CERN Summer student 2025

Development of a Metric for Quantifying Energy Efficiency for HVAC Plants at CERN

Asad Javed

Jasad557@gmail.com

Supervised by

Diogo Monteiro, Doru-Octavian Nitu, Nikolina Bunijevac

August 2025

Contents

Abstract

Cooling and air conditioning systems are essential to maintaining the stable operating conditions required by CERN's accelerator and experimental infrastructure. These HVAC systems are significant energy consumers, making it critical to assess and improve their energy efficiency. The objective of this project was to contribute to the development of a scalable metric to evaluate the energy efficiency of HVAC systems across CERN, with a focus on HVAC Plant 311. After a thorough literature review, the **Total System Performance Ratio (TSPR)** was selected as the core performance metric. Operational and design data including live and historical process values, system schematics, and basic building characteristics were collected and analysed to compute the TSPR for Plant 311. The resulting TSPR value of **1.4** indicates the plant's current energy performance and serves as a reference for future improvements. This plant-specific case study demonstrates the applicability of TSPR within CERN's operational context and provides a foundation for benchmarking performance and guiding energy-saving strategies across the wider HVAC infrastructure.

Introduction

Cooling and air-conditioning plants at CERN are vital for maintaining the stable thermal and humidity conditions required by particle accelerators and experimental detectors. These complex systems account for a significant portion of the site's electrical consumption, and any inefficiency directly impacts the operating costs. While individual plants vary in size and design, a unified framework for assessing their performance has been lacking.

To address this gap, this project set out to develop and pilot a standardized energy-efficiency metric tailored to CERN's operational context. After surveying existing benchmarks and industry best practices, Total System Performance Ratio (TSPR) a holistic indicator that relates delivered cooling capacity to total energy input was adopted. By focusing on TSPR, a single comparable figure that captures the combined effects of all the individual components of the HVAC plant was developed.

This approach was applied to HVAC Plant 311 as a representative case study. This involved collecting and synthesizing live and historical process data (temperatures, relative humidities, control signals) and reviewing plant design documentation (P&IDs, equipment specifications). The computed TSPR of 1.4 for Plant 311 not only quantifies its current efficiency but also highlights opportunities for targeted optimization. Lessons learned from this pilot will inform the roll-out of TSPR-based benchmarking across CERN's broader HVAC infrastructure, enabling data-driven decisions to improve energy performance and reduce environmental impact.

Literature Review

(Alves et al., 2016) emphasize the growing need for comprehensive frameworks to evaluate the energy efficiency of HVAC systems, particularly given their substantial contribution to building energy consumption. The authors critique the traditional reliance on isolated component metrics such as COP and EER, arguing that these fail to capture the dynamic and interactive behaviour of full HVAC systems under real operating conditions. Instead, they propose a classification system that incorporates multiple performance indicators at different levels component, subsystem, and whole system thereby enabling more accurate benchmarking and identification of inefficiencies.

HVAC systems represent a critical energy consumption point in industrial facilities, with semiconductor fabrication plants (fabs) alone allocating 40–50% of total energy to HVAC operations (Zhao et al., 2021). To address this, researchers have developed metrics targeting different scopes:

Industrial Facility Metrics (High-Tech Fabs)

- **SCL (Specific Cooling Load)**: Measures cooling load per unit airflow rate ($kW/m^3 \cdot h$), demonstrating superior consistency over area-based metrics in cleanrooms due to linear load-flow relationships (Zhao et al., 2021).
- **SFC (Specific Fan Consumption)**: Quantifies fan energy per unit airflow ($kWh/m^3 \cdot h$), exposing inefficiencies in air-handling subsystems.
- **EI_AFR (Energy per Air Flow Rate)**: Annual HVAC energy divided by airflow rate ($kWh/m^3 \cdot h$), enabling cross-fab comparisons by decoupling efficiency from production volatility.

Hierarchical Efficiency Frameworks

Pérez-Lombard et al. (2012) propose a structured approach to EEI construction:

- **Four-Level Pyramid:**

Level	Focus	Example Metrics
Global	Whole system	HVAC Energy Intensity ($kWh/m^2 \cdot y$)
Service	Heating/cooling/ventilation	Heating Efficiency (η_HEAT)
Subsystem	Generation/transport	η_CG (Cool Gen), SC_AT (Air Transp.)
Equipment	Components	COP, SFP, Fan Efficiency

Full-System Metrics and TSPR

The **Total System Performance Ratio (TSPR)** is a metric designed to evaluate the **overall efficiency of an HVAC system** by comparing the annual heating and cooling loads of a building to the annual energy consumed by the HVAC system. It is calculated as:

$$TSPR = \frac{Annual\ Heating + Cooling\ Load}{Annual\ HVAC\ Energy\ Consumption}$$

- **Higher TSPR** = More efficient system (less energy used per unit of heating/cooling delivered).
- **Lower TSPR** = Less efficient system.

Methodology

The methodology followed in this project was structured into four main phases: **metric selection, system analysis, Component-by-Component Investigation and TSPR computation**. The objective was to ensure that the calculated Total System Performance Ratio (TSPR) accurately reflected the real operational efficiency of the plant.

1. Metric Selection

After reviewing various HVAC efficiency metrics, including COP, EER, Specific Cooling Load (SCL), and Specific Fan Consumption (SFC), the **Total System Performance Ratio (TSPR)** was chosen for its ability to capture the overall system-level performance. TSPR quantifies the relationship between thermal output and energy input by dividing the total delivered heating and cooling load by the total energy consumed by the HVAC system, making it particularly suitable for assessing entire HVAC installations operating under varied load conditions.

2. System Analysis

A thorough analysis of HVAC Plant 311 was conducted to understand its architecture and operational dynamics. This included:

- **Reviewing system schematics and P&IDs** to identify the arrangement of chillers, pumps, air handling units (AHUs), valves, sensors, and control loops.
- **Examining individual equipment specifications**, such as chiller rated capacity and input power, pump curves, fan ratings, and sensor accuracy ranges.

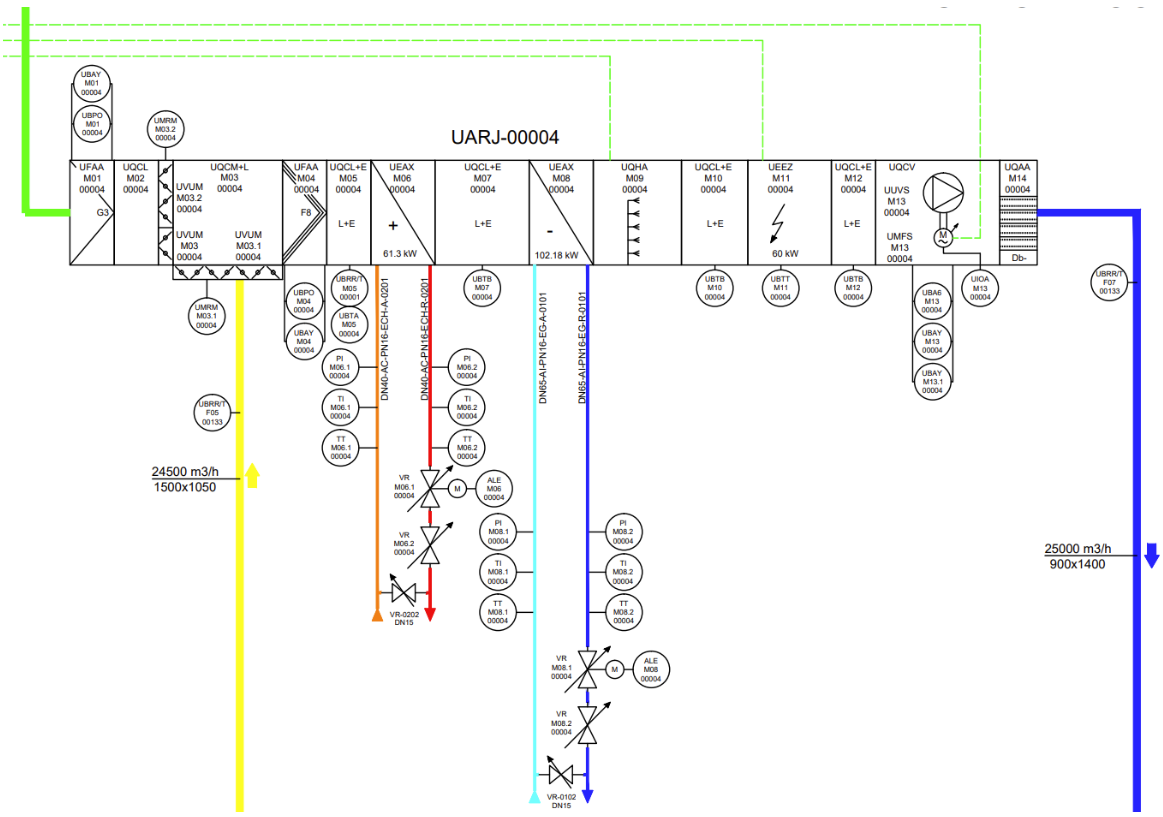

Figure 1 P&ID Diagram

3.Component-by-Component Investigation

Hot Water Heating Coil

- **Measurement Approach:** Thermal power delivered to the airstream was calculated every 15 minutes using

$$Q_{th} = \dot{m}_{air}.c_p.\Delta T \qquad [W]$$

$$Q_{el,kW} = \frac{Q_{th,kW}}{COP}$$

$$E_{el,kWh} = Q_{el,kW}.\frac{15}{60}$$

- **Assumption:** For each 15-minute interval, a logical filter is applied to identify active heating periods, defined by the condition:

$$valve > 2 \ and \ \Delta T > 0.2\ C$$

Here valve > 2 indicates the time when out heating coil is functioning. It is assumed that below this threshold it is not working. Another filter is applied here on temperature to consider those changes which are significant. $c_{p,air}$ value is assumed to be 1005 J/kg.K and density of air is assumed constant 1.2 kg/m^3. Cop used here is 0.93.

Result: Total heating-coil energy use = 3631.98 kWh.

Chilled Water-Cooling Coil

- **Measurement Approach:** Analogous to heating coil. Just the latent change is also included here.

$$Q_{sensible} = \dot{m_{air}} . c_p . \Delta T$$

$$Q_{latent} = \dot{m_{air}} . h_{fg} . \Delta W$$

$$Q_{Total} = Q_{sensible} + Q_{latent}$$

  and electrical consumption estimated using a chiller COP of 3.

- **Challenge:** No measurement of temperature and relative humidity available directly at the exit of the cooling coil air unit.

- **Workaround:**

  1. Determined "coil off" periods when control valve < 2%.
  2. Measure the absolute humidity at the entry of the cooling coil and then at the exit of the humidifier for those durations when valve < 2%.
  3. Correlated absolute-humidity change with humidifier control signal to infer coil-outlet humidity.
  4. Assumed isothermal humidifier (T_out coil ≈ T_in humidifier)
  5. Use the above formulas to calculate the energy consumed.

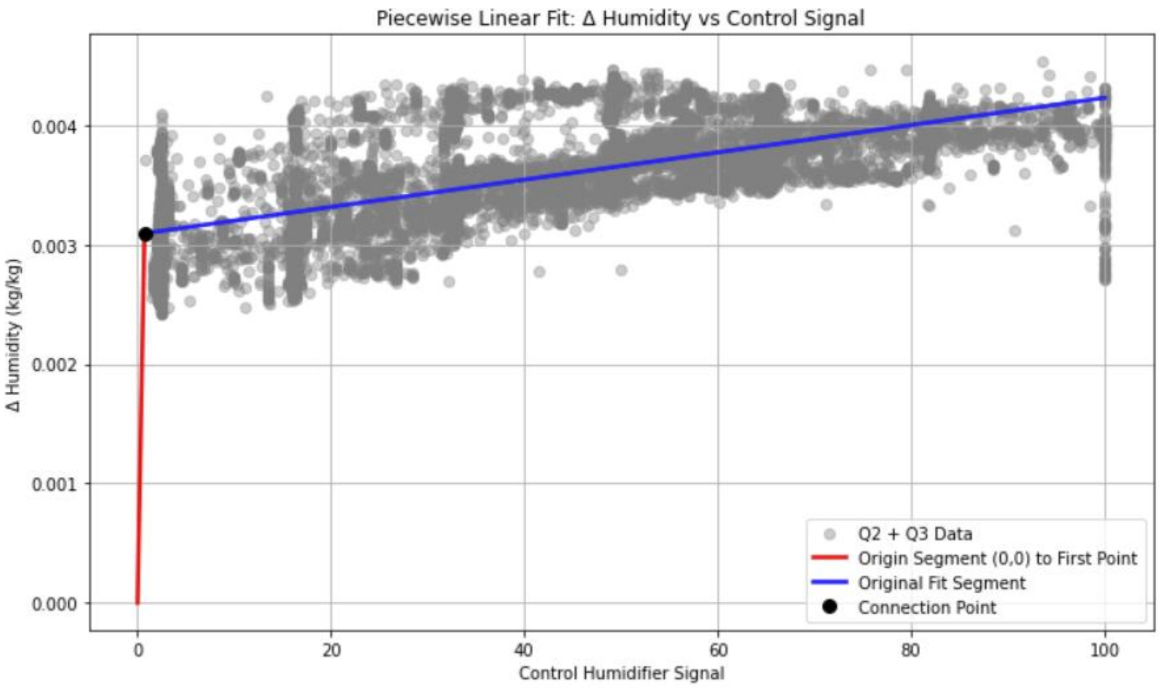

Figure 2 Control signal vs Absolute Humidity Change

This plot shows a piecewise linear fit between Δ Humidity and the humidifier control signal. While the full absolute humidity vs control signal relationship isn't directly provided, this model serves as a proxy. I used the Δ Humidity from the fit and subtracted it from the known supply humidity to estimate the humidity at the humidifier inlet, which is also the cooling coil outlet.

- **Result:** Total cooling-coil energy use = 14295.43 kWh.

Steam Humidifier & Electric Heater

- **Challenge:** No dedicated energy measure available for these components.
- **Workaround:** Installed a temporary energy meter on the PLC unit, ran step-tests from 0 – 100% control signal, and recorded power drawn at each level. All other components were kept at a constant power consumption of 7389.43 KW. Based on the below trends the energy consumption was measured for all the control signals.

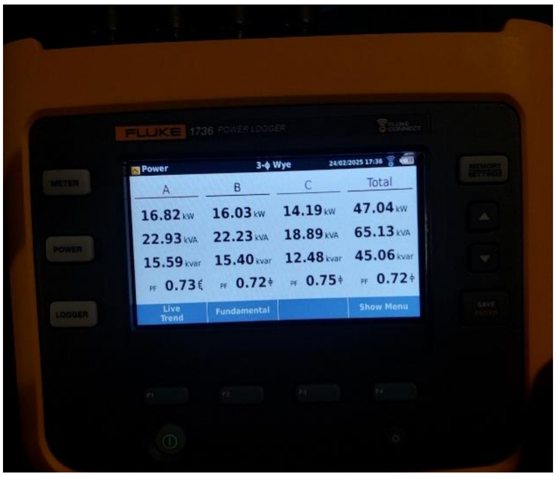

Figure 3 Energy Meter

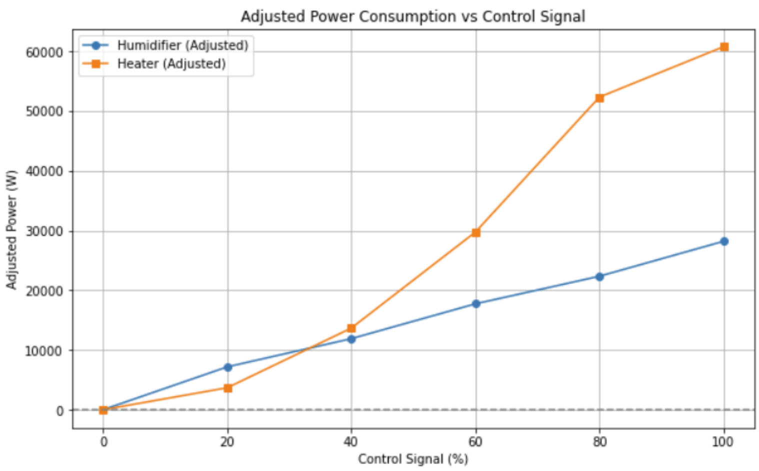

Figure 4 Power Consumed vs Control signal

- **Results:**
    - Humidifier energy use = 52053.08 kWh
    - Electric-heater energy use = 7524.21 kWh.

Supply Fan

- **Challenge:** Faulty power consumption sensor for the supply fan in.
- **Workaround:** Direct measurement of fan speed (rpm), drive frequency, and power from the VFD. On-site visits to read VFD output values across control signal settings. Based on the below trends the energy consumption was measured for all the control signals.

S

Figure 5 Variable Frequency Drive (VFD)

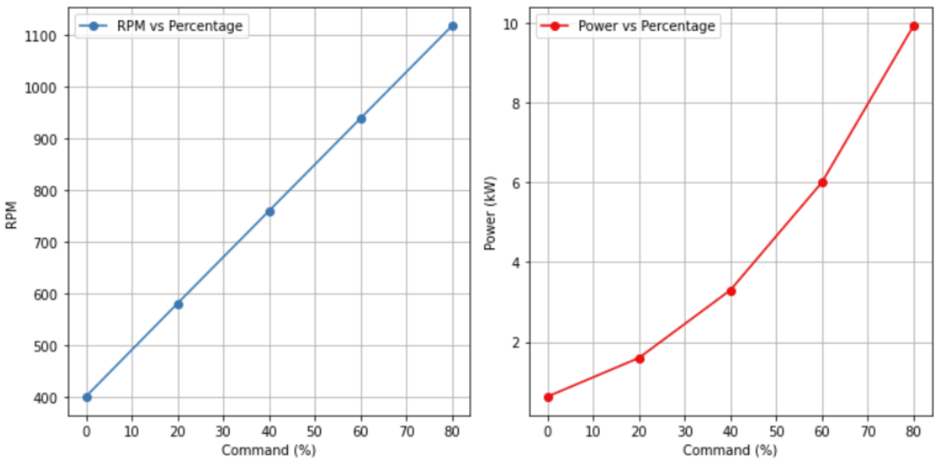

Figure 6 RPM and Power Consumption vs Control signal

- **Result:** Total fan energy use = 62902.97 kWh.

Air Mass Flow Rate

- **Measurement Approach:** Derived mass flow from fan curves using recorded rpm and ΔP.
- **Challenge:** Absence of direct flow sensors on the AHU.
- **Workaround:** Developed an empirical function mapping (rpm, ΔP) → flow rate, calibrated against design-curve data; further refinement required for extrapolated operating points. Since most of our estimated point lie inside the curves no extrapolation function was included.

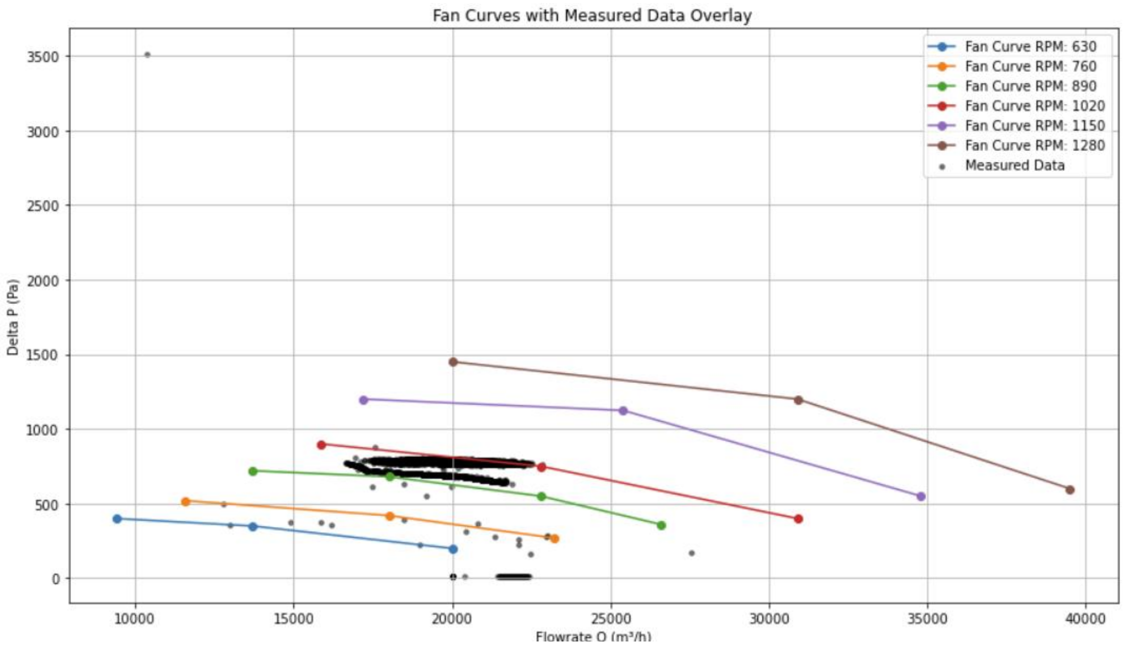

Figure 7 Fan Curves with Estimated Flowrates

4. System Thermal Load & TSPR Computation

- **Thermal Load Calculation:**

  Having established reliable energy-use estimates for each HVAC component, the next step was to compute the **annual thermal load** delivered to the conditioned zone and then derive the TSPR.

1. **Sensible Load**

   Measures temperature-driven energy transfer as the supply air heats or cools the room air.

$$Q_{sensible} = \dot{m}_{air} . c_p . (T_{room(t+1)} - T_{supply})$$

2. **Latent Load**

   Captures moisture-driven energy, where W is humidity ratio and h_{fg} is the latent heat of vaporization.

$$Q_{sensible} = m_{air}^{\cdot}.h_{fg}.(W_{return} - W_{supply})$$

$$h_{fg} \ value\ is\ assumed\ to\ be\ consatnat\ and\ 2.5e6\ \ J/k$$

3. **Room-Air Storage Load**

   Accounts for the thermal inertia of the zone air mass as its temperature changes over time.

$$Q_{room} = m_{room}.c_p.\frac{dT_{room}}{dt}$$

   Summing these three terms for every time step yielded the **total annual thermal load**:

$$Q_{total} = Q_{sensible} + Q_{latent} + Q_{room}$$

$$Q_{total} = 196667.15\ kWh$$

- **Component Energy Aggregation:**

Component	Energy Use (kWh)
Heating unit	3631.98
Cooling unit	14295.43
Heater	7524.21
Humidifier	52053.08
Fan	62902.97
Total Energy Use	**140407.67**

- **TSPR Calculation:**

$$TSPR = \frac{Annual\ Heating + Cooling\ Load}{Annual\ HVAC\ Energy\ Consumption}$$

$$\boldsymbol{TSPR = \frac{140407.67}{196667.15} \approx 1.4}$$

This value provides a holistic indicator of Plant 311's annual energy performance and establishes a benchmark for comparative and seasonal analyses.

Conclusion

This study has demonstrated the feasibility and value of deploying the Total System Performance Ratio (TSPR) as a unified, system-level metric for quantifying the energy efficiency of large HVAC installations at CERN. Through a detailed component-by-component audit of Plant 311 robust methodologies to overcome data gaps and measurement challenge were developed.

The resulting TSPR provides a clear, benchmarkable indicator of Plant 311's operational performance and highlights opportunities for targeted improvements. Importantly, the approach and lessons learned here are directly transferable to other CERN HVAC plants, enabling network-wide benchmarking, seasonal analysis, and data-driven decision-making.

The current work establishes a foundational framework for evaluating HVAC system efficiency using the TSPR metric. However, there is no existing standard reference for comparison, making it essential to develop internal baselines. By benchmarking similar HVAC systems using TSPR, a consistent basis for evaluating performance across systems can be created. Additionally, applying this metric to historical data would enable the identification of long-term trends, seasonal patterns, and potential efficiency degradation. This approach not only provides insights into overall system performance but also allows for component-level analysis, helping to isolate and evaluate the efficiency of individual units such as fans, coils, and humidifiers. Ultimately, this supports more informed decisions for targeted upgrades and maintenance. By systematically applying TSPR across CERN's infrastructure, the EN-CV group can drive continuous energy performance improvements, reduce operating costs, and advance its sustainability mission.

References

1. Crespi, G., Abbà, I., & Corgnati, S. P. (2022). Innovative metrics to evaluate HVAC systems performances for meeting contemporary loads in buildings. *Science and Technology for the Built Environment, 28*(5), 561–574. https://www.sciencedirect.com/science/article/pii/S2352484722012756

2. Zhao, Y., Porowski, M., & Xu, T. (2021). A comparative study on energy performance assessment for HVAC systems in high-tech fabs. *Sustainable Computing: Informatics and Systems, 29*, 100–108. A comparative study on energy performance assessment for HVAC systems in high-tech fabs - ScienceDirect

3. Pérez-Lombard, L., Ortiz, J., & Pout, C. (2012). A review on buildings energy consumption information. *Energy and Buildings, 40*(3), 394–398. A review on buildings energy consumption information - ScienceDirect

4. Alves, O., Graça, M., Fonseca, A. J., & Fernandes, J. M. (2016). Measurement and classification of energy efficiency in HVAC systems: A framework. *Energy and Buildings, 128*, 22–34. https://www.sciencedirect.com/science/article/abs/pii/S0378778816307800

5. Goel S., R. Hart, M.M. Tillou, M.I. Rosenberg, J.C. Gonzalez Matamoros, K. Devaprasad, and J. Lerond. 2021.**HVAC System Performance for Energy Codes Technical Brief** Richland, WA: Pacific Northwest National Laboratory.