2021). As indicated by this graph, the prescriptive improvements alone are not aggressive enough to pave the path to net zero energy for buildings by 2030. ASHRAE, along with several jurisdictions are working on defining pathways for aggressive energy reductions or net zero energy by 2030 (ASHRAE 2020, WSEC 2020). The HVAC Systems Performance Rating path relies on a move to performance-based codes that treat the building as a system and encourage creative solutions more likely to lead to deep savings than the prescriptive alternative (Rosenberg et al. 2015).

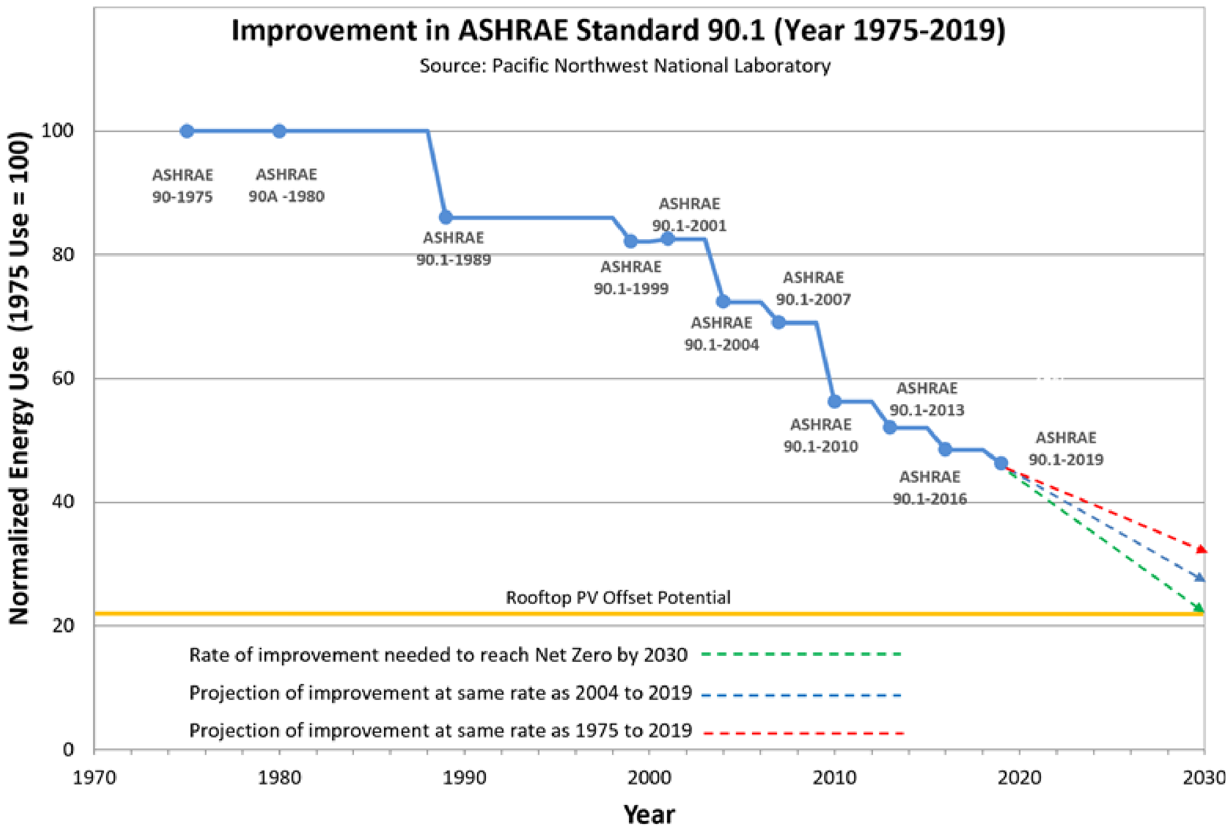


Figure 1. Past and Projected Savings from Prescriptive Code Compliance

## 1.2 System Performance Approach

Building energy performance has typically been evaluated at a whole building level (energy use intensity, peak demand) or at an equipment level [e.g., chiller efficiency coefficient of performance (COP)] (Li et al. 2020). A whole building metric can be affected by the performance of any building system, including building envelope; lighting; heating, ventilation, and air conditioning (HVAC); and service water heating; among others. Isolating the performance of individual building systems (for instance, reduced infiltration rate) using whole building metrics can be challenging. National model codes in the U.S. evaluate HVAC systems at either an equipment level (prescriptive approach) or through a whole building performance approach (the Performance Rating Method or Energy Cost Budget) (Rosenberg et al. 2020).

Prescriptive evaluation of HVAC systems includes the equipment's rated efficiency to determine compliance with the code. Commonly used HVAC system efficiency metrics include COP, energy efficiency ratio (EER), seasonal energy efficiency ratio (SEER), integrated part load value, heating seasonal performance factor (HSPF), and annual fuel utilization efficiency (AFUE). Though excellent metrics for evaluating efficiency of system components at standard conditions, these ratings are not effective in quantifying actual system performance, which is affected by part load conditions. These metrics do not account for prescriptive requirements for associated HVAC system components such as energy recovery ventilation (ERV), economizers, and variable frequency drives on fans and pumps, as well as control requirements for things like temperature resets, fan speed control, and reheat limitations. While a whole building performance-based approach looks at the overall building performance, it is resource intensive, and distilling HVAC system performance from that analysis can be quite challenging. Additionally, whole building performance approaches allow trade-offs between long-lived components such as the building envelope and short-lived components such as HVAC equipment and controls (Jonlin et al. 2018a)

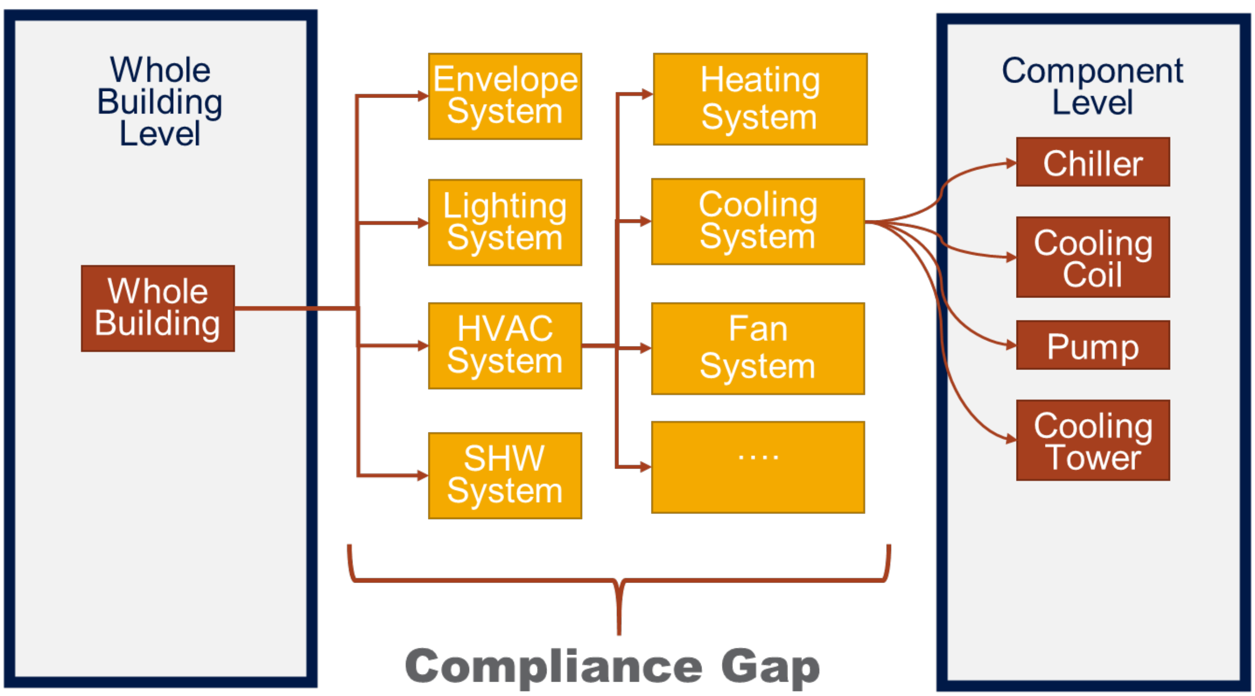


Figure 2. Compliance Paths and Need for a System Performance Approach (recreated from HPB 2019)

A more appropriate metric for evaluating an HVAC system would therefore be one that analyzes all components of the HVAC system, accounts for part load performance and system controls, normalizes for building loads, and does not allow for trade-offs between different building systems (such as envelope and HVAC system) (Figure 2). The TSPR metric addresses all of these issues as it measures the amount of energy required to deliver each unit of heating and cooling to the building over the course of a typical year (Goel et al. 2014a; Jonlin et al. 2018b). Systems using less overall energy each year to meet the building's annual thermal and ventilation loads would be rated as more efficient. The TSPR metric does not allow trade-offs between different building systems, and performance needs to be demonstrated through improvements to the HVAC systems in the building. The TSPR metric and the related calculation procedures are further discussed in Section 2.0

The TSPR metric and the HVAC System Performance methodology are currently employed in Appendix D of the WSEC (WSEC 2018) and are currently undergoing public review as an addendum to ASHRAE Standard 90.1-2019. This approach has the advantage of encouraging increasing levels of performance while maintaining flexibility in allowing designers to optimize the most appropriate HVAC system based on the attributes of each particular project. The next section discusses the various ways this methodology could be adopted in code to meet different objectives.

## 1.3 The Code Approach

The HVAC System Performance approach is a discipline performance approach rather than a whole building approach.[1] It has been proposed as an alternative approach for Standard 90.1 where it provides an alternative to prescriptive or performance compliance. Mandatory requirements are still required to be met.

The System Performance approach has also been adopted into the Energy Credits approach (Hart et al. 2021). The Energy Credits approach, adopted in the 2021 International Energy Conservation Code (IECC) (ICC 2020), includes extra efficiency measures, and adequate measures must be selected to satisfy an "additional" efficiency requirement. The efficiency requirement is stated on a point scale, with each measure assigned points or energy credits based on percentage of reduction in total building cost. Energy credits representing a 5% reduction in HVAC energy input can be included in the list of energy credit measures and can be scaled up where greater efficiency improvements are achieved. The HVAC System Performance approach can be used to demonstrate how the proposed system is more efficient overall than a target system. Then that improvement can be used to prorate the energy credit points. This approach has been proposed for the Energy Credits section of the 2022 WSEC (Hart 2021).

## 1.4 Technical Considerations

**How does the proposed measure compare to what's required in current codes?**

Existing energy codes already include System Performance approaches. Appendix C of Standard 90.1-2019 is an envelope system performance approach. The 2021 IECC has a similar envelope UA trade-off approach. The 2018 WSEC includes an HVAC System Performance approach that follows the HVAC Minimum Efficiency code approach outlined in Section 1.3. The HVAC System Performance approach has also been proposed for Standard 90.1-2022 and is currently under review.

The approach proposed for Standard 90.1 uses mechanical performance factors (MPFs) to calculate compliance. The Standard 90.1 approach sets the reference performance level equivalent to the Standard 90.1-2019 Appendix G baseline (ASHRAE 2019), which is based on 2004 prescriptive requirements and the target level of performance is based on the current code requirements. In the approach represented here, the target levels of performance, defined through the MPFs, could be updated with each code cycle. This is further discussed in Section 2.0.

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[1] An example of a discipline Performance Rating path is the Building Envelope Trade-Off Compliance Path in the envelope discipline of Standard 90.1 that is supported by Appendix C. There are current proposals under public review in Standard 90.1 for discipline Performance Rating paths for both lighting and HVAC disciplines. The HVAC performance approach is similar to the TSPR approach proposed here.

**Why is the System Performance approach superior to other approaches?**

The System Performance approach incorporates the best of the prescriptive compliance path and the performance compliance path. It has the ease of use of the prescriptive path and the flexibility of the Performance Rating path. Stringency (represented through the MPF) could be increased over time. These characteristics make the System Performance approach a highly viable option to facilitate the transition to performance-based codes and to meet aggressive energy efficiency goals.

**What strategies are considered to minimize compliance burdens?**

To achieve deeper savings in response to energy and carbon reduction policy goals, the HVAC System Performance path provides a much more expedient path as compared to the whole building Performance Rating path, which requires a detailed custom-building energy model. The HVAC System Performance ruleset requires several model simplifications to be implemented in the simulation software used to comply with this approach. For instance, the reference baseline model is required to be generated automatically and the compliance tool should be able to determine the compliance outcome. A standard output report documents all building inputs and simulation results to facilitate the review process. These requirements have been incorporated in the TSPR tool and implemented as an extension of the U.S. Department of Energy's (DOE's) Building Energy Asset Score Tool (Wang et al. 2015) and provide a simple web-based interface to demonstrate compliance using the HVAC System Performance approach.

**Are there existing codes and standards that take a similar approach?**

The outlined approach is a rework of the requirements in the 2018 WSEC, although here an optional path is considered rather than a minimum requirement. The Seattle Energy Code has also adopted the WSEC with additional amendments for a more stringent requirement by setting the compliance target to be a certain percentage higher that what is required in the WSEC (SEC 2018). While not yet adopted, proposed addendum AG to Standard 90.1-2019 used the alternative trade-off approach, and proposed addendums to the 2018 WSEC expand the building types covered by TSPR.

# 2.0 HVAC System Performance Methodology

This section defines the TSPR metric and provides an overview of the compliance approach. It provides additional details on the process used to calculate the MPFs and how these details factor into the compliance determination calculation.

## 2.1 TSPR: Definition and Calculation

TSPR is a ratio of the annual heating and cooling provided for a building to the energy consumed for heating, cooling, and ventilating a building. The calculation is performed using whole building simulation, similar to whole building performance energy modeling, but using a simplified methodology as defined by the HVAC System Performance Rating path.

### 2.1.1 TSPR Input Metric

TSPR is calculated as the ratio of the sum of a building's annual heating and cooling load to some metric that represents the annual energy consumed by the building HVAC systems. That input metric could be annual site energy, source energy, energy cost, or carbon emissions. The appropriate TSPR metric can be chosen based on the policy goals and priorities of the jurisdiction adopting the HVAC System Performance approach. There are several ways to evaluate energy input to an HVAC system. Among them are:

- Energy cost inputs, based on local or national average prices
- Site energy inputs, based on delivered (metered) energy measured in a consistent conversion to a common metric such as British thermal units (Btu) or gigajoules (GJ)
- Source energy inputs, which include adjustments to site energy inputs to reflect the conversion efficiency of electrical generation and drilling and distribution losses for natural gas
- Emissions resulting from energy inputs, usually expressed as carbon dioxide equivalent ($CO_2e$), which may be based on a national conversion rate, regional electric conversion rates, or various streams of future emission impact resulting in a range of possible results

For addendum AG to 90.1-2019, the TSPR is based on an input value energy cost using national average energy prices. This approach produces a consistent result that does not change based on region or serving utility considerations. For specific applications, different metrics can be used based on local jurisdiction policy, and alternative metric MPFs are included as informative tables.

Currently, different jurisdictions use different approaches:

- The State of Washington and City of Seattle use a carbon basis, with state-adopted carbon conversion factors.
- A proposal undergoing review for Standard 90.1-2022 uses a cost basis, with national average energy prices, although alternative informative metric options are included.

### 2.1.2 The TSPR Concept

A larger TSPR indicates lower HVAC energy use to meet the loads, and therefore a system with a larger TSPR can be considered more efficient than one with a smaller TSPR. The annual heating and cooling loads include envelope loads; solar gains through fenestration; internal loads due to lights, equipment, and occupants; as well as ventilation and infiltration loads. This metric provides a single evaluation criterion that addresses all components of the HVAC systems used to move heat and air into, out of, and within a building. It includes distribution system effectiveness, considers both full and part load performance, and accounts for system controls. This differs from standard system efficiency ratings (such as SEER, COP, or kilowatts per ton) that usually address part of a system and fail to account for all the system inefficiencies that may be present within a building as well as their interaction with building loads and ventilation requirements. In addition, such component efficiency ratings are based on standard rating conditions that may not reflect actual building conditions and the ambient conditions at the building site. The HVAC System Performance approach accounts for all of these parameters to provide a comprehensive evaluation of a building's HVAC system.

To calculate the TSPR, annual energy use of all system components, including auxiliary components, is included in calculations for a complete HVAC system evaluation. Hence, the total HVAC energy use includes fuel-fired and electric heating coils (including reheat coils), direct expansion cooling coils, boilers, chillers, heat rejection, energy recovery, and distribution system fans and pumps. $E_{Heating\text{-}elec}$ and $E_{Heating\text{-}gas}$ account for the energy use of all heating coils in a system, include the pre-heating coil, main heating coil, supplementary heating coil, and reheat coil. Similarly, $E_{fan}$ includes the energy use of all fans in a system, including the supply fan, exhaust fan, return fan, and relief fan. $E_{Pump}$ includes the energy use of all hot water pumps, chilled water pumps, and condenser water pumps serving the system. The impact of HVAC system controls, such as fan static pressure and variable speed control, is accounted for through the energy use of that particular component. For example, the energy consumption of a fan in a variable air volume (VAV) system with static pressure reset will typically be lower than that for the same system without static pressure reset. Hence, the component $E_{fan}$ accounts for the impact of system controls affecting fan energy use; similarly, $E_{cooling}$ accounts for the impacts of economizer control and $E_{Heating}$ accounts for the impact of energy recovery.

$$HVAC\ Electric\ Energy\ \mathrm{Cost}_{Total} = (E_{Heating-Elec} + E_{Cooling} + E_{Fan} + E_{Pump} + E_{Heat-Rejection} + E_{Heat-Recovery})[kWh] \times Cost_{Electricity}$$

$$HVAC\ Gas\ Energy\ \mathrm{Cost}_{Total} = (E_{Heating-Gas})[Therm] \times Cost_{Gas}$$

$$HVAC\ Propane\ Energy\ \mathrm{Consumption}_{Total} = (E_{Heating-\mathrm{Propane}})[Therm] \times Cost_{Propane}$$

$$HVAC\ Fuel-Oil\ Energy\ \mathrm{Cost}_{Total} = (E_{Heating-\mathrm{Propane}})[Gallon] \times Cost_{Oil}$$

where

$E_{Heating\text{-}elec}$ = heating electric energy consumption (kWh)
$E_{Heating\text{-}gas}$ = heating gas energy consumption (therm)
$E_{Heating\text{-}propane}$ = heating propane energy consumption (therm)
$E_{Heating\text{-}oil}$ = heating oil energy consumption (gallon)
$E_{Cooling}$ = cooling electric energy consumption (kWh)
$E_{Fan}$ = fan electric energy consumption (kWh)

$E_{Pump}$ = pump electric energy consumption (kWh)
$E_{Heat\ Rejection}$ = heat rejection energy consumption (kWh)
$E_{Heat\ Recovery}$ = heat recovery energy consumption (kWh)
$Cost_{Electricity}$ = electric energy cost ($/kWh)
$Cost_{Gas}$ = natural gas energy cost ($/therm)
$Cost_{Propane}$ = propane energy cost ($/therm)
$Cost_{Fuel\text{-}Oil}$ = distillate fuel oil energy cost ($/gallon)

$$HVAC\ Energy\ \text{Cost}_{\ Total} = HVAC\ Electric\ Energy\ \text{Cost}_{\ Total} + HVAC\ Gas\ Energy\ \text{Cost}_{\ Total} + HVAC\ Propane\ Energy\ \text{Cost}_{\ Total} + HVAC\ Fuel\ Oil\ Energy\ \text{Cost}_{\ Total}$$

To determine the annual heating, cooling, and total loads for each building, the simulation uses a special HVAC system type available in DOE's EnergyPlus software called the Ideal Loads system (DOE 2018a). This system calculates the annual heating and cooling load (including ventilation load) for each zone in the building and supplies heating or cooling air to meet the setpoints as if the heating and cooling system efficiency was 100%. In other words, it determines how much heating and cooling service is actually delivered to each zone. This system includes setpoints for temperature and humidity control, and indoor air quantity, so it truly represents the complete load on the HVAC system. Thus, the TSPR is calculated according to Eq. (1).

$$Total\ System\ Performance\ Ratio = \frac{Ideal\ annual\ heating\ load + Ideal\ annual\ cooling\ load\ (kBtu)}{(HVAC\ Energy\ \text{Cost}_{\ Total})\ (\$)} \tag{1}$$

## 2.2 Compliance Calculations

The HVAC System Performance approach in energy codes follows a performance-based analysis with a minimum performance level identified through "target systems." The basic idea is to compare a proposed system to a target system using the TSPR metric. Since target systems are changing with each code cycle, for simulation software stability, a reference system is used as a touchstone. Reference and target systems are summarized in Table 1 and further detailed below.

Table 1. Summary of Reference and Target Systems by Building Type

| | Building Type Parameter | Large Office | Small Office | Retail | School | Hotel | Apartment |
|---|---|---|---|---|---|---|---|
| **Reference** | **System Type (Warm)** | VAV/ RH Water cooled chiller/ Elec RH | Packaged air-source Heat Pump; with air econo-ex CZ 1-2 | Packaged air-source Heat Pump; with air econo-ex CZ 1-2 | Packaged DX VAV/ Elec RH | Packaged terminal air-source Heat Pump | Packaged terminal air-source Heat Pump |
| | **System Type (Cold)** | VAV/ RH Water cooled chiller/ gas boiler | Packaged air-source AC / Furnace; with air econo | Packaged air-source AC / Furnace; with air econo | Packaged DX VAV/ Hydeonic RH/ gas boiler | Packaged terminal AC / Furnace | Packaged terminal AC / Furnace |
| **Target** | **System Type (Warm)** | VAV/ RH Water cooled chiller/ Elec RH | Packaged air-source Heat Pump; with air econo-ex CZ 1-2 | Packaged air-source Heat Pump; with air econo-ex CZ 1-2 | VAV/ RH Water cooled chiller/ Elec RH; ERV | Packaged terminal air-source Heat Pump | Split air-source Heat Pump w/ ERV |
| | **System Type (Cold)** | VAV/ RH Water cooled chiller/ gas boiler | Packaged air-source AC / Furnace; with air econo | Packaged air-source AC / Furnace; with air econo | VAV/ RH Water cooled chiller/ gas boiler; ERV | Packaged terminal AC / Furnace | Split air-source AC Gas Furnace / w/ERV |

- Target systems are defined for each climate zone and building type and represent minimum prescriptive levels of performance for a "good" HVAC system installation. The HVAC system selected for the target attempts to strike a balance between the least efficient system configuration and a highly efficient system configuration by selecting a "good system," which is used to calculate the desired performance for each building type and climate zone. "Good systems" are at the minimum efficiency required in Standard 90.1-2019. These are more fully documented in Appendix B of this report.

- A "reference system" is also defined, which follows the Standard 90.1 Appendix G baseline configuration, which meets the Standard 90.1-2004 code (ASHRAE 2004) requirements and provides a stable baseline for comparison. The reference systems and parameters are listed in Appendix A of this report.

Similar to the building performance factors (Rosenberg and Hart 2016) in Standard 90.1 Appendix G, MPFs are defined using the reference and target systems for each climate zone and building type. An MPF is simply the ratio of the reference TSPR to the target TSPR and represents the improvement in system output per cost for a target system ($TSPR_t$) compared to the reference system ($TSPR_r$). This allows the reference systems to remain stable in the simulation tool used to comply with HVAC System Performance Rating path, with only a table of MPFs updated for each edition of code.

$$MPF = TSPR_r \,/\, TSPR_t \tag{2}$$

where

$TSPR_t$ = target TSPR
$TSPR_r$ = reference TSPR

*MPF* = mechanical performance factor based on climate zone and building use type

The System Performance approach compares a proposed mechanical system ($TSPR_p$) with a reference mechanical system ($TSPR_r$) using the MPF. Proposed systems using the same or less overall annual energy as a selected target system to meet the building's annual thermal and ventilation loads would be rated as equivalent or more efficient. Then the improvement for the proposed system would need to be greater than or equal to the improvement for a target system ($TSPR_t$). So, efficiency equivalence is demonstrated where:

$$TSPR_p \geq TSPR_t \ OR \ \frac{TSPR_p}{TSPR_r} \geq \frac{TSPR_t}{TSPR_r} \ OR \quad \frac{TSPR_p}{TSPR_r} \geq MPF \tag{3}$$

where

$TSPR_t$ = target TSPR
$TSPR_r$ = reference TSPR
$TSPR_p$ = proposed TSPR
*MPF* = mechanical performance factor based on climate zone and building use type

## 2.3 Reference HVAC Systems

The HVAC System Performance approach establishes reference HVAC system specifications for five covered building types: office, retail, multifamily, hotel, and school. The reference systems have been separately defined for large offices (gross conditioned floor area > 150,000 $ft^2$ or > 5 floors), medium offices (gross conditioned floor area 5000 to 150,000 $ft^2$ and ≤ 5 floors), and small offices (gross conditioned floor area ≤ 5000 $ft^2$ and ≤ 5 floors). Together, these five building types represent approximately 72% of new construction starts in the United States for commercial buildings (Lei et al. 2020). The reference systems are climate zone specific, where warm climate zones, classified as climate zones 0 to 3A, have an electric system, such as a packaged rooftop heat pump for the small office reference building or a packaged variable air volume system (P-VAV) with fan-powered parallel induction units and electric resistance reheat for the large office buildings. The cold climate zones, classified as climate zones 3B, 3C, and 4-8, have gas-fired systems, such as packaged rooftop gas furnaces for small offices and VAV with hot water reheat systems for large offices. Each of these systems are defined to represent a baseline level of performance, as prescribed by Standard 90.1-2019, Appendix G.

Reference systems are listed in Appendix A of this document.

## 2.4 Target HVAC Systems

The target systems, defined through a consensus process within the Standard 90.1 committee, represent standard energy-efficient design practice. All aspects of the target system are defined to comply with the code. The system choice is meant to represent common practice for a particular use type and climate zone and has not been set to represent the most efficient HVAC system configuration or the least efficient HVAC system configuration, as an attempt to provide a compliance path that is viable. This approach places a great deal of importance on the selection of the appropriate HVAC system type. The target systems are listed in Appendix B of this document. In most cases, the target system is the same type as the reference (for example, the small office systems) and includes higher equipment efficiencies as required by the prescriptive energy code as well as additional HVAC system controls or features such as air-side economizers, ERV, or demand control ventilation (DCV), requirements for which have since been added to the code. For some use types, the system has been modified between the reference and target (as in the case of the multifamily use type) to represent more efficient design choices that are more prevalent for that use type. This is seen in the case of the multifamily use type, where a reference system is defined using packaged terminal heat pumps (PTHPs) and packaged terminal air conditioners (PTACs) and the target system uses split direct expansion systems for heating and cooling with a single zone dedicated outdoor air system (DOAS) and ERV.

Target systems are listed in Appendix B of this document. Section 5.0 of this report also analyzes various systems to evaluate their performance against the Target systems.

## 2.5 Defining the Proposed Building

To comply with the HVAC System Performance approach, the ratio of the TSPR of a proposed building design to that of the reference building design needs to be greater than the MPF for that building type and climate zone. This indicates that the proposed TSPR is greater than the target system TSPR. A higher TSPR indicates that more HVAC “services” are delivered per energy dollar (or per other input metric). Simulation software, which implements the HVAC System Performance ruleset and meets all the requirements outlined in the ruleset (addendum AG to Standard 90.1-2019), would be used to analyze the proposed building. The simulation software is required to automatically generate the reference building and determine the proposed building TSPR and reference building TSPR.

The proposed building is required to be modeled in accordance with rules defined in the HVAC System Performance Rating path (addendum AG to Standard 90.1-2019). These include a simplified modeling approach for the building geometry, envelope construction, interior loads, HVAC system specifications, and so on. The ruleset prescribes several simplifications that are required to be automatically applied to the proposed building by the simulation tool, including a simplified thermal zoning requirement, standard loads and schedules, prescribed envelope construction assemblies, and calculation of capacity weighted average equipment efficiencies for similar HVAC system types serving the building (Jonlin et al. 2018b). These simplifications improve consistency and reduce the input detail required of the user. The user is required to create a simplified geometric “block” representation of the building and define the use type for each block, the thermal properties for each unique envelope construction, and the proposed HVAC systems. The simulation tool workflow is discussed in additional detail in Section 3.0.

# 3.0 Analysis Tool

The HVAC System Performance Rating path specifies the requirements for a simulation tool that can be used to demonstrate compliance with the HVAC System Performance Rating path. It outlines the requirements for defining the proposed building along with the necessary simplifications required to be implemented by the simulation tool. One of the key simplifications is a capability to automatically generate reference building models. It outlines all the capabilities a simulation tool would need to incorporate, including an output report with the compliance outcome that would need to be automatically generated by the tool. Any tool that implements these requirements could be used for compliance analysis for the HVAC System Performance Rating path. The HVAC System Performance ruleset has been implemented into DOE's Building Energy Asset Score tool (Asset Score Tool), to provide a no-cost software tool that can used by jurisdictions interested in adopting this approach.

The following sections describe the simulation tool requirements, as outlined in HVAC System Performance ruleset, software architecture of the Asset Score Tool, the various simplifications implemented within the tool to support the HVAC System Performance ruleset, and the compliance report generated by the tool.

## 3.1 Simulation Tool Requirements in the HVAC System Performance Rating Path

The HVAC System Performance ruleset defines the requirements for a simulation tool implementing the ruleset. The defined approach employs several simplifications, which are required to be supported by the simulation tool for defining the proposed building design. The intent of these simplifications is to reduce the level of effort associated with developing an energy model by both limiting the parameters that can be entered by the user and using standard modeling defaults for parameters not available for the user to edit. The HVAC System Performance Rating path outlines the required inputs for defining the proposed building HVAC system and also lists several defaults that are required to be implemented by the simulation tool. Building operation schedules and loads, including schedules of operation, plug loads, ventilation loads, equipment performance and operation, and more, are prescribed based on ASHRAE Standard 90.1 Appendix C and cannot be modified by the user (ASHRAE 2016).

The simulation tool implementing the HVAC System Performance ruleset is required to automatically generate the standard reference design based on the user-specified proposed building design. The standard reference design should be specified to be the same as the proposed design except for the HVAC systems, which are modified as prescribed by the ruleset. The tool is then required to run annual simulations for the reference and proposed buildings to determine the annual HVAC energy use and annual heating and cooling loads. Compliance is determined in the simulation tool by calculating the proposed building TSPR and reference building TSPR, and comparing its ratio against the required MPF for that climate zone and building type.[1] The simulation tool is also required to provide a compliance report that outlines the compliance outcome and additional details including user-specified inputs, and simulation results, to facilitate the compliance review. Any simulation tool that meets the requirements laid out in the HVAC System Performance ruleset in addendum AG to 90.1-2019 can be used to determine compliance with this approach.

[1] An area weighted average MPF would be calculated for a mixed-use building.

## 3.2 Overview of Asset Score Tool

One implementation of the software ruleset in addendum AG to 90.1-2019 is under development by Pacific Northwest National Laboratory (PNNL) and supported by DOE. Other implementations can be developed by other software vendors and can easily be included in HVAC design software available on the market. The DOE-developed version is based on the Asset Score Tool. While other implementations may vary from the Asset Score implementation, there are likely to be similarities in structure.

The Asset Score Tool, developed by PNNL for DOE, is a web-based tool to help building owners and managers assess the efficiency of a building's energy-related systems and to encourage investment in cost effective improvements (DOE 2018b; Wang et al. 2015). Asset Score Tool uses EnergyPlus and OpenStudio to develop a whole building energy model of a building and provides an assessment of building systems based on the specified building characteristics (DOE 2018a; OpenStudio 2018). The tool uses a simplified block schema to represent the building rather than a detailed building architectural description as shown in Figure 3. This allows for rapid input, with a completed analysis in 4 to 12 hours rather than 1 to 3 weeks of professional time.

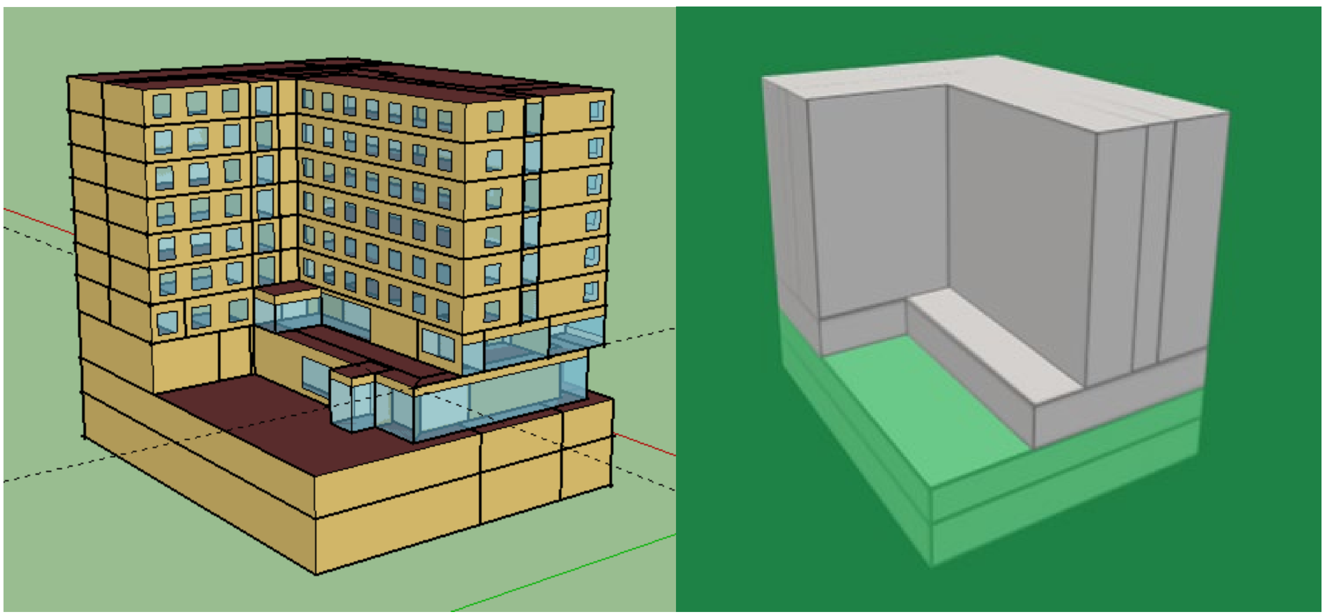

Figure 3. Simplified Building Block Model (left) vs. Detailed Model (right)

The simplified interface allows a user to define their building characteristics and runs whole building energy simulation using standard operating assumptions to generate an Asset Score for the user's building. The tool also identifies upgrade opportunities for energy savings and a corresponding "potential" Asset Score. An additional module has been added to the Asset Score Tool for HVAC System Performance analysis that allows a user to define their proposed building design in accordance with the proposed code requirements and automatically generates the reference design following the rules defined in the code. The tool also applies the appropriate MPFs to the results to determine the compliance outcome, which is documented in the compliance report generated by the tool. The following sections explain the tool workflow for defining the proposed building and generating compliance results.

## 3.3 TSPR Analysis Workflow in Asset Score Tool

The Asset Score Tool provides a simplified interface for a user to define their proposed building design and automatically generates the reference building based on the rules defined in the HVAC System Performance ruleset for compliance analysis. Simulation runs generate a PDF report that includes the compliance results and additional details about the building for a code official to verify against design drawings. The tool itself is modular in design for a clean separation of functionalities and easier testing and development. The core components of the Asset Score Tool application are functionally separated into the following four subsystems:

- User interface that allows a user to define the properties of the proposed building
- Asset Score Application that stores all user inputs and additional code requirements (e.g., MPFs) in a database and translates this information into the Asset Score data model
- Modeling Engine that takes in the Asset Score data model and generates the corresponding OpenStudio models for simulation using EnergyPlus.
- Report Generator that post-processes the simulation results.

The TSPR module has been built on top of the Asset Score Tool structure and adds the capability to automatically generate the reference building based on the rules defined in the HVAC System Performance ruleset. In Figure 4, the reference building is referred to as a baseline.

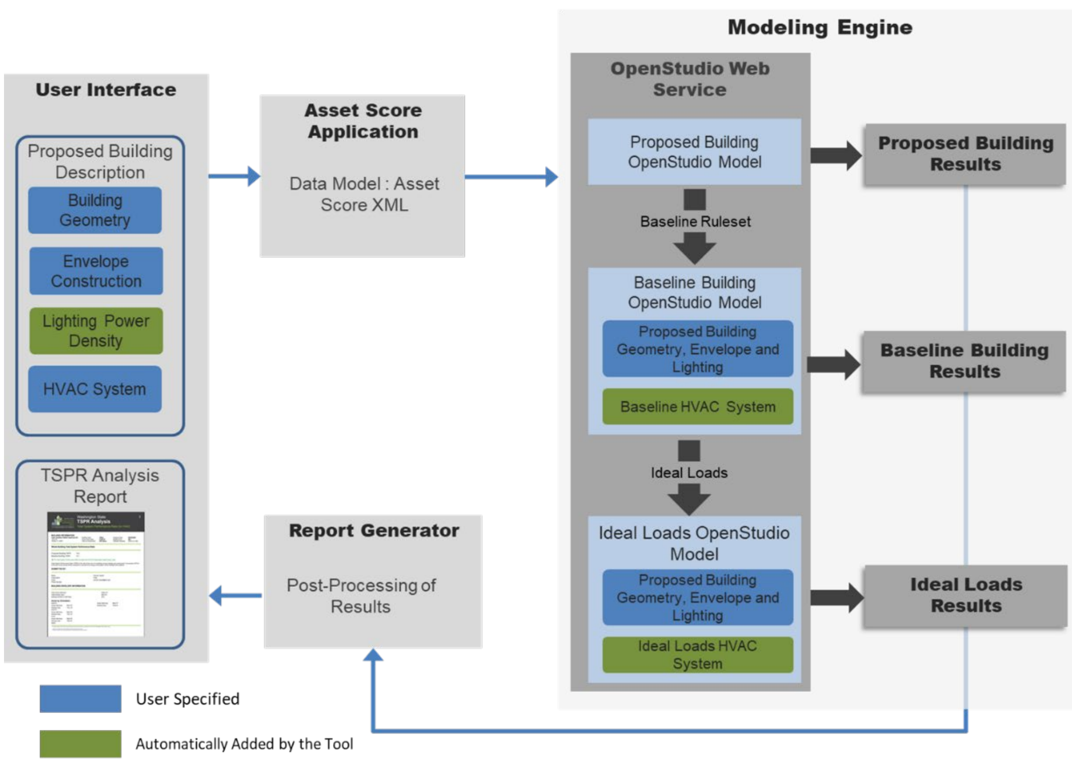


Figure 4. HVAC System Performance Tool Structure for HVAC System Performance Analysis

The Asset Score Application's web interface allows users to define their building geometry, envelope, HVAC, and lighting systems. For a TSPR analysis, certain values are prescribed and automatically defaulted based on the code requirement. For example, the code prescribes the lighting power density and infiltration rate, which are automatically added by the tool. User-specified values, in conjunction with the ruleset's default values, provide the required inputs for constructing an OpenStudio simulation model. The Asset Score Modeling Engine ingests these inputs to generate three separate analyses used to calculate a TSPR: the ideal loads run, the sizing run, and the annual run.

The ideal loads analysis calculates the annual heating and cooling loads of the building. The sizing run calculates the design system capacities and flow rates used to inform values for certain parameters in the annual run (e.g., cooling tower fan power, minimum airflow fraction for VAV with reheat terminals). Lastly, the annual run calculates the annual energy use by end use for the entire building. These three analyses are done for both the proposed building and the reference building. The proposed run represents a user's inputs as entered in the Asset Score Application. The reference building run is identical to the proposed building run in terms of its geometry, envelope construction, internal loads, and ventilation loads, but with a code reference HVAC system in place of the user's HVAC system. The Report Generator ingests the simulation outputs and calculates the TSPR for the proposed and reference buildings. The Asset Score Application provides the required MPFs for the building based on its climate zone and building type(s) to determine the compliance outcome. Outputs are written to a PDF report documenting the calculated baseline and proposed TSPRs along with all model inputs defined by the user in the user interface. A sample report generated from the tool can be viewed here.[1]

## 3.4 Analysis Tool Output Report

The HVAC System Performance Rating path includes requirements for a standard output report, which needs to include all parameters specified by a user in the simulation tool as well as results generated by the tool, including the annual HVAC energy use by end use and energy type, annual heating and cooling loads, as well as the TSPR for the reference and proposed designs.

The TSPR analysis tool provides all information required by the HVAC System Performance Rating path and also includes a detailed mechanical equipment schedule that provides equipment rated capacities, design airflow, rated efficiencies, and more for all specified equipment. In addition to specifying the whole building TSPR, which is used to determine the compliance outcome, the TSPR analysis tool also provides the TSPR results for each unique system type in the building being analyzed. A sample report generated from the tool can be viewed here.

### 3.4.1 End Use Results of TSPR Models for Reference and Target Systems

The TSPR analysis tool provides the HVAC energy use by end use and fuel type for the proposed building model and the reference building model. Along with the HVAC energy use, it also provides the annual heating and cooling loads for the proposed building and the reference building. The sections below provide the results for the medium office building in climate zones 2A and 5A. Here, the "Proposed" building is the "Target" medium office building, as defined in Section 2.4, and the "Baseline" is the "Reference" medium office building as defined in Section 2.3. Note that in the % savings columns, some changes are large, but a small part of the total HVAC energy use. Also note that increases in heating energy use, or negative savings, often occur when there are significant fan savings.

[1] https://buildingenergyscore.energy.gov/documents/TSPR_Analysis_Report_Example_1.pdf

#### 3.4.1.1 Warm Climate End Use Results

Table 2. End Use Comparison, Medium Office, Warm Climate (2A)

| End Use | Proposed Building | | Reference Building | | % Electric Savings | % Gas Savings |
|---|---|---|---|---|---|---|
| | Electricity (kWh) | Gas (therms) | Electricity (kWh) | Gas (therms) | | |
| Heating | 5,016 | 0 | 2,950 | 0 | -70% | 0% |
| Cooling | 136,347 | | 180,690 | | 25% | 0% |
| Fans | 24,850 | | 69,710 | | 64% | 0% |
| Pumps | 0 | | 0 | | 0% | 0% |
| Heat rejection | 0 | | 0 | | 0% | 0% |
| Heat recovery | 0 | | 0 | | 0% | 0% |
| Total HVAC energy use | 166,213 | 0 | 253,350 | 0 | 34% | 0% |
| **Total HVAC energy use (kBtu)** | **567,088** | | **864,381** | | **34%** | |
| **Total HVAC energy cost ($)** | **18,267** | | **27,843** | | **34%** | |

#### 3.4.1.2 Cold Climate End Use Results

Table 3. Medium Office End Use Cost comparison, Cold Climate (5A)

| End Use | Proposed Building | | Reference Building | | % Electric Savings | % Gas Savings |
|---|---|---|---|---|---|---|
| | Electricity (kWh) | Gas (therms) | Electricity (kWh) | Gas (therms) | | |
| Heating | 0 | 6,166 | 0 | 6,622 | 0% | 7% |
| Cooling | 33,607 | | 45,210 | | 26% | 0% |
| Fans | 15,176 | | 51,775 | | 71% | 0% |
| Pumps | 444 | | 94 | | -370% | 0% |
| Heat rejection | 0 | | 0 | | 0% | 0% |
| Heat recovery | 0 | | 0 | | 0% | 0% |
| Total HVAC energy use | 49,227 | 6,166 | 97,079 | 6,622 | 49% | 7% |
| **Total HVAC energy use (kBtu)** | **784,586** | | **993,454** | | **21%** | |
| **Total HVAC energy cost ($)** | **11,472** | | **17,179** | | **33%** | |

# 4.0 Mechanical Performance Factor Development

As described in Section 2.2, the TSPR calculation requires an MPF to compare the reference system with a target system and verify that the proposed system is just as efficient. In order to calculate the MPFs, simplified prototype building models were generated based on the requirements specified in the HVAC System Performance approach. Section 4.1 outlines the modifications that were made to the prototype building models (Thornton et al. 2011; Goel et al. 2014b) to develop the simplified TSPR prototypes. These were then simulated to calculate the TSPR for each prototype and climate zone.

## 4.1 Development of the Simplified Prototype Building Models

- Simplified prototype models were developed for the relevant building types that were based on the PNNL 90.1 building prototypes (Thornton et al. 2011; Goel et al. 2014b). General parameters are shown in Table 4. Systems for reference and target are discussed in Sections 2.3 and 2.4.
- The prototype building models were modified to follow the HVAC System Performance requirements. The modifications made included:
  - Building schedules: HVAC System Performance approach requires the use of schedules as defined in Standard 90.1 Appendix C. These schedules are defined for building area types and do not specify requirements for spaces in a building. The simplified prototypes use the schedules as prescribed in Standard 90.1 Appendix C.
  - Internal loads: Internal loads (including lighting power densities, plug loads, and ventilation rates) were modified based on the prescribed values in Standard 90.1 Appendix C, as required by the HVAC System Performance approach.
  - Envelope construction: The HVAC System Performance approach, in Section J4.1.6, prescribes the building envelope construction type. Roof, wall, floor constructions are prescribed along with simplifications for window and skylight specification. The prototypes were modified to follow these requirements.
  - Lighting: The HVAC System Performance Rating path requires lighting power densities to be specified based on Standard 90.1 Table 9.5.1, and no explicit controls (including daylighting controls) can be modeled. The prototypes were modified to meet these requirements.
  - Thermal zoning: The HVAC System Performance approach, in Section J4.1.2, prescribes the thermal zoning requirements where each floor is required to be modeled with perimeter and core zones if all facades in a block are greater than 45 ft. The prototype building models were modified to follow these thermal zoning requirements.
  - HVAC system: HVAC systems have been analyzed following the requirements specified in Section J4.2.3 of the HVAC System Performance Rating path and have been modeled as specified for the reference and target systems (Appendix A and Appendix B of this document).
- TSPRs for the reference systems (see Appendix A) and target systems (see Appendix B) were calculated using the TSPR analysis tool (discussed in Section 3.0). The EnergyPlus model input files (IDFs) for the reference and target runs for each applicable prototype are available here.[1]

[1] https://www.energycodes.gov/sites/default/files/2021-10/20211012_hpf_idfs.zip

## 4.2 Calculation of MPF

Simulation runs were completed for 17 climate zones for seven prototypes. Table 4 shows the characteristics of each of the prototypes as analyzed for the MPF development. TSPR was calculated for all reference and target buildings for each climate zone. These results are documented in Appendix C. Table 5 shows the MPFs defined using energy cost as the metric, as defined by the HVAC System Performance approach proposed for Standard 90.1. MPFs for alternative metrics like carbon emissions, site energy, and source energy are given in Appendix D.

Table 4. Simplified Prototype Characteristics by Building Type

| Building Type | Floor | Stories | Wall Construction | Roof Construction | WWR | Ventilation Rate (CFM/ft²) | LPD, W/ft² |
|---|---|---|---|---|---|---|---|
| Office, small | 5,400 | 1 | Steel frame | Steel deck | 0.208 | 0.085 | 0.66 |
| Office, medium[(a)] | 53,660 | 3 | Steel frame | Steel deck | 0.33 | 0.085 | 0.66 |
| Office, large[(a)] | 486,400 | 12 (above grade), 1 (below grade) | Steel frame | Steel deck | 0.40 | 0.085 | 0.66 |
| Retail | 24,560 | 1 | Steel frame | Steel deck | 0.07 | 0.23 | 1.01 |
| Hotel/Motel | 43,200 | 4 | Steel frame | Steel deck | 0.105 | 0.085 | 1.01 |
| Multi-Family/Dormitory | 33,740 | 4 | Steel frame | Steel deck | 0.20 | 0.06 | 0.66 |

(a) Office sizes are as follows:

- Large office (*gross conditioned floor area* > 150,000 ft² (14,000 m²) or > 5 floors)
- Medium office (*gross conditioned floor area* 5000 to 150,000 ft² (460 to 14,000 m²) and ≤ 5 floors)
- Small office (*gross conditioned floor area* ≤ 5000 ft² (460 m²) and ≤ 5 floors)

LPD is lighting power density; WWR is window to wall ratio.

Table 5. Mechanical Performance Factors, Cost Basis

| Climate Zone: Building type | 0A | 0B | 1A | 1B | 2A | 2B | 3A | 3B | 3C | 4A | 4B | 4C | 5A | 5B | 5C | 6A | 6B | 7 | 8 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Office (small and medium)[a] | 0.72 | 0.71 | 0.70 | 0.70 | 0.68 | 0.65 | 0.71 | 0.66 | 0.62 | 0.69 | 0.64 | 0.65 | 0.72 | 0.66 | 0.65 | 0.74 | 0.70 | 0.75 | 0.77 |
| Office (large)[a] | 0.83 | 0.83 | 0.84 | 0.84 | 0.79 | 0.82 | 0.72 | 0.84 | 0.78 | 0.69 | 0.80 | 0.67 | 0.72 | 0.75 | 0.67 | 0.73 | 0.73 | 0.71 | 0.70 |
| Retail | 0.60 | 0.57 | 0.50 | 0.55 | 0.46 | 0.46 | 0.43 | 0.46 | 0.38 | 0.40 | 0.45 | 0.48 | 0.41 | 0.50 | 0.47 | 0.44 | 0.39 | 0.40 | 0.36 |
| Hotel/Motel | 0.62 | 0.62 | 0.63 | 0.63 | 0.62 | 0.68 | 0.61 | 0.71 | 0.73 | 0.59 | 0.66 | 0.65 | 0.55 | 0.59 | 0.68 | 0.51 | 0.54 | 0.47 | 0.40 |
| Multi-Family/Dormitory | 0.64 | 0.63 | 0.67 | 0.63 | 0.65 | 0.64 | 0.59 | 0.68 | 0.54 | 0.59 | 0.57 | 0.52 | 0.58 | 0.53 | 0.48 | 0.57 | 0.53 | 0.55 | 0.52 |
| School/Education | 0.82 | 0.81 | 0.80 | 0.79 | 0.75 | 0.72 | 0.71 | 0.72 | 0.68 | 0.67 | 0.71 | 0.65 | 0.72 | 0.68 | 0.60 | 0.75 | 0.69 | 0.72 | 0.68 |

(a) Office sizes as shown in Table 4.

# 5.0 System Comparisons: Validation of the TSPR Approach

PNNL used the TSPR tool to validate differences in HVAC system performance. The prototype building models (Goel et al. 2014b) for small office, medium office, and stand-alone retail were modified to include the HVAC System Performance Rating path requirements for each respective use type. The ruleset includes several requirements for the proposed building (Appendix A, Section CD 105) such as schedules of operations, envelope construction type, lighting power densities, and so forth. It also requires averaging of HVAC equipment efficiency, fan power, pump power, and other parameters for similar system types to simplify the process of defining the energy model (Appendix A, Section CD105.2.10.2). All of these requirements have been implemented into the TSPR analysis tool, which was used to define the proposed building and automatically generate the reference building. Each of the prototypes were analyzed in climate zones 2A and 5A, with several different HVAC system configurations, including (1) the reference HVAC system, (2) the target HVAC system, (3) a base-efficiency configuration that meets the Standard 90.1-2019 prescriptive code and is the least efficient system configuration that complies with the code, and (4) several advanced system configurations that exceed the code requirement. The reference system configurations are summarized in Appendix A. The target systems, summarized in Appendix B, include improved equipment performance (as required by minimum prescriptive code requirements in Standard 90.1-2019), lower fan power, and economizer control, if required by code.

A comparison of the target system to the reference-efficiency configuration demonstrates the additional savings that can result from adoption of the HVAC System Performance approach. Each of the advanced cases look at different system configurations, including variable refrigerant flow (VRF), water-loop heat pumps (WLHPs), or ground source heat pump systems. Several advanced scenarios include DOAS systems with heat recovery and DCV.

For each of the building type and climate zone comparisons, the TSPR results are color coded in the figures in the following subsections as follows:

- Reference and target system TSPRs are shown in blue. The target TSPR for the building needs to be exceeded to meet the TSPR compliance criteria, and a red line is drawn for that threshold.
- System configurations that do not meet the target TSPR are shown with red bars.
- Alternative system configurations that meet or exceed the target TSPR are shown in green. These systems qualify as passing the HVAC System Performance Rating path.

The associated tables for climate zone and building type in the following subsections show the details of the systems analyzed.

## 5.1 Small Office

The small office reference system is a packaged single zone heat pump for the warm climate zones (climate zones 0-3A) or a packaged single zone gas furnace for the cold climate zones (climate zones 3B, 3C, 4-8). Table 6 and Table 7 summarize the additional scenarios analyzed for climate zones 2A and 5A and Figure 5 and Figure 6 show the resulting TSPR-cost for each of these scenarios.

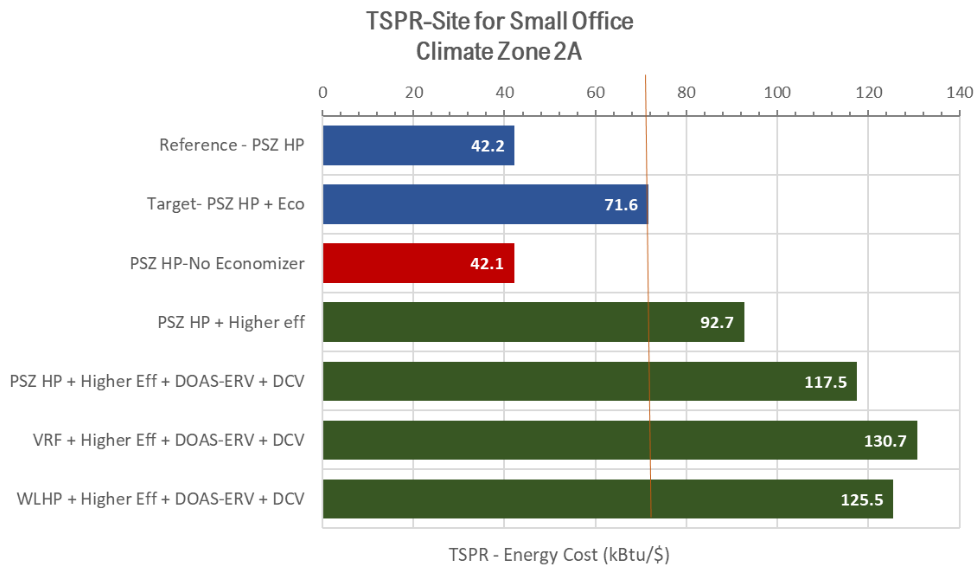


Figure 5. Small Office Results for Different System Configurations (climate zone 2A)

Table 6. Small Office System Configurations Analyzed for Climate Zone 2A

| Run Description | Reference - PSZ HP | Target-PSZ HP + Eco | Base-Efficiency-PSZ HP | PSZ HP + Higher efficiency | PSZ HP + Higher Eff + DOAS-ERV + DCV | VRF + Higher Eff + DOAS-ERV + DCV | WLHP + Higher Eff + DOAS-ERV + DCV |
|---|---|---|---|---|---|---|---|
| System type | PSZ HP | PSZ HP | PSZ HP | PSZ HP | PSZ HP | VRF | WLHP |
| Cooling efficiency | 3.0 COPnf | SEER 14 | SEER 14 | 115% target efficiency | 115% target efficiency | 12.4 EER | 16.8 EER |
| Heating efficiency | 3.4 COPnf | HSPF 8.0 | HSPF 8.0 | 115% target efficiency | 115% target efficiency | 3.65 COP | 5.5 COP |
| Fan control | CAV | CAV | CAV | Two-speed fan | Cycling | Cycling | Cycling |
| Fan power | 0.916 W/CFM | 0.486 W/CFM | 1.12 W/CFM | 0.438 W/CFM | 0.413 W/CFM | 0.316 W/CFM | 0.365 W/CFM |
| DOAS | No | No | No | No | Yes | Yes | Yes |
| ERV | No | No | No | 70% ERR ERV with bypass | 70% ERR ERV with bypass | 70% ERR ERV with bypass | 70% ERR ERV with bypass |
| DCV | No | No | No | Yes, 20% area | Yes, 20% area | Yes, 20% area | Yes, 20% area |
| Economizer | No | Yes | No | Yes | Yes | No | No |

The low-efficiency heat pump meets all Standard 90.1-2019 prescriptive requirements and yet has a TSPR equivalent to that of the reference building system and ~40% lower than the target. The “advanced options” include WLHPs and VRF systems with DOAS for ventilation and cycling fans, which provide conditioned air. The improvement in TSPR ranges from ~60% to over 130% over the target system for these configurations.

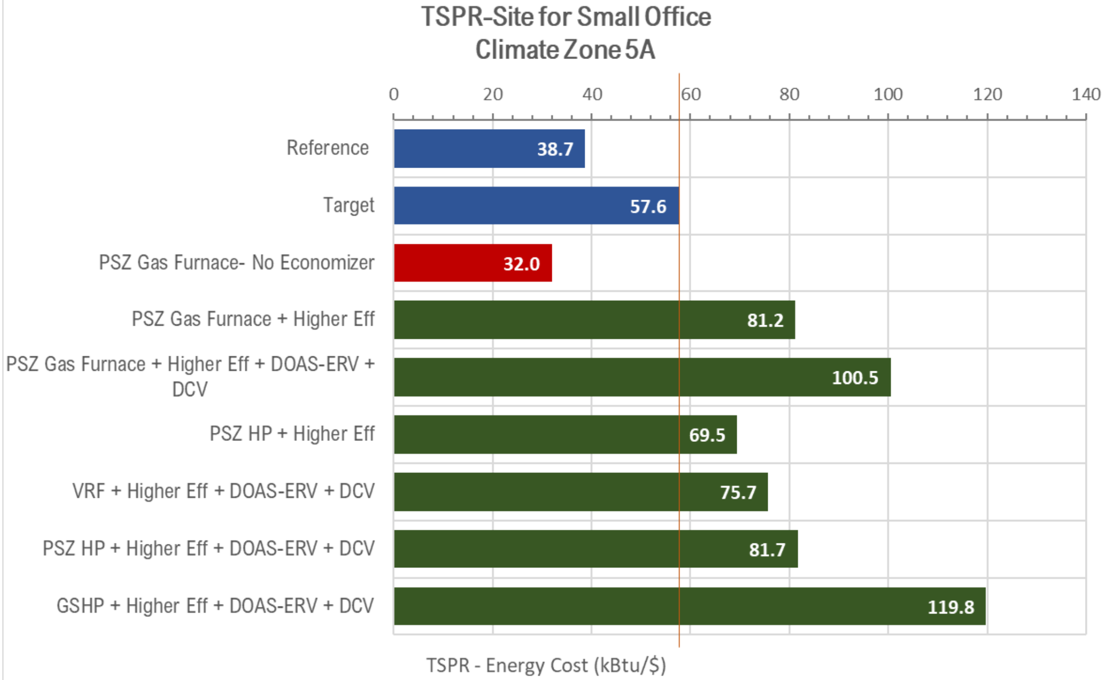


Figure 6. Small Office Results for Different System Configurations (climate zone 5A)

Table 7. Small Office System Configurations Analyzed for Climate Zone 5A

| Run Description | Reference | Target | Base-efficiency - PSZ Gas Furnace | PSZ Gas Furnace + Higher Eff | PSZ Gas Furnace + Higher Eff + DOAS-ERV + DCV | PSZ HP + Higher Eff | VRF + Higher Eff + DOAS-ERV + DCV | PSZ HP + Higher Eff + DOAS-ERV + DCV | GSHP + Higher Eff + DOAS-ERV + DCV |
|---|---|---|---|---|---|---|---|---|---|
| System type | PSZ AC | PSZ AC | PSZ AC | PSZ AC | PSZ AC | PSZ HP | VRF | PSZ HP | GSHP |
| Cooling efficiency | 3.0 COPnf | SEER 14 | SEER 14 | 115% target efficiency | 115% target efficiency | 115% target efficiency | 12.4 EER | 115% target efficiency | 19.6 EER |
| Heating efficiency | 80% Et | 81%Et | 80% Et | 93.5 Et | 93.5 Et | 115% target efficiency | 3.65 COP | 115% target efficiency | 3.8 COP |
| Fan control | CAV | CAV | CAV | Two-speed fan | Cycling | Two-speed fan | Cycling | Cycling | Cycling |
| Fan power | 0.916 W/CFM | 0.486 W/CFM | 1.12 W/CFM | 0.438 W/CFM | 0.438 W/CFM | 0.438 W/CFM | 0.316 W/CFM | 0.365 W/CFM | 0.365 W/CFM |
| DOAS | No | No | No | No | Yes | No | Yes | Yes | Yes |
| ERV | No | No | No | No | 70% ERR ERV with bypass | No | 70% ERR ERV with bypass | Yes, ERR=70% | 70% ERR ERV with bypass |
| DCV | No | No | No | No | Yes, 20% area | No | Yes, 20% area | Yes, 20% area | Yes, 20% area |
| Economizer | Yes | Yes | No | Yes | Yes | Yes | No | Yes | No |

## 5.2 Medium Office

The medium office reference system is a packaged VAV with fan-powered parallel induction units with electric resistance reheat for the warm climate zones (climate zones 0-3A) or a packaged VAV with hot-water reheat for the cold climate zones (climate zones 3B, 3C, 4-8). Table 8 and Table 9 summarize the additional scenarios analyzed for climate zones 2A and 5A and Figure 7 and Figure 8 show the resulting TSPR-cost for each of these scenarios. In each case, the base-efficiency option, which meets Standard 90.1-2019 minimum prescriptive code requirements, has a significantly lower TSPR than the target.

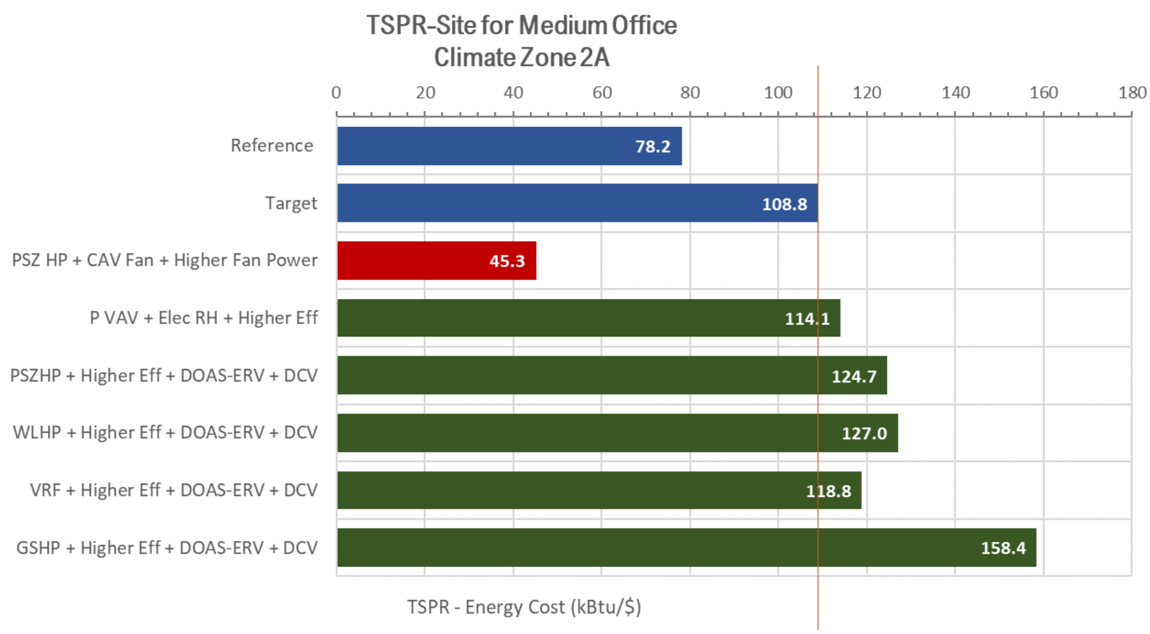


Figure 7. Medium Office Results for Different System Configurations (climate zone 2A)

Table 8. Medium Office System Configurations Analyzed for Climate Zone 2A

| Run Description | Reference | Target | Base-efficiency - PSZ HP | P VAV + Elec RH + Higher Eff | PSZHP + Higher Eff + DOAS-ERV + DCV | WLHP + Higher Eff + DOAS-ERV + DCV | VRF + Higher Eff + DOAS-ERV + DCV | GSHP + Higher Eff + DOAS-ERV + DCV |
|---|---|---|---|---|---|---|---|---|
| System type | P-VAV with Elec RH PIU | P-VAV with Elec RH PIU | PSZ HP | P-VAV with Elec RH PIU | PSZ HP | WLHP | VRF | GSHP |
| Cooling efficiency | 3.4 COPnf | 11.0 EER | 11.0 EER | 115% target efficiency | 115% target efficiency | 16.8 EER | 12.4 EER | 19.6 EER |
| Heating efficiency | 100% Et | 100% Et | 3.3 COP | 100% Et | 115% target efficiency | 5.5 COP | 3.65 COP | 3.8 COP |
| Fan control | VAV | VAV | CAV | VAV | Two-speed fan | Cycling | Cycling | Cycling |
| Fan power | 1.285 W/CFM | 0.634 W/CFM | 1.12 W/CFM | 0.571 W/CFM | 0.438 W/CFM | 0.365 W/CFM | 0.316 W/CFM | 0.365 W/CFM |
| DOAS | No | No | No | No | Yes | Yes | Yes | Yes |
| ERV | No | No | No | No | 70% ERR ERV with bypass | 70% ERR ERV with bypass | 70% ERR ERV with bypass | 70% ERR ERV with bypass |
| DCV | No | Yes, 20% area | No | Yes, 20% area | Yes, 20% area | Yes, 20% area | Yes, 20% area | Yes, 20% area |
| Economizer | No | Yes | No | Yes | Yes | No | No | No |

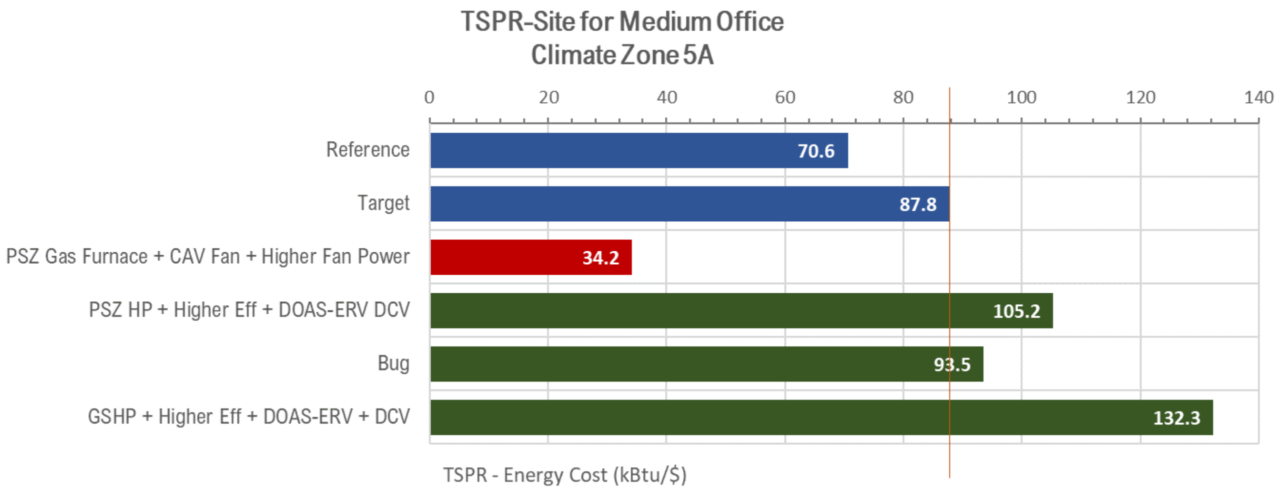


Figure 8. Medium Office Results for Different System Configurations (climate zone 5A)

Table 9. Medium Office System Configurations Analyzed for Climate Zone 5A

| Run Description | Reference | Target | (Base-Efficiency) PSZ Gas Furnace + CAV Fan + Higher Pan Power | PSZ HP + Higher Eff + DOAS-ERV DCV | VRF + Higher Eff + DOAS-ERV + DCV | GSHP + Higher Eff + DOAS-ERV + DCV |
|---|---|---|---|---|---|---|
| System type | P-VAV with HW RH | P-VAV with HW RH | PSZ AC | PSZ HP | VRF | GSHP |
| Cooling efficiency | 3.4 COPnf | 11.0 EER | 11.0 EER | 115% target efficiency | 12.4 EER | 19.6 EER |
| Heating efficiency | 75% Et | 81% Et | 80% Et | 115% target efficiency | 3.65 COP | 3.8 COP |
| Fan control | VAV | VAV | CAV | Two-speed fan | Cycling | Cycling |
| Fan power | 1.285 W/CFM | 0.634 W/CFM | 1.12 W/CFM | 0.438 W/CFM | 0.316 W/CFM | 0.365 W/CFM |
| DOAS | No | No | No | Yes | Yes | Yes |
| ERV | No | No | No | 70% ERR ERV with bypass | 70% ERR ERV with bypass | 70% ERR ERV with bypass |
| DCV | No | Yes, 20% area | No | Yes, 20% area | Yes, 20% area | Yes, 20% area |
| Economizer | Yes | Yes | No | Yes | No | No |

## 5.3 Mid-Rise Apartment

The mid-rise multifamily reference system is a PTHP for the warm climate zones (climate zones 0-3A) or a PTAC (with a gas-fired boiler) for the cold climate zones (climate zones 3B, 3C, 4-8). The target system adds a single-zone DOAS with ERV for ventilation and the PTHP is replaced with a split heat pump for the warm climate zones and a split air conditioner for the cold climate zones. Table 10 and Table 11 summarize the additional scenarios analyzed for climate zones 2A and 5A and Figure 9 and Figure 10 show the resulting TSPR cost for each of these scenarios.

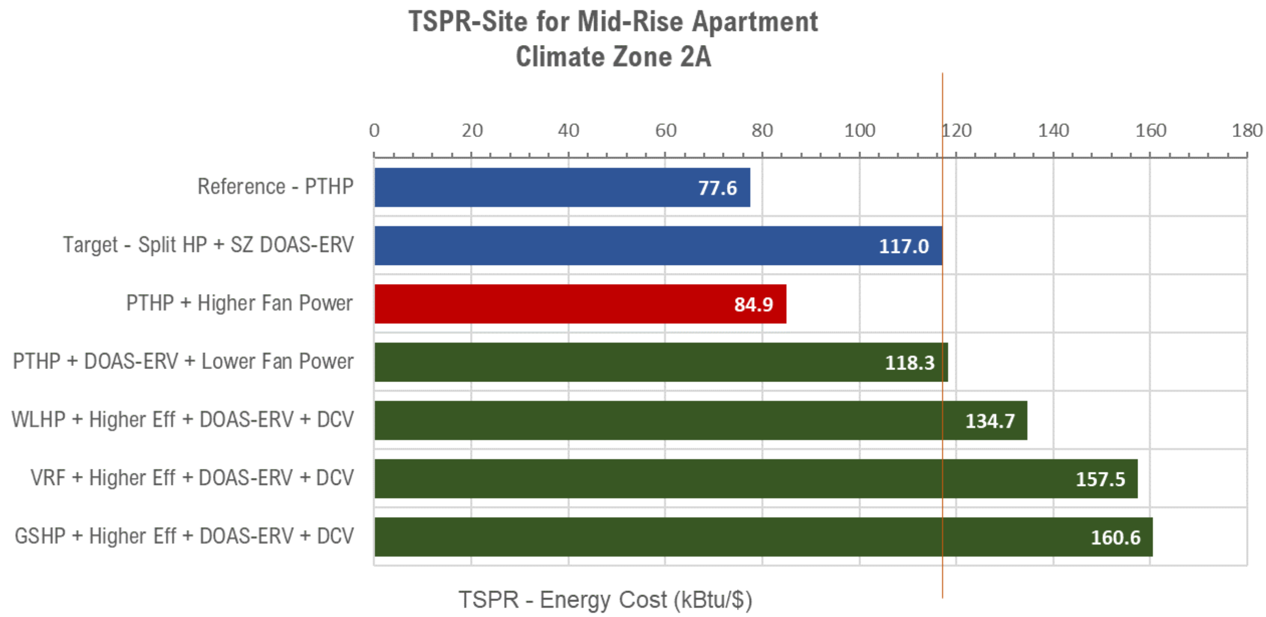


Figure 9. Mid-Rise Apartment Results for Different System Configurations (climate zone 2A)

Table 10. Mid-Rise Apartment System Configurations Analyzed for Climate Zone 2A

| Run Description | Reference - PTHP | Target - Split HP + SZ DOAS-ERV | PTHP + Higher Fan Power | PTHP + DOAS-ERV + Lower Fan Power | WLHP + Higher Eff + DOAS-ERV + DCV | VRF + Higher Eff + DOAS-ERV + DCV | GSHP + + Higher Eff + DOAS-ERV + DCV |
|---|---|---|---|---|---|---|---|
| System type | PTHP | Split heat pump | PTHP | PTHP | WLHP | VRF | GSHP |
| Cooling efficiency | 3.1 COPnf | SEER 14 | EER 11.3 | EER 11.3 | 16.8 EER | 12.4 EER | 19.6 EER |
| Heating efficiency | 3.1 COPnf | HSPF 8.2 | 3.232 COP | 3.232 COP | 5.5 COP | 3.65 COP | 3.8 COP |
| fan Control | CAV | Cycling | CAV | Cycling | Cycling | Cycling | Cycling |
| fan Power | 0.3 W/CFM | 0.246 W/CFM | 0.3 W/CFM | 0.185 W/CFM | 0.185 W/CFM | 0.148 W/CFM | 0.185 W/CFM |
| DOAS | No | Yes | No | Yes | Yes | Yes | Yes |
| ERV | No | Single zone ERV with no bypass, 50% ERR | No | Single zone ERV with no bypass, 70% ERR | 70% ERR ERV with bypass | 70% ERR ERV with bypass | 70% ERR ERV with bypass |
| DCV | No | No | No | No | Yes, 50% area | Yes, 50% area | Yes, 50% area |
| Economizer | No | No | No | No | No | No | No |

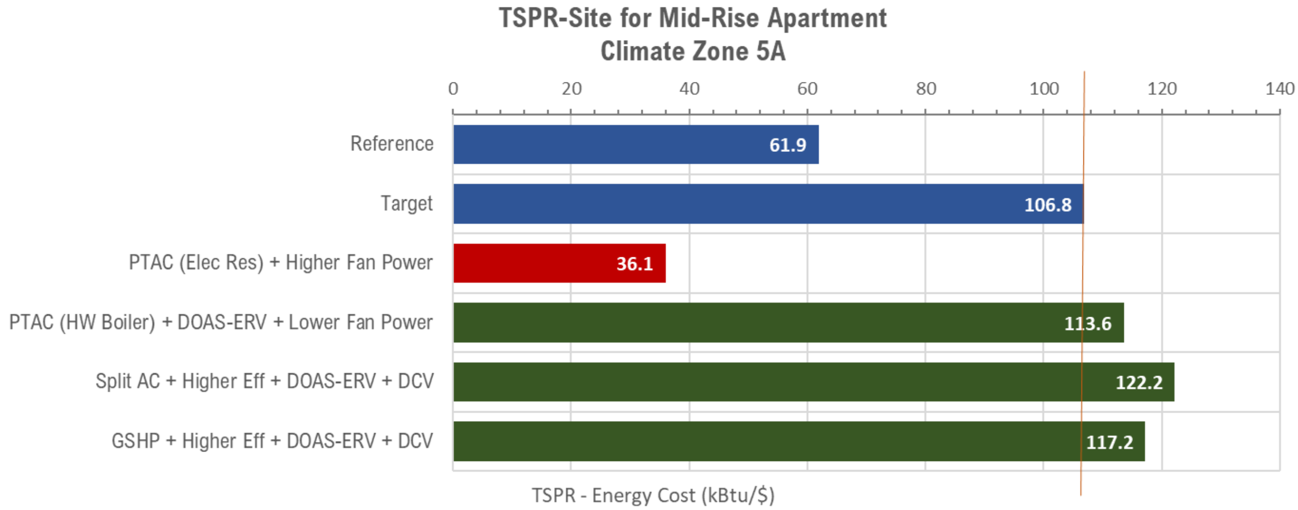


Figure 10. Mid-Rise Apartment Results for Different System Configurations (climate zone 5A)

Table 11. Mid-Rise Apartment System Configurations Analyzed for Climate Zone 5A

| Run Description | Reference | Target | PTAC (Elec Res) – Higher Fan Power | PTAC (HW Boiler) + DOAS-ERV + Lower Fan Power | Split AC + Higher Eff + DOAS-ERV + DCV | GSHP + + Higher Eff + DOAS-ERV + DCV |
|---|---|---|---|---|---|---|
| System type | PTAC | Split AC | PTAC | PTAC | Split AC | GSHP |
| Cooling efficiency | 3.2 COPnf | SEER 13 | EER 11.3 | EER 11.3 | SEER 15.5 | 19.6 EER |
| Heating efficiency | 75% Et | 80% AFUE | 1 | 80% Et | 95% Et | 3.8 COP |
| Fan control | CAV | Cycling | CAV | CAV | Two-speed | Cycling |
| Fan power | 0.3 W/CFM | 0.271 W/CFM | 0.3 W/CFM | 0.217 W/CFM | 0.217 W/CFM | 0.203 W/CFM |
| DOAS | No | Yes | No | Yes | Yes | Yes |
| ERV | No | Single zone ERV with no bypass, 50% ERR | No | Single zone ERV with no bypass, 70% ERR | Single zone ERV with no bypass, 50% ERR | 70% ERR ERV with bypass |
| DCV | No | No | No | No | No | Yes, 50% area |
| Economizer | No | No | No | No | No | No |

# 6.0 Simplified Modeling Approaches

## 6.1 Demand Control Ventilation

DCV shall be modeled using a simplified approach that adjusts the design outdoor supply air flow rate based on the area of the building that is covered by DCV. There are two approaches to DCV: (1) analog DCV that modulates outdoor air based on space occupancy, typically using $CO_2$ sensors; and (2) binary DCV that shuts off outdoor air when the space is completely unoccupied, typified in 90.1 Section 6.5.3.8, occupied standby controls. Since TSPR models (and often more detailed performance models) do not typically represent every separate high-density space, such as conference rooms or lobbies, a more simplified approach is used that looks at the percentage of floor area with DCV control, the expected occupancy level, and the share of the building with high vs. low occupancy areas. Because binary DCV (occupied standby) requires the space to be completely vacant to activate, the reduction in outdoor air for binary DCV is taken as 1/3 the analog DCV (e.g., $CO_2$) reduction.

Looking at the graph, break points can be seen that vary by building type, with the understanding that DCV will be applied to high-density spaces first. For example, in the office, there is a moderate increase in overall outside air (OSA) reduction for the first 15% of floor area representing conference rooms, and then as more area is added, the reduction is much less. In contrast, a school experiences good reduction in outdoor air for DCV in up to 65% of floor area representing classrooms, and more modest reductions if DCV is extended further. Similarly, retail has a large sales area, although at a lower ventilation density than classrooms, resulting in lower impact than schools. With this method, the simplified reduction can be applied to the gross outdoor air requirement to simulate average reductions.

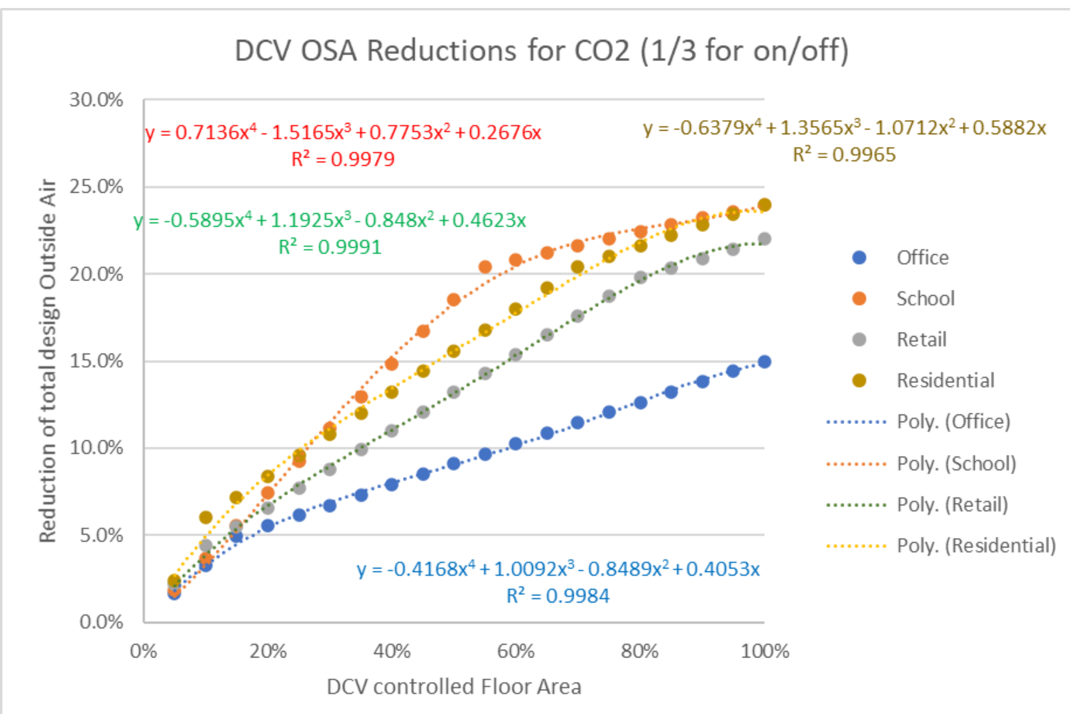


Figure 11. DCV OSA Reduction as a Function of Controlled Floor Area

## 6.2 Variable Flow Fan Curves

Variable flow fans for the reference are based on Standard 90.1 Appendix G, Table G3.1.3.15, a variable flow fan curve without static pressure reset. The target systems have been analyzed with a variable speed fan with static pressure reset. Part-load variable speed_fan power has been calculated using a cubic function with coefficients as shown in Table 12 and Figure 12.

Table 12. Variable Flow Fan Curve Coefficients

| Equation Term | Fan Power Coefficients | |
|---|---|---|
| | VSD (without SP reset) | VSD + SP Reset |
| b | 0.0013 | 0.0408 |
| x | 0.1470 | 0.088 |
| $x^2$ | 0.9506 | -0.0729 |
| $x^3$ | -0.0998 | 0.9437 |

SP is static pressure; VSD is variable speed drive.

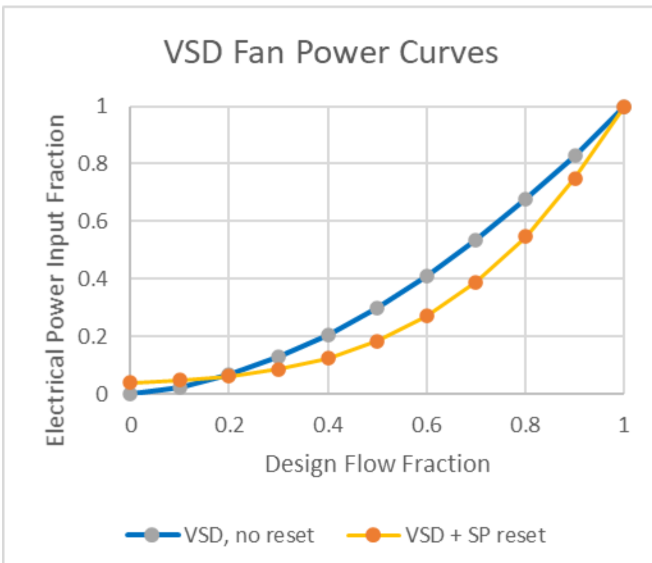


Figure 12. Fan Power Performance as a Function of Design Air Flow Rate

## 6.3 Variable Flow Pump Curves

Part-load variable pump power has been calculated using a cubic function with coefficients as shown in Table 13. The independent variable is the fraction of design water flow rate as shown in Figure 13.

Table 13. Variable Flow Pump Curve Coefficients

| Equation Term | *Pump* Power Coefficients | |
|---|---|---|
| | Ride *Pump* Curve | VSD + DP/valve reset |
| b | 0 | 0 |
| x | 3.2485 | 0.0205 |
| $x^2$ | -4.7443 | 0.4101 |
| $x^3$ | 2.5295 | 0.5753 |

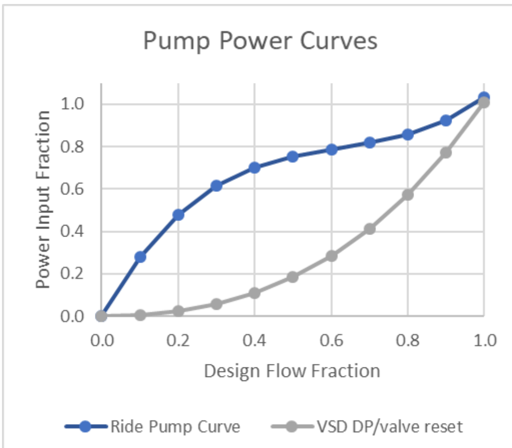


Figure 13. Pump Power Performance as a Function of Design Water Flow Rate

## 6.4 Chillers and Heat Rejection

A three-chiller plant is modeled to represent chilled water plants with three or more chillers (Figure 14). If a plant includes less than three chillers, the actual number of chillers is modeled. For water-cooled chillers, the condenser loop is a four-cell tower that operates the maximum number of cells possible with no more than 50% turndown in active cells at all times.

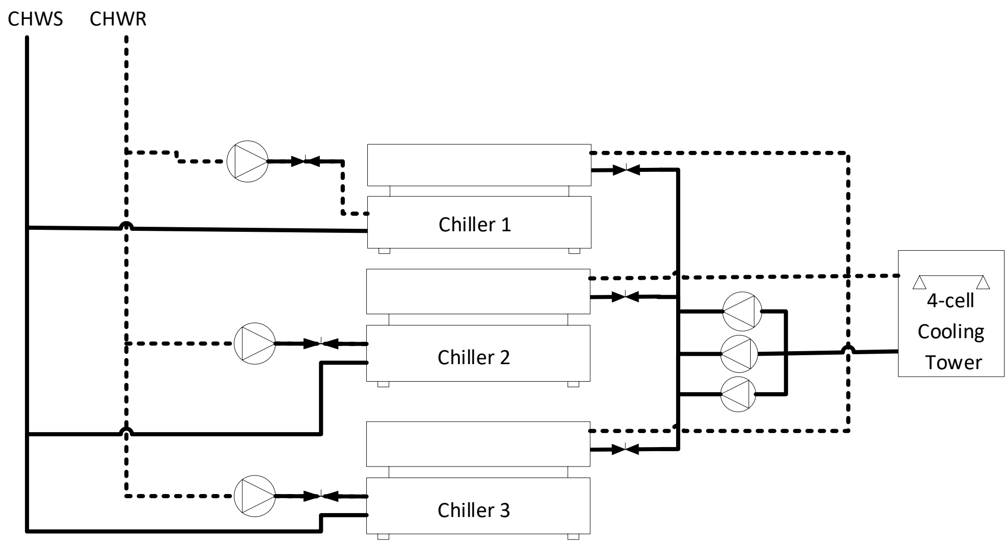


Figure 14. Three-Chiller Plant

Sequence of operation for chilled water plants including **two** chillers:

1. The smallest chiller is loaded first, to either 100% for fixed speed chillers or 80% for chillers with variable speed compressors.
2. Both chillers are then loaded equally until they are fully loaded.

Sequence of operation for chilled water plants including **three or more** chillers:

1. The smallest chiller is loaded first, to either 100% for fixed speed chillers or 80% for chillers with variable speed compressors.
2. The small chiller is then turned off and the most efficient of the two larger ones is turned on until it is fully loaded.
3. Both larger chillers are then loaded equally until they are fully loaded.
4. The small chiller is then turned back on to meet any remaining load.

Where there are more than three chillers, their capacity is assigned to the three modeled chillers by chiller type.

Cooling towers can be modeled as either single speed or variable speed. Single-speed towers are modeled with cycling fan and variable-speed towers are modeled with variable-speed fans using the performance curve shown in Figure 15.

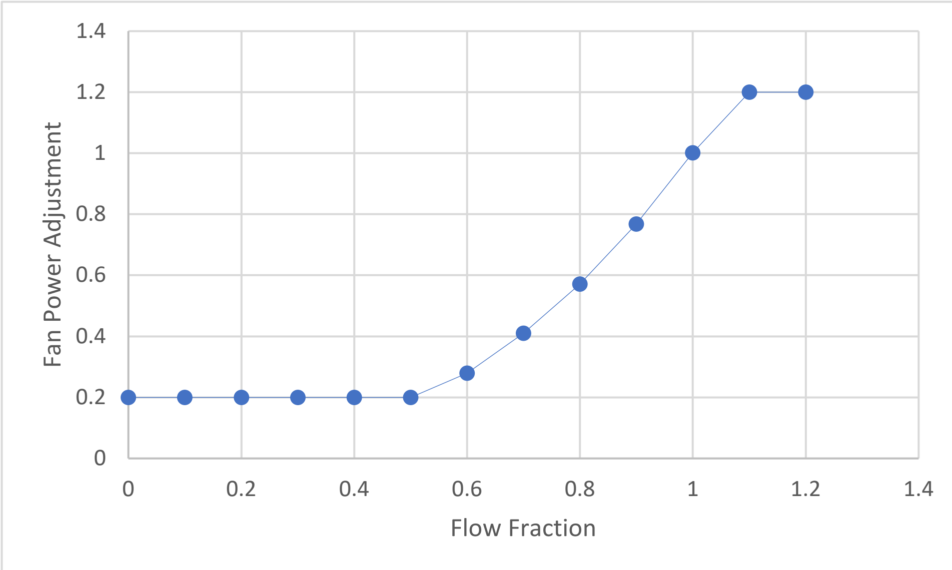


Figure 15. Cooling Tower Fan Power Adjustment

## 6.5 Condensing Gas and Non-condensing Gas Boilers

Part load and off-rated operation of condensing and non-condensing boiler are described using performance curves.

A performance curve for condensing boilers was determined using manufacturer data describing a unit's combustion efficiency as a function of return water temperature. Thermal efficiency was calculated assuming that standby losses were 2% of a boiler's nominal capacity.

A performance curve for non-condensing boilers was determined by performing a regression through data points generated from the performance curves used by the DOE Commercial Prototype Building models for different minimum part load ratios (0.2, 0.25, 0.33).

While only one boiler is effectively modeled, one- and two-boiler curves were generated to approximate the benefits of boiler staging by reducing losses at lower hot water plant part load ratios. Losses were reduced by 50% at part load ratios below 0.45 for both the two-condensing and non-condensing boilers curves.

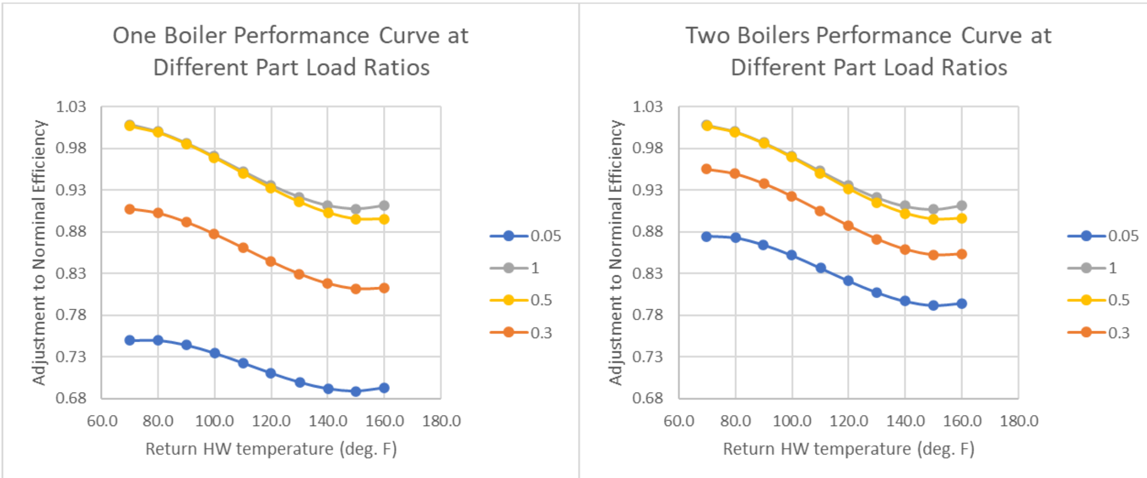


Figure 16. Condensing Boilers Performance Curves

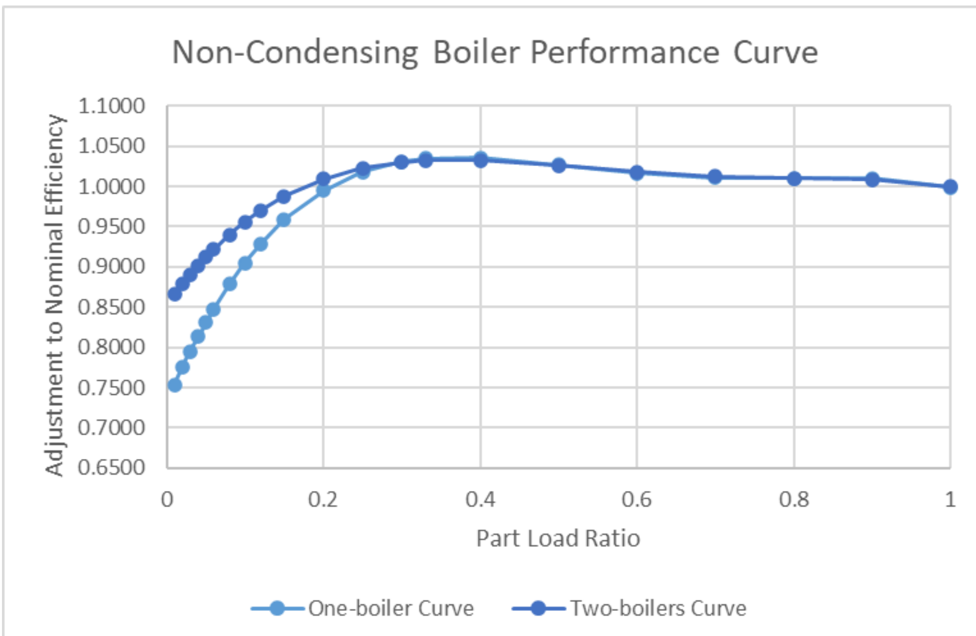


Figure 17. Non-condensing Boilers Performance Curves

## 6.6 Packaged Equipment Fan Power Adjustments

Where the supply fan power is modeled separately, the COP for packaged equipment needs to be modified to remove the effect of the indoor fan power and the rated power consumption of the supply air fan needs to be subtracted from the COP. The equations listed below have been used to calculate the $COP_{nf}$ ($COP_{No\ Fan}$) for both heating and cooling.

- For packaged single-zone air conditioners (cooling only), WLHPs, ground-source heat pumps, and packaged rooftop heat pumps:

$$COP_{nfheating} = 1.48\text{E-}7 \times COP_{47} \times Q + 1.062 \times COP_{47}$$

$(COP_{nfheating} = 5.05\text{E-}4 \times COP_{H8.3} \times Q + 1.062 \times COP_{H8.3})$

$COP_{nfheating} = -0.0296 \times HSPF^2 + 0.7134 \times HSPF$

$(COP_{nfheating} = -0.3446 \times SCOP_H^2 + 2.434 \times SCOP_H)$

$COP_{nfcooling} = 7.84\text{E-}8 \times EER \times Q + 0.338 \times EER$

$(COP_{nfcooling} = 9.13\text{E-}4 \times COP_C \times Q + 1.15 \times COP_C)$

$COP_{nfcooling} = -0.0076 \times SEER^2 + 0.3796 \times SEER$

$(COP_{nfcooling} = -0.0885 \times SCOP_C{}^2 + 1.295 \times SCOP_C)$

- Packaged terminal heat pumps

$COP_{nfcooling} = 0.3322 \times EER - 0.2145$

$(COP_{nfcooling} = 9.13\text{E-}4 \times COP_C \times Q + 1.15 \times COP_C)$

$COP_{nfheating} = 1.1329 \times COP - 0.214$

$(COP_{nfheating} = 1.1329 \times COP - 0.214)$

- Packaged terminal air conditioners

$COP_{nfcooling} = 0.3322 \times EER - 0.2145$

# 7.0 References


ASHRAE. 2004. ANSI/ASHRAE/IESNA Standard 90.1-2004. *Energy Efficient Design of New Low-Rise Residential Buildings*. Atlanta, GA

ASHRAE. 2016. ANSI/ASHRAE/IES Standard 90.1-2016. *Energy Efficient Design of New Low-Rise Residential Buildings*. Atlanta, GA

ASHRAE. 2019. *ASHRAE/ANSI/IES Standard 90.1-2019: Energy Standard for Buildings except Low-Rise Residential Buildings*. Atlanta, GA.

ASHRAE. 2019 Addendum AG. https://www.ashrae.org/technical-resources/standards-and-guidelines/standards-addenda/addenda-to-standard-90-1-2019

ASHRAE. 2020 ASHRAE Vision 2020. https://www.ashrae.org/File%20Library/About/Strategic%20Plan/ASHRAE-Vision-2020-color.pdf

DOE. 2018a. EnergyPlus Energy Simulation Software. U.S. Department of Energy, Washington, D.C. https://energyplus.net/

DOE. 2018b. Building Energy Asset Score. U.S. Department of Energy, Washington, D.C. https://www.energy.gov/eere/buildings/building-energy-asset-score

Franconi, E.; Lerond, J.; Nambiar, C.; Kim, D.;Winiarski, D.; Rosenberg, M. Filling the Efficiency Gap to Achieve Zero Energy Buildings with Energy Codes (PNNL-30547); Pacific Northwest National Laboratory: Richland, WA, USA, 2021; publication pending.

Hart R. 2021. "Revision of Section C406." Pacific Northwest National Laboratory, Richland, WA. https://www.sbcc.wa.gov/sites/default/files/2021-06/C406-PNNL-Code%20Change_21i.pdf

Hart R, J McNeill, M Tillou, C Cejudo, C Nambiar, H Nagda, D Maddox, J Lerond, and M Rosenberg. 2021. *Energy Credits for Energy Codes.* Pacific Northwest National Laboratory, Richland WA.

HPB. 2019. System Level Key Performance Indicators. http://www.hpbmagazine.org/System-Level-Key-Performance-Indicators/

Goel S, N Wang, M Rosenberg, and V Mendon. 2014a. "Performance-Based Building System Evaluation for DOE Energy Asset Score." Presented at the ASHRAE Annual Conference, Atlanta, GA, June 28-July 2.

Goel S, RA Athalye, W Wang, J Zhang, MI Rosenberg, Y Xie, R Hart, et al. 2014b. *Enhancements to ASHRAE Standard 90.1 Prototype Building Models*. PNNL-23269, Pacific Northwest National Laboratory, Richland, WA.

ICC. 2020. *2021 International Energy Conservation Code (IECC)*. International Code Council, Inc., Country Club Hills, IL.

Jonlin D, B Thornton, and MI Rosenberg, 2018a. "Can High Performance Equipment Lead to a Low-Performing Building?" In *Proceedings of the 2016 ACEEE Summer Study on Energy Efficiency in Buildings* 3:1–13. Washington, DC: ACEEE.

Jonlin D, MI Rosenberg, and S Goel. 2018b. "TSPR: The Total System Performance Ratio as a Metric for HVAC System Efficiency." In *Proceedings of the 2018 ACEEE Summer Study on Energy Efficiency in Buildings*. Asilomar, CA.

Lei X, JB Butzbaugh, Y Chen, J Zhang, and MI Rosenberg. 2020. *Development of National New Construction Weighting Factors for the Commercial Building Prototype Analyses (2003-2018)*. PNNL-29787, Pacific Northwest National Laboratory, Richland, WA. https://www.energycodes.gov/sites/default/files/documents/Commercial_Weighting_Factors_2003_to_2018_20200730.pdf

Li H, T Hong, S H Lee, and M Sofos. 2020. *System Level Key Performance Indicators for Building Performance Evaluation*. Lawrence Berkeley National Laboratory, Berkeley, CA. https://eta-publications.lbl.gov/sites/default/files/system-level_key_performance_indicators.pdf

OpenStudio. 2018. https://openstudio.net

Rosenberg M and R Hart. 2016. *Developing Performance Cost Index Targets for ASHRAE Standard 90.1 Appendix G*. PNNL-25202, Rev. 1, Pacific Northwest National Laboratory, Richland, WA. https://www.pnnl.gov/main/publications/external/technical_reports/PNNL-25202Rev1.pdf

Rosenberg M, R Hart, J Zhang, and R Athalye. 2015. *Roadmap for the Future of Commercial Energy Codes*. PNNL-24009, Pacific Northwest National Laboratory, Richland, WA. https://www.pnnl.gov/main/publications/external/technical_reports/PNNL-24009.pdf

Rosenberg M, S Goel, and M Tillou. 2020. "Paving the Way for Net Zero Energy Codes through Performance Based Approaches." *In Proceedings 2020 ACEEE Summer Study on Energy Efficiency in Buildings*, Asilomar, CA.

SEC. 2018. *Seattle Energy Code*. http://www.seattle.gov/sdci/codes/codes-we-enforce-(a-z)/energy-code#2018seattleenergycode

Thornton BA, W Wang, H Cho, Y Xie, VV Mendon, EE Richman, J Zhang, RA Athalye, MI Rosenberg, and B Liu. 2011. "Achieving the 30% Goal: Energy and Cost Saving Analysis of ASHRAE/IES Standard 90.1-2010." PNNL for USDOE, May 2011. http://www.energycodes.gov/sites/default/files/documents/BECP_Energy_Cost_Savings_STD2010_May2011_v00.pdf. http://www.energycodes.gov/development/commercial/90.1_models.

Wang N, S Goel, V Srivastava, and A Makhmalbaf. 2015. *Commercial Building Energy Asset Score System: Program Overview and Technical Protocol (Version 1.2)*. PNNL-22045, Rev. 1.2, Pacific Northwest National Laboratory, Richland, WA. https://buildingenergyscore.energy.gov/documents/energy_asset_score_technical_protocol.pdf

WSEC. 2018. *Washington State Energy Code, 2018*. Washington State Building Code Council, Olympia, WA. https://sbcc.wa.gov/sites/default/files/2020-04/2018%20WSEC_C%202nd%20print.pdf

WSEC 2020. Washington State Energy Code: Progress Towards 2030. https://sbcc.wa.gov/sites/default/files/2020-12/Final%202018%20Report.pdf

# Appendix A – Reference HVAC System Parameters

**CD105.3.11 HVAC equipment.**

The *reference building design* HVAC equipment consists of separate space conditioning systems as described in Table CD105.3.11(1) through Table CD105.3.11(3) for the appropriate building use types. In these tables, 'Warm' refers to climate zones 0 to 2 and 3A and 'Cold' refers to climate zones 3B, 3C, and 4 to 8.

**Table CD105.3.11(1) Reference Building Design HVAC Complex Systems**

| Building Type Parameter | Large Office (warm) | Large Office (cold) | School (warm) | School (cold) |
|---|---|---|---|---|
| System Type | *VAV*/ RH Water-cooled Chiller/ Electric Reheat (PIU) | *VAV*/ RH Water-cooled Chiller/ Gas *Boiler* | *VAV*/ RH Water-cooled Chiller/ Electric Reheat (PIU) | *VAV*/ RH Water-cooled Chiller/ Gas *Boiler* |
| Fan control | VSD | VSD | VSD | VSD |
| Main fan power (W/CFM (W·s/L) Proposed ≥ MERV13 | 1.165 (2.468) | 1.165 (2.468) | 1.165 (2.468) | 1.165 (2.468) |
| Main fan power (W/CFM (W·s/L) proposed < MERV13 | 1.066 (2.259) | 1.066 (2.259) | 1.066 (2.259) | 1.066 (2.259) |
| Zonal fan power (W/CFM (W·s/L)) | 0.35 (0.75) | NA | 0.35 (0.75) | NA |
| Minimum zone airflow fraction | 1.5* Voz | 1.5* Voz | 1.2* Voz | 1.2 * Voz |
| Heat/cool sizing factor | 1.25/1.15 | 1.25/1.15 | 1.25/1.15 | 1.25/1.15 |
| *Outdoor air* economizer | No | Yes except 4A | No | Yes except 4A |
| Occupied OSA (= proposed) | Sum(Voz)/0.75 | Sum(Voz)/0.75 | Sum(Voz)/0.65 | Sum(Voz)/0.65 |
| *Energy* recovery ventilator *efficiency* ERR (Enthalpy Recovery Ratio)<br>ERV bypass SAT *set point* | NA | NA | 50%<br>No Bypass | 50%<br>60°F except 4A |
| *DCV* | No | No | No | No |
| Cooling Source | (2) Water-cooled Centrifugal Chillers | (2) Water-cooled Centrifugal Chillers | (2) Water-Cooled Screw Chillers | (2) Water-Cooled Screw Chillers |
| Cooling *COP* (net of fan) | Path B for profile | Path B for profile | Path B for profile | Path B for profile |
| Heating source (reheat) | *Electric resistance* | Gas *Boiler* | *Electric resistance* | Gas *Boiler* |
| Furnace or *boiler efficiency* | 1.0 | 75% Et | 1.0 | 80% Et |
| Condenser heat rejection | Cooling Tower | Cooling Tower | Cooling Tower | Cooling Tower |
| Cooling tower *efficiency* (gpm/fan-hp (L/s·fan-*kW*)) | 38.2 (3.23) | 38.2 (3.23) | 38.2 (3.23) | 38.2 (3.23) |
| Tower turndown (> 300 ton (1060 *kW*)) | 50% | 50% | 50% | 50% |
| *Pump* (constant flow/variable flow) | Constant Flow; 10°F (5.6°C) range | Constant Flow; 10°F (5.6°C) range | Constant Flow; 10°F (5.6°C) range | Constant Flow; 10°F (5.6°C) range |
| Tower approach | 25.72 – (0.24 x WB), where WB is the 0.4% evaporation design wet-bulb temperature (°F) | | | |
| Cooling condenser *pump* power (W/gpm (W·s/L)) | 19 (300) | 19 (300) | 19 (300) | 19 (300) |
| Cooling primary *pump* power (W/gpm (W·s/L)) | 9 (142) | 9 (142) | 9 (142) | 9 (142) |
| Cooling secondary *pump* power (W/gpm (W·s/L)) | 13 (205) | 13 (205) | 13 (205) | 13 (205) |
| Cooling coil chilled water delta-T, °F (°C) | 12 (6.7) | 12 (6.7) | 12 (6.7) | 12 (6.7) |

| Building Type Parameter | Large Office (warm) | Large Office (cold) | School (warm) | School (cold) |
|---|---|---|---|---|
| Design chilled water supply temperature, °F (°C) | 44 (6.7) | 44 (6.7) | 44 (6.7) | 44 (6.7) |
| Chilled water supply temperature (CHWST) reset *set point* vs OAT, °F (°C) | CHWST/OAT : 44-54/ 80-60 (6.7-12.2/ 26.7-15.6) | CHWST/OAT : 44-54/ 80-60 (6.7-12.2/ 26.7-15.6) | CHWST/OAT : 44-54/ 80-60 (6.7-12.2/ 26.7-15.6) | CHWST/OAT : 44-54/ 80-60 (6.7-12.2/ 26.7-15.6) |
| CHW cooling loop *pump*ing control | 2-way Valves & *pump* VSD | 2-way Valves & *pump* VSD | 2-way Valves & *pump* VSD | 2-way Valves & *pump* VSD |
| Heating *pump* power (W/gpm (W·s/L)) | 16.1 (254) | 16.1 (254) | 19 (254) | 19 (254) |
| Heating oil HW dT. °F (°C) | 50 (10) | 50 (10) | 50 (10) | 50 (10) |
| Design HWST. °F (°C) | 180 (82) | 180 (82) | 180 (82) | 180 (82) |
| HWST reset *set point* vs OAT, °F (°C) | HWST/OAT: 180-150/ 20-50 (82-65.6/ -6.7-10) | HWST/OAT: 180-150/ 20-50 (82-65.6/ -6.7-10) | HWST/OAT: 180-150/ 20-50 (82-65.6/ -6.7-10) | HWST/OAT: 180-150/ 20-50 (82-65.6/ -6.7-10) |
| Heat loop *pumping* control | 2-way Valves & *pump* VSD | 2-way Valves & *pump* VSD | 2-way Valves & *pump* VSD | 2-way Valves & *pump* VSD |

**Table CD105.3.11(2)**

**TSPR Reference Building Design HVAC Simple Systems**

| Building Type Parameter | Medium Office (warm) | Medium Office (cold) | Small Office (warm) | Small Office (cold) | Retail (warm) | Retail (cold) |
|---|---|---|---|---|---|---|
| *System* type | Package *VAV* - Electric Reheat | Package *VAV* - Hydronic Reheat | PSZ-HP | PSZ-AC | PSZ-HP | PSZ-AC |
| Fan control | VSD | VSD | Constant Volume | Constant Volume | Constant Volume | Constant Volume |
| Main fan power (W/CFM (W·s/L)) proposed ≥ MERV13 | 1.285 (2.723) | 1.285 (2.723) | 0.916 (1.941) | 0.916 (1.941) | 0.899 (1.905) | 0.899 (1.905) |
| Main fan power (W/CFM (W·s/L)) proposed < MERV13 | 1.176 (2.492) | 1.176 (2.492) | 0.850 (1.808) | 0.850 (1.801) | 0.835 (1.801) | 0.835 (1.801) |
| Zonal fan power (W/CFM (W·s/L)) | 0.35 (0.75) | NA | NA | NA | NA | NA |
| Minimum zone airflow fraction | 30% | 30% | NA | NA | NA | NA |
| Heat/cool sizing factor | 1.25/1.15 | 1.25/1.15 | 1.25/1.15 | 1.25/1.15 | 1.25/1.15 | 1.25/1.15 |
| Supplemental heating availability | NA | NA | <40°F (<4.4°C) OAT | NA | <40°F (<4.4°C) OAT | NA |
| *Outdoor air* economizer | No | Yes except 4A | No | Yes except 4A | No | Yes except 4A |
| Occupied OSA source | Packaged unit, occupied damper, all *building* use types | | | | | |
| *Energy* recovery ventilator | No | No | No | No | No | No |
| *DCV* | No | No | No | No | No | No |
| Cooling source | DX, multi-stage | DX, multi-stage | DX, 1 stage (heat pump) | DX, single stage | DX, 1 stage (heat pump) | DX, single stage |
| Cooling *COP* (net of fan) | 3.40 | 3.40 | 3.00 | 3.00 | 3.40 | 3.50 |
| Heating source | *Electric resistance* | Gas *Boiler* | Heat Pump | Furnace | Heat Pump | Furnace |

| Building Type Parameter | Medium Office (warm) | Medium Office (cold) | Small Office (warm) | Small Office (cold) | Retail (warm) | Retail (cold) |
|---|---|---|---|---|---|---|
| Heating *COP* (net of fan) / furnace or *boiler efficiency* | 1.0 | 75% $E_t$ | 3.40 | 80% $E_t$ | 3.40 | 80% $E_t$ |

**Table CD105.3.11(3)-**

**TSPR Reference Building Design HVAC Simple Systems**

| **Building Type Parameter** | **Hotel (warm)** | **Hotel (cold)** | **Multifamily** (warm) | **Multifamily** (cold) |
|---|---|---|---|---|
| *System* type | *PTHP* | *PTAC* | *PTHP* | *PTAC* |
| Fan control | Constant Volume | Constant Volume | Constant Volume | Constant Volume |
| Main fan power (W/CFM (W·s/L)) | 0.300 (0.636) | 0.300 (0.636) | 0.300 (0.636) | 0.300 (0.636) |
| Heat/cool sizing factor | 1.25/1.15 | 1.25/1.15 | 1.25/1.15 | 1.25/1.15 |
| Supplemental heating availability | <40°F (<4.4°C) | NA | <40°F (<4.4°C) | NA |
| *Outdoor air* economizer | No | No | No | No |
| Occupied OSA source | Packaged unit, occupied damper | Packaged unit, occupied damper | Packaged unit, occupied damper | Packaged unit, occupied damper |
| *Energy* recovery ventilator | No | No | No | No |
| *DCV* | No | No | No | No |
| Cooling source | DX, 1stage (heat pump) | DX, 1 stage | DX, 1 stage (heat pump) | DX, 1 stage |
| Cooling *COP* (net of fan) | 3.10 | 3.20 | 3.10 | 3.20 |
| Heating source | *PTHP* | (2) Hydronic *Boiler* | *PTHP* | (2) Hydronic *Boiler* |
| Heating *COP* (net of fan) / furnace or *boiler efficiency* | 3.10 | 75% $E_t$ | 3.10 | 75% $E_t$ |
| Heating *pump* power (W/gpm (W·s/L)) | NA | 19 (300) | NA | 19 (300) |
| Heating coil heating water delta-T, °F (°C) | NA | 50 (27.8) | NA | 50 (27.8) |
| Design HWST, °F (°C) | NA | 180 (82.2) | NA | 180 (82.2) |
| HWST reset *set point* vs OAT, °F (°C) | NA | HWST/OAT: 180-150/ 20-50 (82-65.6/ -6.7-10) | NA | HWST/OAT: 180/150 20/50 (82-65.6/ -6.7-10) |
| Heat loop *pump*ing control | NA | 2-way Valves & ride *pump* curve | NA | 2-way Valves & ride *pump* curve |

# Appendix B – Target HVAC System Parameters

**CD106.1 Target Design HVAC Systems.**

Target system descriptions described in Tables CD105.4(1) through CD105.4(3) are provided as reference for MPF development. The target systems are used for developing MPF values and do not need to be programmed into TSPR software.

**<u>Table CD106.1(1) Target Building Design Criteria HVAC Complex Systems</u>**

| Building Type Parameter | Large Office (warm) | Large Office (cold) | School (warm) | School (cold) |
|---|---|---|---|---|
| System Type | *VAV*/ RH | *VAV*/ RH | *VAV*/ RH | *VAV*/ RH |
| | Water-cooled Chiller/ | Water-cooled Chiller/ | Water-cooled Chiller/ | Water-cooled Chiller/ |
| | Electric Reheat (PIU) | Gas *Boiler* | Electric Reheat (PIU) | Gas *Boiler* |
| Fan control | VSD | VSD | VSD | VSD |
| Main fan power (W/CFM (W·s/L) Proposed ≥ MERV13 | 1.127 (2.388) | 1.127 (2.388) | 1.127 (2.388) | 1.127 (2.388) |
| Zonal fan power (W/CFM (W·s/L)) | 0.35 (0.75) | NA | 0.35 (0.75) | NA |
| Minimum zone airflow fraction | 1.5* Voz | 1.5* Voz | 1.2* Voz | 1.2 * Voz |
| Heat/cool sizing factor | 1.25/1.15 | 1.25/1.15 | 1.25/1.15 | 1.25/1.15 |
| *Outdoor air* economizer | *Yes except 0-1* | Yes | *Yes except 0-1* | Yes |
| Occupied OSA (= proposed) | Sum(Voz)/0.75 | Sum(Voz)/0.75 | Sum(Voz)/0.65 | Sum(Voz)/0.65 |
| *Energy* recovery ventilator *efficiency* ERR | NA | NA | 50% | 50% |
| (Enthalpy Recovery Ratio) | | | No Bypass | 60°F except 4A |
| ERV bypass SAT *set point* | | | | |
| DCV | Yes | Yes | Yes | Yes |
| % Area Variable Control | 15% | 15% | 70% | 70% |
| % Area On/Off Control | 65% | 65% | 20% | 20% |
| Cooling Source | (2) Water-cooled Centrif Chillers | (2) Water-cooled Centrif Chillers | (2) Water-Cooled Screw Chillers | (2) Water-Cooled Screw Chillers |
| Cooling *COP* (net of fan) | Path B for profile | Path B for profile | Path B for profile | Path B for profile |
| Heating source (reheat) | *Electric resistance* | Gas *Boiler* | *Electric resistance* | Gas *Boiler* |
| Furnace or *boiler efficiency* | 1.0 | 90% Et | 1.0 | 80% Et |
| Condenser heat rejection | Cooling Tower | Cooling Tower | Cooling Tower | Cooling Tower |
| Cooling tower *efficiency* (gpm/hp (L/s·*kW*))—See G3.1.3.11 | 40.2 (3.40) | 40.2 (3.40) | 40.2 (3.40) | 40.2 (3.40) |
| Tower turndown (> 300 ton (1060 *kW*)) | 50% | 50% | 50% | 50% |

| Building Type Parameter | Large Office (warm) | Large Office (cold) | School (warm) | School (cold) |
|---|---|---|---|---|
| *Pump* (constant flow/variable flow) | Constant Flow; 10°F (5.6°C) range | Constant Flow; 10°F (5.6°C) range | Constant Flow; 10°F (5.6°C) range | Constant Flow; 10°F (5.6°C) range |
| Tower approach | G3.1.3.11 | G3.1.3.11 | G3.1.3.11 | G3.1.3.11 |
| Cooling condenser *pump* power (W/gpm (W·s/L)) | 19 (300) | 19 (300) | 19 (300) | 19 (300) |
| Cooling primary *pump* power (W/gpm (W·s/L)) | 9 (142) | 9 (142) | 9 (142) | 9 (142) |
| Cooling secondary *pump* power (W/gpm (W·s/L)) | 13 (205) | 13 (205) | 13 (205) | 13 (205) |
| Cooling coil chilled water delta-T, °F (°C) | 18 (10) | 18 (10) | 18 (10) | 18 (10) |
| Design chilled water supply temperature, °F (°C) | 42 (5.56) | 42 (5.56) | 42 (5.56) | 42 (5.56) |
| Chilled water supply temperature (CHWST) | CHWST/OAT: | CHWST/OAT: | CHWST/OAT: | CHWST/OAT: |
| reset *set point* vs OAT, °F (°C) | 44-54/ 80-60 | 44-54/ 80-60 (6.7-12.2/ 26.7-15.6) (see Apx G) | 44-54/ 80-60 (6.7-12.2/ 26.7-15.6) (see Apx G) | 44-54/ 80-60 (6.7-12.2/ 26.7-15.6) (see Apx G) |
| | (6.7-12.2/ 26.7-15.6) (see Apx G) | | | |
| CHW cooling loop *pump*ing control | 2-way Valves & *pump* VSD | 2-way Valves & *pump* VSD | 2-way Valves & *pump* VSD | 2-way Valves & *pump* VSD |
| Heating *pump* power (W/gpm (W·s/L)) | 16.1 (254) | 16.1 (254) | 19 (254) | 19 (254) |
| Heating HW dT. °F (°C) | 50 (27.78) | 20 (11.11) | 50 (27.78) | 20 (11.11) |
| Design HWST. °F (°C) | 180 (82) | 140 (60) | 180 (82) | 140 (60) |
| HWST reset *set point* | HWST/OAT: 180-150/ 20-50 (82-65.6/ -6.7-10) | HWST/OAT: 180-150/ 20-50 (82-65.6/ -6.7-10) | HWST/OAT: 180-150/ 20-50 (82-65.6/ -6.7-10) | HWST/OAT: 180-150/ 20-50 (82-65.6/ -6.7-10) |
| vs OAT, °F (°C) | | | | |
| Heat loop *pumping* control | 2-way Valves & *pump* VSD | 2-way Valves & *pump* VSD | 2-way Valves & *pump* VSD | 2-way Valves & *pump* VSD |

**Table CD106.1(2) Target Building Design Criteria HVAC Simple Systems**

| Building Type<br>Parameter | Medium Office (warm) | Medium Office (cold) | Small Office (warm) | Small Office (cold) | Retail (warm) | Retail (cold) |
|---|---|---|---|---|---|---|
| *System type* | *Package VAV - Electric Reheat* | *Package VAV - Hydronic Reheat* | *PSZ-HP* | *PSZ-AC* | *PSZ-HP* | *PSZ-AC* |
| *Fan control* | *VSD* | *VSD* | *Constant Volume* | *Constant Volume* | *2-speed* | *2-speed* |
| *Main fan power (W/CFM (W·s/L))*<br>*proposed ≥ MERV13* | *0.634 (1.343)* | *0.634 (1.343)* | *0.486 (1.03)* | *0.486 (1.03)* | *0.585 (1.245)* | *0.585 (1.245)* |
| *Zonal fan power (W/CFM (W·s/L))* | *0.35 (5.53)* | *NA* | *NA* | *NA* | *NA* | *NA* |
| *Minimum zone airflow fraction* | 1.5* Voz | 1.5* Voz | *NA* | *NA* | *NA* | *NA* |
| *Heat/cool sizing factor* | *1.25/1.15* | *1.25/1.15* | *1.25/1.15* | *1.25/1.15* | *1.25/1.15* | *1.25/1.15* |
| *Supplemental heating availability* | *NA* | *NA* | *<40°F (<4.4°C) OAT* | *NA* | *<40°F (<4.4°C) OAT* | *NA* |
| *Outdoor air economizer* | *Yes except 0-1* | Yes | *Yes except 0-1* | *Yes* | *Yes except 0-1* | *Yes* |
| *Occupied OSA source* | *Packaged unit, occupied damper, all building use types* | | | | | |
| *Energy recovery ventilator* | *No* | *No* | *No* | *No* | *Yes, in 0A, 1A, 2A, 3A* | *Yes all A, 6,7,8 CZ* |
| *ERR* | | | | | *50%* | *50%* |
| DCV | Yes | Yes | No | No | *Yes* | *Yes* |
| % Area Variable Control | 15% | 15% | | | *80%* | *80%* |
| % Area On/Off Control | 65% | 65% | | | *0%* | *0%* |
| *Cooling source* | *DX, multi-stage* | *DX, multi-stage* | *DX, 1 stage (heat pump)* | *DX, single stage* | *DX, 2 stage (heat pump)* | *DX, 2 stage* |
| *Cooling COP (net of fan)* | *3.83* | *3.83* | *3.82* | *3.8248* | *3.765* | *3.765* |
| *Heating source* | *Electric resistance* | *Gas Boiler* | *Heat Pump* | *Furnace* | *Heat Pump* | *Furnace* |
| *Heating COP (net of fan) / furnace or boiler efficiency* | *100%* | *81% $E_t$* | *3.81* | *81% $E_t$* | *3.536* | *81% $E_t$* |
| Heating coil HW dT. °F (°C) | *NA* | 20 (11.11) | *NA* | *NA* | *NA* | *NA* |
| Design HWST. °F (°C) | *NA* | 140 (60) | *NA* | *NA* | *NA* | *NA* |
| HWST reset *set point*<br>vs OAT, °F (°C) | NA | HWST/OAT: 180-150/ 20-50 (82-65.6/ -6.7-10) | NA | NA | *NA* | *NA* |
| Heat loop *pumping* control | NA | 2-way Valves & ride *pump* curve | NA | NA | *NA* | *NA* |
| Heating pump power (W/gpm (W·s/L)) | NA | 16.1 | *NA* | NA | *NA* | *NA* |

**Table CD106.1(3) Target Building Design Criteria HVAC Simple Systems**

| **Building Type**<br>Parameter | **Hotel (warm)** | **Hotel (cold)** | **Multifamily (warm)** | **Multifamily (cold)** |
|---|---|---|---|---|
| *System* type | *PTHP* | *PTAC with Hydronic Boiler* | *Split HP* | *Split AC* |
| Fan control | Cycling | Cycling | Cycling | Cycling |
| Main fan power (W/CFM (W·s/L)) | 0.300 (0.638) | 0.300 (0.638) | 0.246 (0.523) | 0.271 (0.576) |
| Heat/cool sizing factor | 1.25/1.15 | 1.25/1.15 | 1.25/1.15 | 1.25/1.15 |
| Supplemental heating availability | <40°F (<4.4°C) | NA | <40°F (<4.4°C) | NA |
| *Outdoor air* economizer | Only CZ 2, 3 | No | No | No |
| Occupied OSA source | DOAS | DOAS | DOAS | DOAS except 3C |
| *Energy* recovery ventilator | NA | NA | Yes | Yes except 3C |
| DCV | Yes | Yes | No | No |
| % Area Variable Control | 70% | 70% | | |
| % Area On/Off Control | 0% | 0% | | |
| Cooling source | DX, 1stage (heat pump) | DX, 1 stage | DX, 1 stage (heat pump) | DX, 1 stage |
| Cooling *COP* (net of fan) | 3.83 | 3.83 | 3.823 | 3.6504 |
| Heating source | *Heat Pump* | (2) Hydronic *Boiler* | *Heat Pump* | Furnace |
| Heating *COP* (net of fan) / furnace or *boiler efficiency* | 3.44 | 81% $E_t$ | 3.86 | 80% AFUE |
| Heating *pump* power (W/gpm (W·s/L)) | NA | 16.1 | NA | NA |
| Heating coil heating water delta-T, °F (°C) | NA | 20 (11.11) | NA | NA |
| Design HWST, °F (°C) | NA | 140 (60) | NA | NA |
| HWST reset *set point*<br>vs OAT, °F (°C) | NA | HWST/OAT: 180-150/ 20-50 (82-65.6/ -6.7-10) | NA | NA |
| Heat loop *pump*ing control | NA | 2-way Valves & ride *pump* curve | NA | NA |

# Appendix C – MPF Development

This appendix summarizes the Total System Performance Ratio (TSPR) (cost) results for each reference and target building by climate zone and building type.

Table C.1. Small Office Reference and Target HVAC Energy Cost and MPF by Climate Zone

| | Reference | | | Target | | | |
|---|---|---|---|---|---|---|---|
| Climate Zone | Total HVAC Electricity (kWh) | Total HVAC Gas (therm) | Total HVAC Cost ($) | Total HVAC Electricity (kWh) | Total HVAC Gas (therm) | Total HVAC Cost ($) | MPF-(Energy Cost) |
| 0A | 41,971 | 0 | 4,613 | 31,008 | 0 | 3,408 | 0.74 |
| 0B | 38,445 | 0 | 4,225 | 28,300 | 0 | 3,110 | 0.74 |
| 1A | 28,921 | 0 | 3,178 | 21,244 | 0 | 2,335 | 0.74 |
| 1B | 33,260 | 0 | 3,655 | 24,338 | 0 | 2,675 | 0.73 |
| 2A | 24,800 | 0 | 2,726 | 17,550 | 0 | 1,929 | 0.71 |
| 2B | 23,891 | 0 | 2,626 | 16,225 | 0 | 1,783 | 0.68 |
| 3A | 18,412 | 0 | 2,023 | 13,353 | 0 | 1,467 | 0.73 |
| 3B | 23,869 | 47 | 2,669 | 16,514 | 66 | 1,880 | 0.70 |
| 3C | 14,643 | 19 | 1,628 | 9,863 | 25 | 1,108 | 0.68 |
| 4A | 20,088 | 254 | 2,457 | 13,631 | 375 | 1,867 | 0.76 |
| 4B | 22,801 | 107 | 2,611 | 15,473 | 150 | 1,848 | 0.71 |
| 4C | 15,002 | 195 | 1,840 | 9,931 | 253 | 1,340 | 0.73 |
| 5A | 20,401 | 539 | 2,772 | 13,612 | 646 | 2,131 | 0.77 |
| 5B | 23,521 | 244 | 2,825 | 15,784 | 327 | 2,056 | 0.73 |
| 5C | 14,475 | 232 | 1,819 | 9,516 | 294 | 1,335 | 0.73 |
| 6A | 23,388 | 764 | 3,321 | 15,581 | 898 | 2,595 | 0.78 |
| 6B | 24,280 | 493 | 3,153 | 16,142 | 615 | 2,379 | 0.75 |
| 7.0 | 23,765 | 937 | 3,533 | 15,728 | 1,087 | 2,797 | 0.79 |
| 8 | 23,647 | 1,317 | 3,894 | 15,549 | 1,486 | 3,169 | 0.81 |

Table C.2. Medium Office Reference and Target HVAC Energy Cost and MPF by Climate Zone

| Climate Zone | Reference | | | Target | | | MPF-(Energy Cost) |
|---|---|---|---|---|---|---|---|
| | Total HVAC Electricity (kWh) | Total HVAC Gas (therm) | Total HVAC Cost ($) | Total HVAC Electricity (kWh) | Total HVAC Gas (therm) | Total HVAC Cost ($) | |
| 0A | 394,553 | 0 | 43,361 | 275,606 | 0 | 30,289 | 0.70 |
| 0B | 352,297 | 0 | 38,717 | 243,022 | 0 | 26,708 | 0.69 |
| 1A | 281,430 | 0 | 30,929 | 188,092 | 0 | 20,671 | 0.67 |
| 1B | 302,564 | 0 | 33,252 | 204,491 | 0 | 22,474 | 0.68 |
| 2A | 253,325 | 0 | 27,840 | 166,197 | 0 | 18,265 | 0.66 |
| 2B | 234,458 | 0 | 25,767 | 144,554 | 0 | 15,886 | 0.62 |
| 3A | 206,211 | 0 | 22,663 | 142,932 | 0 | 15,708 | 0.69 |
| 3B | 171,028 | 638 | 19,423 | 103,122 | 576 | 11,899 | 0.61 |
| 3C | 111,664 | 132 | 12,401 | 61,643 | 229 | 6,999 | 0.56 |
| 4A | 132,856 | 3,970 | 18,503 | 70,829 | 3,733 | 11,454 | 0.62 |
| 4B | 145,044 | 1,355 | 17,272 | 80,143 | 1,226 | 10,013 | 0.58 |
| 4C | 71,431 | 2,441 | 10,250 | 32,386 | 2,386 | 5,905 | 0.58 |
| 5A | 97,069 | 6,622 | 17,178 | 49,222 | 6,166 | 11,471 | 0.67 |
| 5B | 120,931 | 3,216 | 16,451 | 61,592 | 3,056 | 9,773 | 0.59 |
| 5C | 61,644 | 2,649 | 9,378 | 24,073 | 2,776 | 5,374 | 0.57 |
| 6A | 106,892 | 9,735 | 21,317 | 53,510 | 9,011 | 14,738 | 0.69 |
| 6B | 95,589 | 6,300 | 16,698 | 44,959 | 6,011 | 10,850 | 0.65 |
| 7.0 | 93,511 | 11,121 | 21,208 | 44,117 | 10,292 | 14,966 | 0.71 |
| 8 | 73,931 | 15,204 | 23,070 | 29,176 | 13,938 | 16,907 | 0.73 |

Table C.3. Large Office Reference and Target HVAC Energy Cost and MPF by Climate Zone

| Climate Zone | Reference | | | Target | | | MPF-(Energy Cost) |
|---|---|---|---|---|---|---|---|
| | Total HVAC Electricity (kWh) | Total HVAC Gas (therm) | Total HVAC Cost ($) | Total HVAC Electricity (kWh) | Total HVAC Gas (therm) | Total HVAC Cost ($) | |
| 0A | 2,611,768 | 0 | 287,033 | 2,175,872 | 0 | 239,128 | 0.83 |
| 0B | 2,298,496 | 0 | 252,605 | 1,917,666 | 0 | 210,752 | 0.83 |
| 1A | 1,807,897 | 0 | 198,688 | 1,524,675 | 0 | 167,562 | 0.84 |
| 1B | 2,010,144 | 0 | 220,915 | 1,683,411 | 0 | 185,007 | 0.84 |
| 2A | 1,771,335 | 0 | 194,670 | 1,402,061 | 0 | 154,086 | 0.79 |
| 2B | 1,513,327 | 0 | 166,315 | 1,239,852 | 0 | 136,260 | 0.82 |
| 3A | 1,495,902 | 0 | 164,400 | 1,082,219 | 0 | 118,936 | 0.72 |
| 3B | 1,183,241 | 4,300 | 134,265 | 1,000,519 | 2,184 | 112,104 | 0.84 |
| 3C | 909,336 | 1,165 | 101,081 | 712,147 | 429 | 78,686 | 0.78 |
| 4A | 1,031,466 | 26,608 | 139,514 | 725,019 | 16,647 | 96,044 | 0.69 |
| 4B | 1,046,405 | 8,751 | 123,602 | 851,539 | 4,892 | 98,393 | 0.80 |
| 4C | 623,680 | 14,695 | 82,988 | 437,211 | 7,923 | 55,838 | 0.67 |
| 5A | 775,761 | 45,953 | 130,427 | 572,697 | 31,716 | 94,116 | 0.72 |
| 5B | 919,747 | 20,777 | 121,504 | 715,075 | 13,047 | 91,412 | 0.75 |
| 5C | 561,089 | 15,900 | 77,294 | 387,444 | 8,999 | 51,426 | 0.67 |
| 6A | 837,589 | 69,462 | 160,332 | 604,553 | 51,068 | 116,640 | 0.73 |
| 6B | 749,805 | 42,478 | 124,159 | 559,155 | 29,284 | 90,238 | 0.73 |
| 7.0 | 746,250 | 79,166 | 159,833 | 529,344 | 56,567 | 113,780 | 0.71 |
| 8 | 598,233 | 108,759 | 172,656 | 403,072 | 77,789 | 120,764 | 0.70 |

Table C.4. Retail Reference and Target HVAC Energy Cost and MPF by Climate Zone

| Climate Zone | Reference | | | Target | | | MPF-(Energy Cost) |
|---|---|---|---|---|---|---|---|
| | Total HVAC Electricity (kWh) | Total HVAC Gas (therm) | Total HVAC Cost ($) | Total HVAC Electricity (kWh) | Total HVAC Gas (therm) | Total HVAC Cost ($) | |
| 0A | 303,558 | 0 | 33,361 | 183,317 | 0 | 20,146 | 0.60 |
| 0B | 293,957 | 0 | 32,306 | 168,403 | 0 | 18,507 | 0.57 |
| 1A | 231,725 | 0 | 25,467 | 115,594 | 0 | 12,704 | 0.50 |
| 1B | 260,965 | 0 | 28,680 | 143,478 | 0 | 15,768 | 0.55 |
| 2A | 213,328 | 0 | 23,445 | 97,581 | 0 | 10,724 | 0.46 |
| 2B | 208,713 | 0 | 22,938 | 95,347 | 0 | 10,479 | 0.46 |
| 3A | 188,110 | 0 | 20,673 | 81,197 | 0 | 8,924 | 0.43 |
| 3B | 168,872 | 497 | 19,048 | 72,961 | 715 | 8,722 | 0.46 |
| 3C | 107,430 | 201 | 12,004 | 39,375 | 207 | 4,530 | 0.38 |
| 4A | 148,880 | 2,651 | 18,968 | 54,997 | 1,590 | 7,607 | 0.40 |
| 4B | 156,281 | 1,077 | 18,234 | 59,961 | 1,597 | 8,160 | 0.45 |
| 4C | 101,930 | 2,017 | 13,185 | 34,361 | 2,587 | 6,319 | 0.48 |
| 5A | 128,706 | 4,688 | 18,753 | 45,889 | 2,614 | 7,613 | 0.41 |
| 5B | 147,779 | 2,375 | 18,575 | 55,381 | 3,166 | 9,199 | 0.50 |
| 5C | 92,990 | 2,441 | 12,619 | 29,697 | 2,768 | 5,984 | 0.47 |
| 6A | 136,435 | 6,559 | 21,442 | 51,431 | 3,820 | 9,408 | 0.44 |
| 6B | 136,280 | 4,333 | 19,236 | 47,075 | 2,398 | 7,531 | 0.39 |
| 7.0 | 129,898 | 8,007 | 22,147 | 45,978 | 3,915 | 8,902 | 0.40 |
| 8 | 114,966 | 11,493 | 23,932 | 37,842 | 4,636 | 8,716 | 0.36 |

Table C.5. School Reference and Target HVAC Energy Cost and MPF by Climate Zone

| Climate Zone | Reference | | | Target | | | MPF-(Energy Cost) |
|---|---|---|---|---|---|---|---|
| | Total HVAC Electricity (kWh) | Total HVAC Gas (therm) | Total HVAC Cost ($) | Total HVAC Electricity (kWh) | Total HVAC Gas (therm) | Total HVAC Cost ($) | |
| 0A | 941,841 | 0 | 103,508 | 772,632 | 0 | 84,912 | 0.82 |
| 0B | 781,433 | 0 | 85,879 | 635,447 | 0 | 69,836 | 0.81 |
| 1A | 617,108 | 0 | 67,820 | 492,856 | 0 | 54,165 | 0.80 |
| 1B | 690,764 | 0 | 75,915 | 545,704 | 0 | 59,973 | 0.79 |
| 2A | 632,697 | 0 | 69,533 | 476,588 | 0 | 52,377 | 0.75 |
| 2B | 481,794 | 0 | 52,949 | 344,867 | 0 | 37,901 | 0.72 |
| 3A | 504,664 | 0 | 55,463 | 360,109 | 0 | 39,576 | 0.71 |
| 3B | 384,519 | 777 | 43,022 | 278,914 | 511 | 31,155 | 0.72 |
| 3C | 297,350 | 513 | 33,183 | 203,400 | 157 | 22,508 | 0.68 |
| 4A | 431,350 | 4,761 | 52,086 | 272,514 | 4,892 | 34,758 | 0.67 |
| 4B | 334,050 | 1,439 | 38,126 | 233,068 | 1,306 | 26,898 | 0.71 |
| 4C | 240,555 | 3,030 | 29,416 | 150,551 | 2,466 | 18,970 | 0.65 |
| 5A | 339,911 | 7,441 | 44,671 | 219,950 | 8,053 | 32,088 | 0.72 |
| 5B | 303,911 | 3,436 | 36,777 | 199,591 | 3,286 | 25,165 | 0.68 |
| 5C | 217,500 | 3,310 | 27,157 | 130,238 | 2,132 | 16,409 | 0.60 |
| 6A | 369,019 | 11,185 | 51,550 | 234,921 | 13,044 | 38,640 | 0.75 |
| 6B | 285,808 | 7,566 | 38,848 | 174,219 | 7,876 | 26,889 | 0.69 |
| 7.0 | 324,594 | 12,665 | 48,122 | 197,758 | 12,915 | 34,429 | 0.72 |
| 8 | 263,378 | 17,426 | 46,075 | 144,500 | 15,497 | 31,114 | 0.68 |

Table C.6. Hotel Reference and Target HVAC Energy Cost and MPF by Climate Zone

| Climate Zone | Reference | | | Target | | | MPF-(Energy Cost) |
|---|---|---|---|---|---|---|---|
| | Total HVAC Electricity (kWh) | Total HVAC Gas (therm) | Total HVAC Cost ($) | Total HVAC Electricity (kWh) | Total HVAC Gas (therm) | Total HVAC Cost ($) | |
| 0A | 393,157 | 0 | 43,208 | 243,737 | 0 | 26,787 | 0.62 |
| 0B | 367,178 | 0 | 40,353 | 226,775 | 0 | 24,923 | 0.62 |
| 1A | 297,556 | 0 | 32,701 | 186,572 | 0 | 20,504 | 0.63 |
| 1B | 311,901 | 0 | 34,278 | 196,535 | 0 | 21,599 | 0.63 |
| 2A | 255,587 | 0 | 28,089 | 157,967 | 0 | 17,361 | 0.62 |
| 2B | 218,016 | 0 | 23,960 | 148,049 | 0 | 16,271 | 0.68 |
| 3A | 192,722 | 0 | 21,180 | 117,744 | 0 | 12,940 | 0.61 |
| 3B | 180,472 | 231 | 20,061 | 127,747 | 155 | 14,192 | 0.71 |
| 3C | 146,399 | 13 | 16,102 | 106,782 | 5 | 11,741 | 0.73 |
| 4A | 140,181 | 3,041 | 18,395 | 97,387 | 210 | 10,909 | 0.59 |
| 4B | 156,547 | 916 | 18,105 | 108,367 | 6 | 11,916 | 0.66 |
| 4C | 101,913 | 1,552 | 12,726 | 75,560 | 25 | 8,329 | 0.65 |
| 5A | 114,677 | 4,914 | 17,433 | 81,555 | 569 | 9,522 | 0.55 |
| 5B | 134,309 | 2,385 | 17,105 | 91,034 | 140 | 10,142 | 0.59 |
| 5C | 88,991 | 1,808 | 11,558 | 71,519 | 12 | 7,872 | 0.68 |
| 6A | 117,785 | 7,197 | 20,020 | 82,286 | 1,143 | 10,167 | 0.51 |
| 6B | 110,504 | 4,577 | 16,644 | 76,079 | 558 | 8,909 | 0.54 |
| 7.0 | 105,503 | 8,819 | 20,264 | 76,315 | 1,219 | 9,586 | 0.47 |
| 8 | 85,477 | 12,553 | 21,733 | 63,281 | 1,847 | 8,771 | 0.40 |

Table C.7. Multifamily Reference and Target HVAC Energy Cost and MPF by Climate Zone

| Climate Zone | Reference | | | Target | | | MPF-(Energy Cost) |
|---|---|---|---|---|---|---|---|
| | Total HVAC Electricity (kWh) | Total HVAC Gas (therm) | Total HVAC Cost ($) | Total HVAC Electricity (kWh) | Total HVAC Gas (therm) | Total HVAC Cost ($) | |
| 0A | 204,408 | 0 | 22,464 | 131,124 | 0 | 14,410 | 0.64 |
| 0B | 192,886 | 0 | 21,198 | 121,214 | 0 | 13,321 | 0.63 |
| 1A | 146,688 | 0 | 16,121 | 97,618 | 0 | 10,728 | 0.67 |
| 1B | 155,968 | 0 | 17,141 | 98,278 | 0 | 10,801 | 0.63 |
| 2A | 119,778 | 0 | 13,164 | 77,625 | 0 | 8,531 | 0.65 |
| 2B | 107,521 | 0 | 11,817 | 68,692 | 0 | 7,549 | 0.64 |
| 3A | 96,632 | 0 | 10,620 | 56,703 | 0 | 6,232 | 0.59 |
| 3B | 83,983 | 483 | 9,704 | 54,983 | 531 | 6,565 | 0.68 |
| 3C | 51,612 | 27 | 5,698 | 27,804 | 41 | 3,096 | 0.54 |
| 4A | 65,204 | 3,785 | 10,886 | 43,292 | 1,729 | 6,457 | 0.59 |
| 4B | 75,680 | 1,322 | 9,617 | 46,473 | 377 | 5,478 | 0.57 |
| 4C | 41,408 | 2,360 | 6,871 | 24,912 | 814 | 3,538 | 0.52 |
| 5A | 52,790 | 5,709 | 11,414 | 34,743 | 2,883 | 6,652 | 0.58 |
| 5B | 64,509 | 2,943 | 9,982 | 37,371 | 1,166 | 5,253 | 0.53 |
| 5C | 36,040 | 2,386 | 6,306 | 22,407 | 596 | 3,048 | 0.48 |
| 6A | 62,072 | 7,742 | 14,432 | 37,522 | 4,136 | 8,189 | 0.57 |
| 6B | 54,156 | 5,284 | 11,146 | 30,998 | 2,514 | 5,878 | 0.53 |
| 7.0 | 51,371 | 8,300 | 13,804 | 34,413 | 3,922 | 7,637 | 0.55 |
| 8 | 42,123 | 10,330 | 14,783 | 29,531 | 4,556 | 7,724 | 0.52 |

# Appendix D – Alternative Metrics

The HVAC System Performance approach proposed for inclusion in Standard 90.1 uses energy cost as the metric for heating, ventilation, and air conditioning (HVAC) energy consumption. Alternative energy metrics may be adopted by a jurisdiction to align with their policy objectives. In such cases, the Total System Performance Ratio (TSPR) metric, as defined in Section 2.1 of the main document, could be modified to use carbon emissions, site energy, or source energy. The example below shows how the metric could be modified to use site energy instead of energy cost.

$$HVAC\ Energy\ \text{Consumption}_{Total} = (E_{Heating-Elec} + E_{Heating-Gas} + E_{Heating-\text{Propane}} + E_{Heating-\text{Oil}} + E_{Cooling} + E_{Fan} + E_{Pump} + E_{Heat-Rejection} + E_{Heat-Recovery})[kBtu] \tag{D.1}$$

where

$E_{Heating\text{-}elec}$ = heating electric energy consumption (kBtu)
$E_{Heating\text{-}gas}$ = heating gas energy consumption (kBtu)
$E_{Heating\text{-}propane}$ = heating propane energy consumption (kBtu)
$E_{Heating\text{-}oil}$ = heating oil energy consumption (kBtu)
$E_{Cooling}$ = cooling electric energy consumption (kBtu)
$E_{Fan}$ = fan electric energy consumption (kBtu)
$E_{Pump}$ = pump electric energy consumption (kBtu)
$E_{Heat\ Rejection}$ = heat rejection energy consumption (kBtu)
$E_{Heat\ Recovery}$ = heat recovery energy consumption (kBtu)

$$Total\ System\ Performance\ Ratio = \frac{Ideal\ annua\ heating\ load + Ideal\ annual\ cooling\ load\ (kBtu)}{(TotalElectricityConsumption + TotalGasConsumption\ )\ (kBtu)} \tag{D.2}$$

The proposal for Standard 90.1 provides mechanical performance factors (MPFs) that can be used for three alternative metrics: site energy, source energy, and carbon emissions. The conversion factors for each of these are provided in Table D.1.

Table D.1. Energy Conversion Factors for Alternate Metrics

| Building Project *Energy* Source | Units | Carbon Emissions $CO_2$e, lb/unit (kg/unit) | Source *Energy* Btu/unit (W·h/unit) |
|---|---|---|---|
| Electricity | kWh | 1.418 (0.643) | 9,008 |
| Natural gas | therm (GJ) | 19.960 (85.833) | 109,000 (302,778) |
| Propane | therm (GJ) | 19.080 (76.367) | 115,000 (319,445) |
| Distillate fuel oil | gallon (L) | 28.830 (13.077) | 163,744 (12,674) |

The MPFs based on these metrics are also documented below.

## Table D.2. Alternate MPF Using Site Energy as the Metric

| Climate Zone: Building Type | 0A | 0B | 1A | 1B | 2A | 2B | 3A | 3B | 3C | 4A | 4B | 4C | 5A | 5B | 5C | 6A | 6B | 7 | 8 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Office (small and medium)[a] | 0.72 | 0.72 | 0.70 | 0.71 | 0.69 | 0.65 | 0.71 | 0.68 | 0.65 | 0.81 | 0.70 | 0.78 | 0.85 | 0.77 | 0.81 | 0.87 | 0.84 | 0.88 | 0.90 |
| Office (large)[a] | 0.83 | 0.83 | 0.84 | 0.84 | 0.79 | 0.82 | 0.72 | 0.81 | 0.77 | 0.67 | 0.76 | 0.63 | 0.71 | 0.72 | 0.63 | 0.73 | 0.71 | 0.71 | 0.71 |
| Retail | 0.60 | 0.57 | 0.50 | 0.55 | 0.46 | 0.46 | 0.43 | 0.51 | 0.40 | 0.45 | 0.57 | 0.68 | 0.46 | 0.68 | 0.67 | 0.50 | 0.45 | 0.44 | 0.38 |
| Hotel/ Motel | 0.62 | 0.62 | 0.63 | 0.63 | 0.62 | 0.68 | 0.61 | 0.71 | 0.73 | 0.45 | 0.59 | 0.52 | 0.38 | 0.47 | 0.51 | 0.35 | 0.38 | 0.31 | 0.26 |
| Apartment/ Dormitory | 0.64 | 0.63 | 0.67 | 0.63 | 0.65 | 0.64 | 0.59 | 0.72 | 0.55 | 0.53 | 0.50 | 0.44 | 0.54 | 0.47 | 0.38 | 0.55 | 0.50 | 0.51 | 0.47 |
| School/ Education | 0.82 | 0.81 | 0.80 | 0.79 | 0.75 | 0.72 | 0.71 | 0.72 | 0.67 | 0.73 | 0.72 | 0.68 | 0.82 | 0.73 | 0.61 | 0.89 | 0.80 | 0.83 | 0.77 |

## Table D.3. Alternate MPF Using Source Energy as the Metric

| Climate Zone: Building Type | 0A | 0B | 1A | 1B | 2A | 2B | 3A | 3B | 3C | 4A | 4B | 4C | 5A | 5B | 5C | 6A | 6B | 7 | 8 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Office (small and medium)[a] | 0.72 | 0.72 | 0.70 | 0.71 | 0.69 | 0.65 | 0.71 | 0.67 | 0.63 | 0.71 | 0.66 | 0.68 | 0.75 | 0.69 | 0.69 | 0.77 | 0.73 | 0.78 | 0.81 |
| Office (large)[a] | 0.83 | 0.83 | 0.84 | 0.84 | 0.79 | 0.82 | 0.72 | 0.83 | 0.78 | 0.68 | 0.79 | 0.67 | 0.72 | 0.75 | 0.66 | 0.73 | 0.72 | 0.71 | 0.70 |
| Retail | 0.60 | 0.57 | 0.50 | 0.55 | 0.46 | 0.46 | 0.43 | 0.47 | 0.38 | 0.41 | 0.47 | 0.52 | 0.42 | 0.53 | 0.52 | 0.45 | 0.40 | 0.41 | 0.37 |
| Hotel/ Motel | 0.62 | 0.62 | 0.63 | 0.63 | 0.62 | 0.68 | 0.61 | 0.71 | 0.73 | 0.56 | 0.65 | 0.63 | 0.51 | 0.57 | 0.65 | 0.47 | 0.50 | 0.43 | 0.36 |
| Apartment/ Dormitory | 0.64 | 0.63 | 0.67 | 0.63 | 0.65 | 0.64 | 0.59 | 0.68 | 0.54 | 0.58 | 0.56 | 0.50 | 0.57 | 0.51 | 0.46 | 0.56 | 0.52 | 0.54 | 0.51 |
| School/ Education | 0.82 | 0.81 | 0.80 | 0.79 | 0.75 | 0.72 | 0.71 | 0.72 | 0.68 | 0.68 | 0.71 | 0.65 | 0.74 | 0.69 | 0.61 | 0.78 | 0.71 | 0.74 | 0.70 |

## Table D.4. Alternate MPF using Carbon Emissions as the Metric (kBtu/lb-$CO_2$)

| Climate Zone: Building Type | 0A | 0B | 1A | 1B | 2A | 2B | 3A | 3B | 3C | 4A | 4B | 4C | 5A | 5B | 5C | 6A | 6B | 7 | 8 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Office (small and medium)[a] | 0.72 | 0.72 | 0.70 | 0.71 | 0.69 | 0.65 | 0.71 | 0.67 | 0.63 | 0.73 | 0.66 | 0.69 | 0.76 | 0.70 | 0.71 | 0.79 | 0.75 | 0.80 | 0.82 |
| Office (large)[a] | 0.83 | 0.83 | 0.84 | 0.84 | 0.79 | 0.82 | 0.72 | 0.83 | 0.78 | 0.68 | 0.79 | 0.66 | 0.72 | 0.74 | 0.66 | 0.73 | 0.72 | 0.71 | 0.70 |
| Retail | 0.60 | 0.57 | 0.50 | 0.55 | 0.46 | 0.46 | 0.43 | 0.47 | 0.38 | 0.42 | 0.48 | 0.54 | 0.42 | 0.55 | 0.54 | 0.46 | 0.41 | 0.42 | 0.37 |
| Hotel/ Motel | 0.62 | 0.62 | 0.63 | 0.63 | 0.62 | 0.68 | 0.61 | 0.71 | 0.73 | 0.55 | 0.64 | 0.61 | 0.49 | 0.55 | 0.63 | 0.45 | 0.48 | 0.41 | 0.34 |
| Apartment/ Dormitory | 0.64 | 0.63 | 0.67 | 0.63 | 0.65 | 0.64 | 0.59 | 0.69 | 0.55 | 0.57 | 0.55 | 0.49 | 0.57 | 0.51 | 0.44 | 0.56 | 0.52 | 0.53 | 0.50 |
| School/ Education | 0.82 | 0.81 | 0.80 | 0.79 | 0.75 | 0.72 | 0.71 | 0.72 | 0.68 | 0.68 | 0.71 | 0.65 | 0.75 | 0.70 | 0.61 | 0.79 | 0.73 | 0.75 | 0.71 |

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