



DOE Data Center Air-Management (AM) Tool: Engineering Reference

Version 2.1 (December 3, 2021)

The Engineering Reference and the Air Management Tool were developed jointly by Lawrence Berkeley National Laboratory (LBNL) and ANCIS Incorporated for the US Department of Energy (DOE)

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OVERVIEW

What does this Tool do?

Air management in data centers is essentially about keeping cold and hot air from mixing. Cold supply air from the air handler should enter the heat-generating IT-equipment without mixing with ambient air and the hot exhaust air should return to the air handler without mixing. Managing the cold and hot air streams in data centers is important for cooling infrastructure energy/capacity management and IT-equipment thermal management.

The DOE Data Center Air-Management Tool was developed to help accelerate the energy savings in data centers without affecting the thermal IT-equipment environment. Based on user input, the Tool provides air management recommendations and the potential for reducing the supply airflow rate and increasing the supply air temperature, both having an impact on energy use. Finally, the Tool estimates the % energy reduction, kWh reduction, and the associated \$ savings for supply fans and chillers.

The underlying assumption for this Tool is sufficiently stable environmental conditions, for example, the air handlers may well have variable air volume (VAV) fans but they are assumed operating at a stable constant reduced airflow. Since the majority of conventional data centers has raised-floor cooling with hot and cold equipment aisles, this Tool is intended mainly for such environments. Having some basic understanding of the physical data center environment makes this Tool easier to understand and use.

How is the Tool used?

First, the user fills in data and answers questions on four input Excel sheets (Steps 1-4). Each sheet includes basic guidance for entering the data correctly. The User's Manual (DOE 2021a) provides additional information. Second, based on this user input, numerical output and recommended actions are given on two result output Excel sheets (Steps 5 and 6). An Engineering Reference (this document) and a Data Collection Guide (DOE 2021b) complete the support documentation.

DOE Software Tool Suite

This Air Management Tool is part of the DOE Software Tool Suite (DOE 2021c) which also includes an online Profiling Tool (DC Pro) and an Excel-based Electrical Tool. These tools are not a substitute for a detailed "investment grade" audit. They provide estimates of savings for various measures, but actual savings may vary based on site-specific conditions that are not addressed in the tools.

Tool Download and Documentation

The Air Management Tool can be downloaded from the Center of Expertise for Energy Efficiency in Data Centers website: <http://datacenters.lbl.gov/data-center-air-management-tool> After downloading the Tool, there are three complementary documents on the same website for facilitating the use of the Tool:

- The *User's Manual* provides information on using the Tool
- The *Engineering Reference* (this document) provides detailed information on the calculations, equations, metrics, and limitations
- The *Data Collection Guide* provides information on collecting the necessary input data.

Questions, comments, and/or suggestions on these documents can be directed to mherrlin@ancis.us

Engineering Reference

This Engineering Reference follows the layout of the Air-Management Tool with seven input/output color coded Excel sheets plus three hidden sheets.

Step 1: AHU	User input: Air-handler unit (AHU) data for calculating the RTI metric
Step 2: Equip	User input: Electronic equipment data for calculating the RTI metric
Step 3: RCI	User input: Equipment intake temperatures for calculating the RCI metric
Step 4: Main Input	User input: Main user input, including metrics from Steps 1-3
Step 5: Main Results	Result output: Main results but excluding energy estimates
Step 6: Energy Results	Result output: Energy estimates for supply fans and chillers
Lookup	Lookup tables for internal use (hidden)
Action Rules	Rules for triggering actions or recommendations (hidden)
Export	Output for post-processing (hidden).

The User's Manual provides information on using the Tool, and this Engineering Reference provides detailed information on the calculations, equations, metrics, and limitations. This document should be studied when knowledge is required of the calculation details. All major calculation steps are outlined in this document. In the Tool, most of the calculations are hidden from view but some intermediate calculation steps are visible as grayed out text.

This Engineering Reference parallels the layout of the User's Manual; switching back and forth between the two documents should be straight forward.

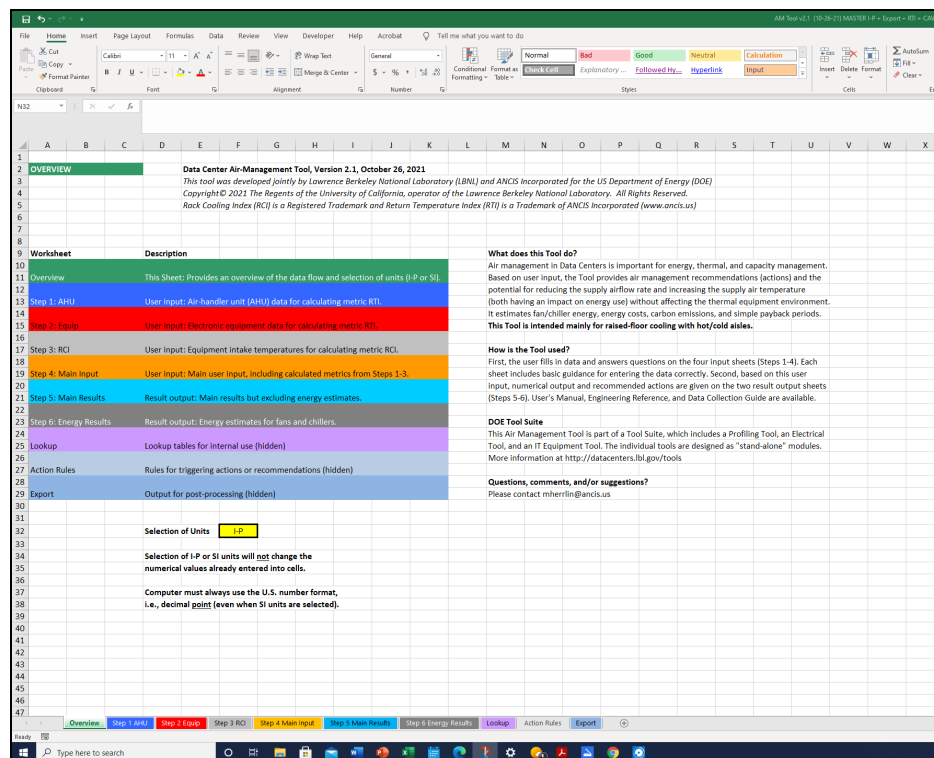


Figure 1: Overview sheet.

INPUT/OUTPUT SHEETS

This section describes the input and output sheets in the order they appear in the Excel Tool. This section is best read as a reference manual for finding particular information on the calculations, equations, metrics, and limitations on any of the sheets.

General Information applicable to all four input sheets includes:

- Yellow cells indicate cells where to input data.
- Dual units are shown next to each yellow input cell (e.g., °F or °C). The first unit represents I-P units and the second unit represents SI units.
- Colored cells (besides yellow) indicate data that are exported to or imported from other sheets. The cells are color coded per the receiving or originating sheet (tab) color.
- Grayed out data are for internal use only, generally showing intermediate calculation steps.
- In equations, entities within quotation marks refer to the values in named cells on input or output sheets.
- The screen shots included in this Engineering Reference can be difficult to read at the conventional 100% zoom level. Use the zoom capability of your software to enlarge the figures. Note that the screen shots may differ slightly from the latest version of the Tool.

Step 1 AHU

“Step 1 AHU” is the first of four input sheets. It is imperative to enter (accurate) data on this sheet.

By entering the requested air-handling unit (AHU) data (yellow cells) for up to 40 operating units, this sheet will calculate five pieces of data (orange boxes) and export them to the Main Input (Step 4) sheet. The principal purpose of this data transfer is to calculate the Return Temperature Index (RTI)TM on the Main Input sheet. This index plays an important role in understanding whether the data center is over-ventilated (by-pass air) or under-ventilated (recirculation air) (Herrlin 2008). For more information on RTI, please see section Step 4 Main Input.

Calculated average AHU temperatures are airflow weighted to take into account different airflow rates for the different AHUs. If the airflow rates are significantly different among the AHUs, simple averages would be high in error.

Calculated data exported to the Main Input sheet (orange cells) (Figure 3):

- Total AHU Airflow [cfm or m³/s] and AHU Count [-]
 - Sum (and count) of all values in column AHU Airflow
- Max-Min AHU Supply Temperature [°F or °C]
 - Maximum value minus minimum value in column Supply Air Temperature
- Typical (airflow weighted) AHU Supply Air Temperature [°F or °C]
 - Sum all AHUs: (“AHU Airflow”/”Total AHU Airflow”) * ”Supply Air Temperature”
- Typical (airflow weighted) AHU temperature drop [°F or °C]
 - [Sum all AHUs: (“AHU Airflow”/”Total AHU Airflow”) * ”Return Air Temperature”]
– [Sum all AHUs: (“AHU Airflow”/”Total AHU Airflow”) * ”Supply Air Temperature”]

Other calculated data (white cells):

Resulting AHU kW Cooling and AHU Ton Cooling (the heat extraction from the room by mechanical means and/or by free cooling) are calculated based on Total AHU Airflow and Typical (airflow weighted) AHU temperature drop.

- AHU kW Cooling
 - (“Total AHU Airflow” * 0.0004719) * (1.2) * (1006) * (“Typical (airflow weighted) AHU temperature drop” / 1.8) * (1/1000) [ignore red numbers for SI calculations]
- AHU Ton Cooling
 - “AHU kW Cooling” / 3.52

Note that AHU data are considered more robust than the equipment data in Step 2; Equipment Power (=AHU cooling) is always assumed equal to Resulting AHU Cooling (heat balance in room).

If there is a separate air-side economizer (one that provides cooling and airflow in addition to the AHUs) it could be specified as another AHU. The Other Calculated Data listed above will then include the associated cooling effect. However, disregard separate fresh-air systems that generally have limited airflows. For built-in economizers, no additional entries are necessary.

For guidance on determining the AHU data, see the *Data Collection Guide*.

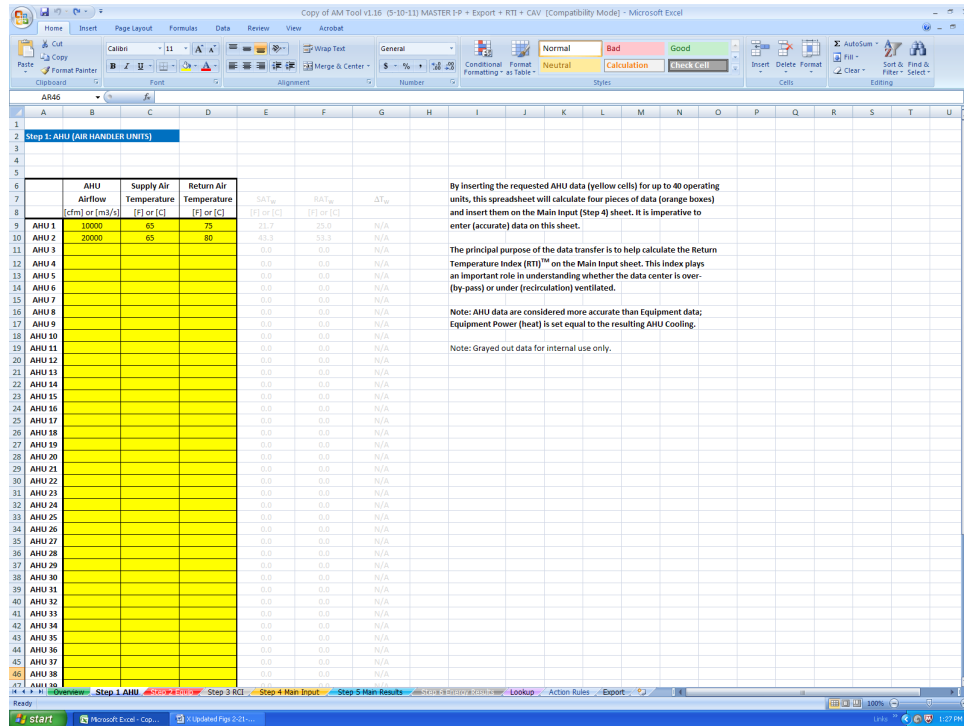


Figure 2: Step 1 AHU sheet, upper part.

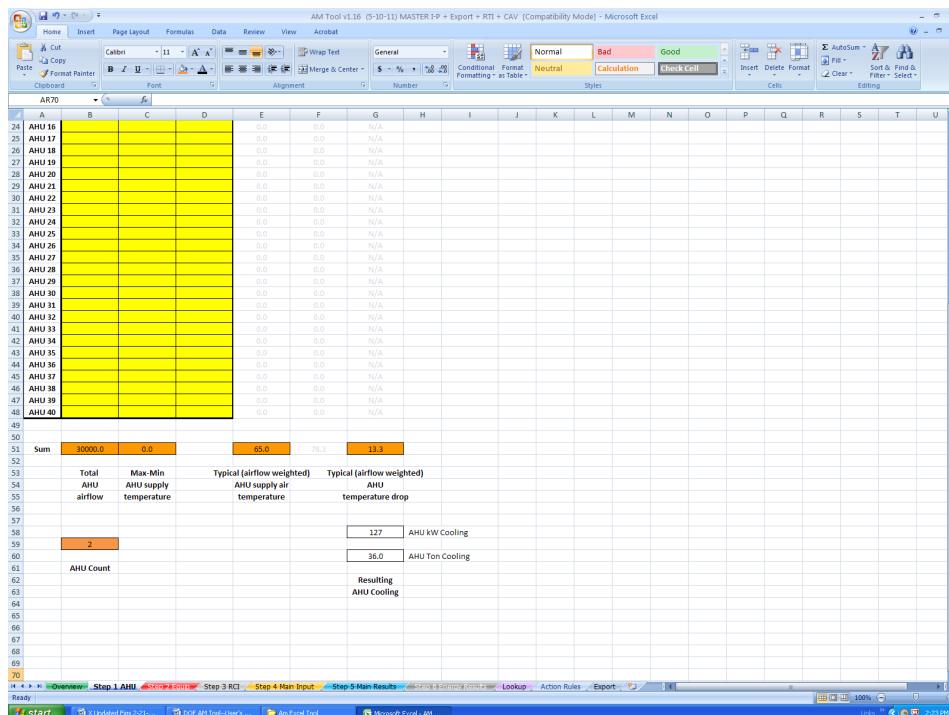


Figure 3: Step 1 AHU sheet, lower part.

Step 2 Equipment

“Step 2 Equipment” is the second of four input sheets.

By inserting the requested equipment data (yellow cells), this spreadsheet will calculate two pieces of data (orange boxes) and export them to the Main Input (Step 4) sheet. Equipment includes heat-generating electronic equipment (IT) as well as electric equipment such as Power Distribution Units (PDU) and Uninterruptible Power Supplies (UPS).

The principal purpose of this data transfer is to calculate the Return Temperature Index (RTI)TM on the Main Input sheet. This index plays an important role in understanding whether the data center is over-ventilated (by-pass air) or under-ventilated (recirculation air) (Herrlin 2008). For more information on RTI, please see section Step 4 Main Input.

Since determining the equipment input data may be a challenging task, three options are available through the Select Class Option drop-down box. Depending on the selection, the equipment is grouped into Classes with similar temperature rise (DT) or airflow rates (V). Unique inputs for every piece of equipment, rather than consolidation into equipment Classes, are not allowed. And, only one Class Option can be selected for all input:

- Similar DT: Equipment with similar Measured Temperature Rise (DT); used with corresponding fair Estimated Airflow (V).
- Similar V: Equipment with similar Estimated Airflow (V); used with corresponding Number of Units (U).
- Similar DT(P): Equipment with similar Measured Temperature Rise (DT); used with corresponding Measured Power (P) (Figure 4).

Calculated data exported to the Main Input sheet (orange cells):

- Typical (airflow weighted) Equipment Temperature Rise [°F or °C]
 - Similar DT: Based on yellow cells
 - Sum all Classes: $(\text{"Estimated Airflow (V)"} / \text{"Total"}) * \text{"Measured Rise (DT)"}$
 - Similar V or Similar DT(P): Based on Total Equipment Airflow and AHU data from Step 1.
 - $[(\text{"Total AHU Airflow (Step 1)"} / \text{"Total Equipment Airflow"}) * [\text{"Typical (airflow weighted) AHU Temperature Drop (Step 1)"}]]$
- Total Equipment Airflow
 - Similar V: Based on yellow cells
 - Sum all Classes: $\text{"Estimated Airflow (V)"} * \text{"Number of Units (U)"}$
 - Similar DT(P): Based on yellow cells
 - Sum all Classes: $\text{"Measured Power (P)"} / ((0.0004719) * (1.2) * (1006) * (\text{"Measured Rise (DT)"} / 1.8))$ [ignore red numbers for SI calculations]
 - Similar DT: Based on Typical (airflow weighted) Equipment Temperature Rise and AHU data from Step 1.
 - $[\text{"Typical (airflow weighted) AHU Temperature Drop (Step 1)"} / \text{"Typical (airflow weighted) Equipment Temperature Rise"}] * [\text{"Total AHU Airflow (Step 1)"}]$

Note that the calculated average equipment temperature rise is airflow weighted to take into account different airflow rates for the different equipment. If the airflow rates are significantly different among the equipment, a simple average would be high in error.

Other calculated data (white cells):

- Equipment Power (= AHU cooling) [kW].
 - =("Total Equipment Airflow"*0.0004719)*(1.2)*(1006)*("Typical (airflow weighted) Equipment Temperature Rise"/1.8)*(1/1000) [ignore red numbers for SI calculations]

This is equal to Resulting AHU Cooling in Step 1. The AHU data (Step 1) are considered more robust than the Equipment data; Equipment Power is always assumed equal to Resulting AHU Cooling (heat balance in room). Here are three principal formulas to consider:

$$P = V * \rho * c_p * \Delta T \quad \text{Equ. 1}$$

$$P_{AHU} = P_{Equip} \quad \text{Equ. 2}$$

$$(V * \Delta T)_{AHU} = (V * \Delta T)_{Equip} \quad \text{Equ. 3}$$

Where

P	Power
V	Volumetric Airflow
ρ	Density of Air
c_p	Heat Capacity of Air
ΔT	Temperature Differential

In this Engineering Reference, note that Equation 1 converts I-P units (American) of temperature (°F) and volumetric airflow (cfm) to SI units before calculating the formula. It is assumed that ρ and c_p are reasonable constant.

Compare Equipment Power (=AHU cooling) with UPS readings—if available. If the UPS equipment is located outside the data center room, use the delivered UPS power. If poor agreement, revisit Steps 1 and 2, looking for potential errors.

- "Total Measured Power" (Similar DT(P) option only) [kW].
 - Sum all Classes: "Measured Power (P)"; this is equal to "Total Measured Power"

Compare with the Equipment Power (=AHU cooling). If poor agreement (>10%) as indicated in the Power Imbalance cell, revisit Steps 1 and 2 to avoid large errors in the Total Equipment Airflow and Typical (airflow weighted) Equipment Temperature Rise. Poor agreement will not affect the product of the two entities or the Equipment Power (=AHU cooling).

For guidance on determining the equipment data, see the *Data Collection Guide*.

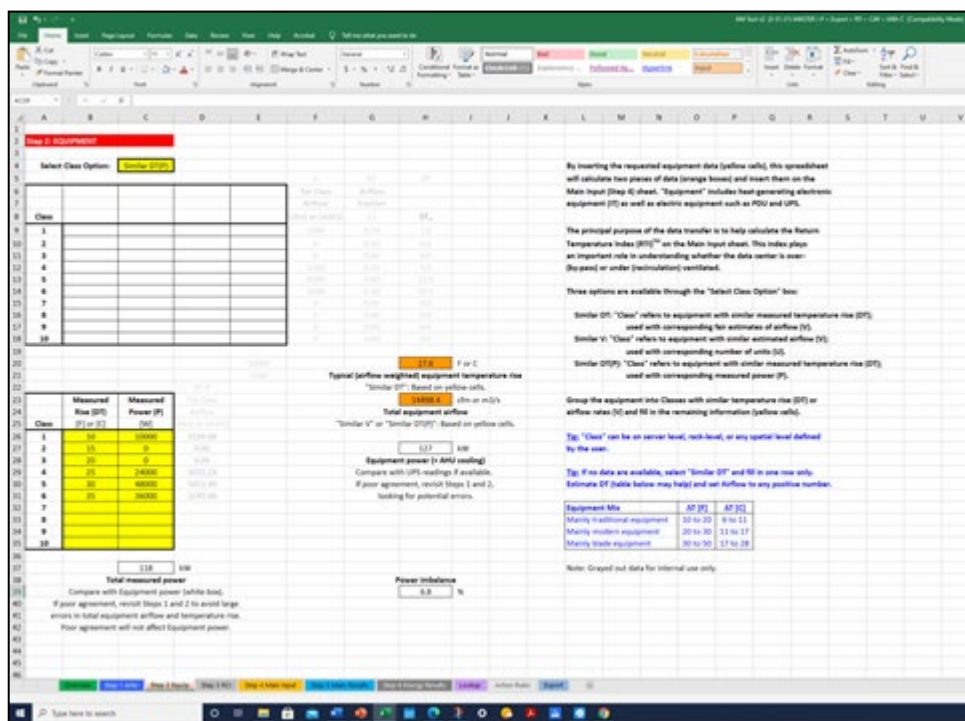


Figure 4: Step 2 Equipment sheet
(Class Option DT(P) is selected in this figure).

Step 3 RCI

“Step 3 RCI” is the third of four input sheets.

The Rack Cooling Index (RCI)[®] provides an unbiased and objective way of quantifying the quality of an air management design from a thermal perspective. The RCI is often used to make sure that no degradation of the thermal IT-equipment environment occurs when air-management measures are introduced for the purpose of saving energy. The Index is a measure of how effectively equipment racks are cooled within a given thermal guideline, both at the high end and at the low end of the temperature range. Specifically, the RCI is a performance metric explicitly designed to gauge compliance with the thermal guidelines of ASHRAE (2021) and NEBS (Telcordia 2001, 2012) for a given data center. The index is included in the ASHRAE Thermal Guideline (2011) for purposes of showing compliance.

Both guidelines use recommended and allowable ranges. The recommended intake temperature range is a statement of reliability (facility operation) whereas the allowable range is a statement of functionality (equipment testing). The numerical values of the recommended and allowable ranges depend on the applied environmental guideline. In the ASHRAE (2021) Class A1 specification, the recommended and allowable ranges are 65°–80°F (18°–27°C) and 59°–90°F (15°–32°C), respectively.

Over-temperature conditions exist once one or more intake temperatures exceed the maximum recommended temperature. Similarly, under-temperature conditions exist when intake temperatures drop below the minimum recommended. The RCI compresses the equipment intake temperatures into two numbers—the RCI_{HI} and the RCI_{LO}. An RCI_{HI} of 100% means no over-temperatures whereas an RCI_{LO} of 100% mean no under-temperatures. Both numbers at 100% mean that all temperatures are within the recommended temperature range—i.e., absolute compliance. The lower the percentage, the greater probability (risk) intake temperatures are above the maximum allowable and below the minimum allowable, respectively. Indication of such potentially harmful thermal conditions is provided by a warning flag “*” appended to the index, often indicating localized overheating.

Figure 4a provides a graphical representation of the RCI_{HI} (RCI_{LO} is analogous). The bold curve is the intake temperature distribution for all N intakes; the temperatures have been arranged in order of increasing values. The Total Over-Temperature represents a summation of all over-temperatures. The Max Allowable Over-Temperature is defined in the figure. The definitions of RCI are as follows (Herrlin 2005):

$$RCI_{HI} = \left[1 - \frac{\text{Total Over-Temp}}{\text{Max Allowable Over-Temp}} \right] 100 \%$$

$$RCI_{LO} = \left[1 - \frac{\text{Total Under-Temp}}{\text{Max Allowable Under-Temp}} \right] 100 \%$$

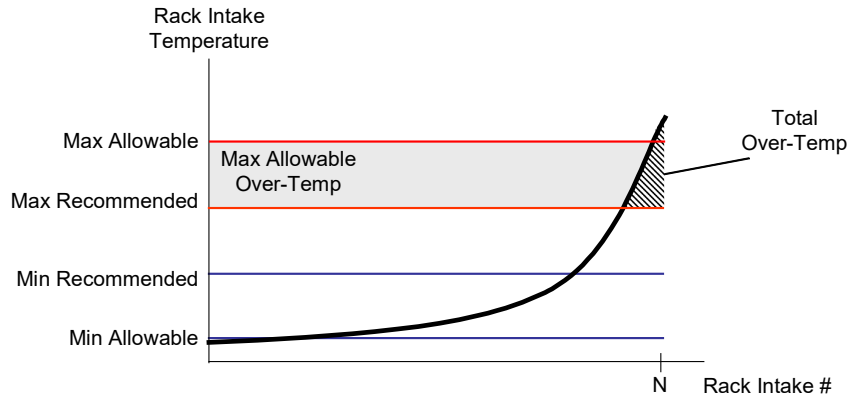


Figure 4a: Intake temperature distribution and graphical representation of RCI_{HI}

Table 1 shows proposed rating of the RCI based on numerous numerical analyses. Lawrence Berkeley National Laboratory (LBNL) is also in the process of benchmarking the metric through the DOE Software Tool Suite (DOE 2021c). The risk for temperatures above (below) the maximum (minimum) allowable temperature increases with declining index values. The value for the intake temperature distribution shown in Figure 4a is $RCI_{HI} = 95\%^*$ where the asterisk indicates the presence of intake temperatures above the maximum allowable temperature.

Table 1: Proposed Rating of the Rack Cooling Index (RCI)[®]

Proposed Rating	RCI
Ideal	100%
Good	$\geq 95\%$
Acceptable	$\geq 90\%$
Poor	$< 90\%$

The DOE Data Center Air-Management (AM) Tool is using more practical expressions of RCI_{HI} and RCI_{LO} for calculating the index values than the definitions shown above.

Calculated data exported to the Main Input sheet (orange cells):

- RCI_{HI} [%]

$$RCI_{HI} = \left[1 - \frac{\sum (T_x - T_{maxrec})_{Tx > T_{maxrec}}}{(T_{maxall} - T_{maxrec}) N} \right] 100 \%$$

where	T_x	"Intake Temperature" at intake x [°F or °C]
	N	"Count" or total number of intakes measured [-]
	T_{maxrec}	"Max Recommended" temperature [°F or °C]
	T_{maxall}	"Max Allowable" temperature [°F or °C]

An asterisk appended to the index value means at least one intake temperature is above the maximum allowable temperature.

- RCI_{LO} [%]

$$RCI_{LO} = \left[1 - \frac{\sum (T_{minrec} - T_x)_{Tx < T_{minrec}}}{(T_{minrec} - T_{minall}) N} \right] 100 \%$$

where	T_x	"Intake Temperature" at intake x [°F or °C]
	N	"Count" or total number of intakes measured [-]
	T_{minrec}	"Min Recommended" temperature [°F or °C]
	T_{minall}	"Min Allowable" temperature [°F or °C]

An asterisk appended to the index value means at least one intake temperature is below the minimum allowable temperature.

Other calculated data (white cells):

- Intake Temperature plot (Figure 5).

The Intake Temperature plot shows a graphical representation of the entered intake temperatures. The plot will dynamically update and scale with changes made to the intake temperatures and number of intake temperatures, respectively. The corresponding RCI values are shown immediately to the right of the plot in the orange boxes.

- Recommended and allowable temperature range table.

The recommended and allowable temperature ranges are specified in Step 4 Main Input, and are echoed next to the Intake Temperature plot.

For guidance on determining the equipment intake temperatures, see the *Data Collection Guide*.

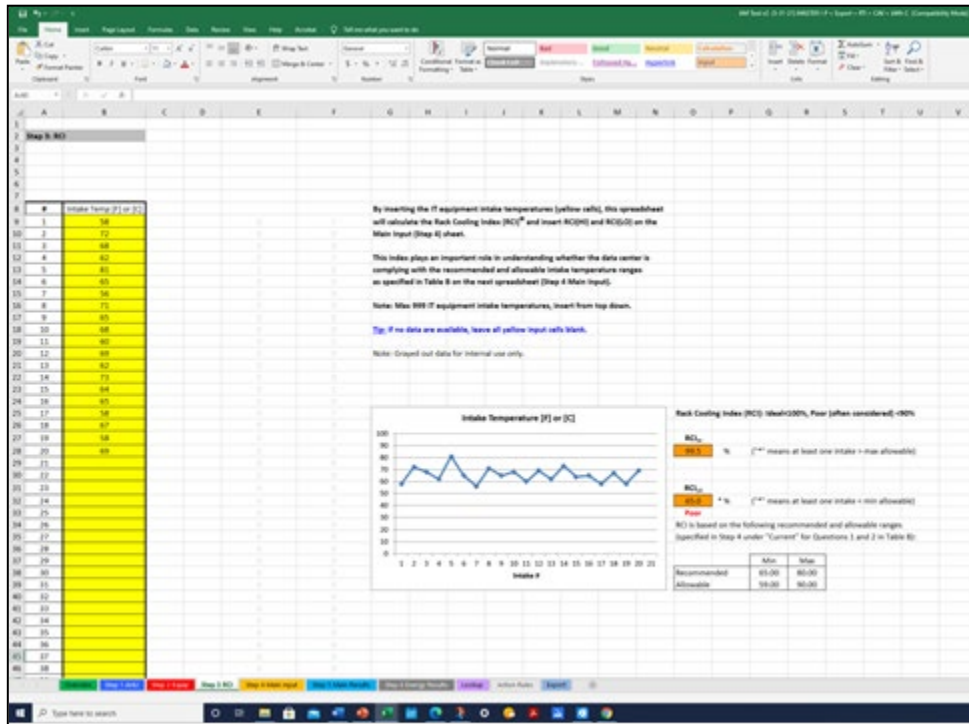


Figure 5: Step 3 RCI sheet, upper part.

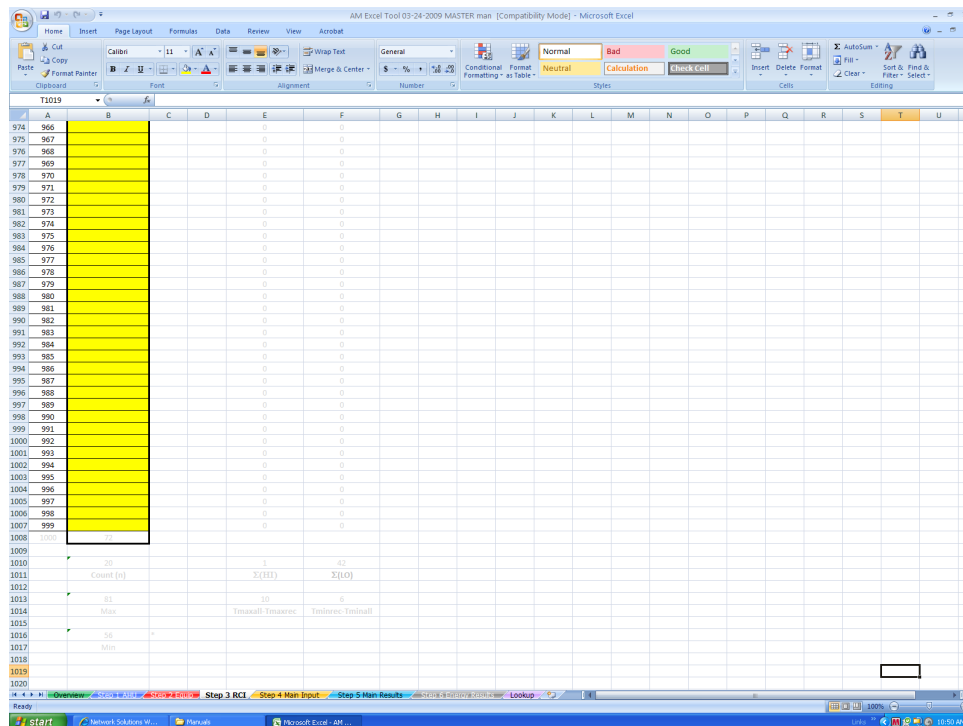


Figure 6: Step 3 RCI sheet, lower part.

Step 4 Main Input

“Step 4” Main Input is the last of four input sheets (although some data can be entered on “Step 6”).

Table A on the Step 4 Main Input sheet shows air-management metrics (Figure 7) either entered or calculated/echoed from the AHU, Equip, and RCI sheets (color coded). If no data or insufficient data are entered in Step 1 AHU and Step 2 Equip, multiple cells in Table A will be empty. If this happens, more likely than not, no energy estimates will be calculated in Step 6.

- RTI [%]

The Return Temperature Index (RTI)TM is a measure of the net level of by-pass air or net level of recirculation air in the equipment room. Both effects are detrimental to the overall energy and thermal performance of the space. By-pass air does not participate in cooling the electronic equipment and depresses the return air temperature. Recirculation, on the other hand, is one of the main reasons for hot spots or areas significantly hotter than the average space temperature.

The RTI is a measure of the performance of the air-management system and how well it controls by-pass and recirculation air. Deviations from 100% are generally an indication of declining performance. The index is defined as follows (Herrlin 2008):

$$RTI = (\Delta T_{AHU} / \Delta T_{Equip}) 100 [\%] = (V_{Equip} / V_{AHU}) 100 [\%]$$

Where

ΔT_{AHU}	“Typical (airflow weighted) AHU Temperature Drop” (echoed from Step 1)
ΔT_{Equip}	“Typical (airflow weighted) Equipment Temperature Rise” (echoed from Step 2))
V_{AHU}	“Total AHU airflow” (echoed from Step 1)
V_{Equip}	“Total Equipment Airflow” (echoed from Step 2)

Since the average temperature rise across the equipment provides the potential for high return temperatures, it makes sense to normalize the RTI with regard to this entity. In other words, the RTI provides a measure of the actual utilization of the available temperature differential. Consequently, a low return air temperature is not necessarily a sign of poor air management. If the equipment only provides a modest temperature rise, the return air temperature cannot be expected to be high.

The equation above shows the link between energy and thermal management. The RTI is also the ratio of total airflow through the IT-equipment to the total airflow through the air handlers. The airflow interpretation of the index is straight forward (see Table 2 below). A value of 100% means balanced airflows; that is, the total equipment flow is equal to the total air-handler airflow. A value above 100% suggests net recirculation air (air re-circulates from equipment exhaust to equipment intake) elevating the return air temperature. Unfortunately, this also means elevated equipment intake temperatures. A value below 100% suggests net by-pass air (air bypasses the equipment and do not contribute to cooling) reducing the return temperature. This may happen when the supply airflow is increased to combat hotspots.

Table 2: Interpretation of the Return Temperature Index (RTI)TM

Interpretation	RTI
Balanced	100%
Net Recirculation	>100%
Net By-Pass	<100%

There might be a number of legitimate reasons to operate below or above 100%. For example, some air-distribution schemes are designed to provide a certain level of air mixing (recirculation) to ensure an even equipment intake temperature. Some overhead air-distribution systems are designed to operate this way. Raised-floor cooling, on the other hand, often needs some excess air to function properly.

Since improving the RCI can lead to an energy penalty, the RTI can help evaluate how severe such a penalty may be.

- RCI_{HI} and RCI_{LO} [%]

Rack Cooling Index (RCI)[®] is a measure of absence of over- and under-temperatures. The values in Table A are echoed from Step 3 RCI. For the RCI definitions, equations, and calculations, see Step 3 RCI.

- IAT max and IAT min [°F or °C]

If no data are entered in Step 3 RCI, the two RCI cells in Table A will be empty (Alt. 1). Typical (not extreme) maximum and minimum IT-equipment intake temperatures can then be entered in the yellow cells (Alt. 2). Alt. 1 has priority over Alt. 2 should all four cells have values.

- SAT [°F or °C]
“Typical (airflow weighted) AHU Supply Air Temperature” (echoed from Step 1)
- ΔSAT [°F or °C]
Maximum difference (“Max-Min AHU Supply Temperature”) between AHU supply air temperatures (echoed from Step1)

Table B on the Step 4 Main Input sheet lists air-management questions (Figure 8). No calculations are associated with these questions/answers on the Step 4 Input sheet. Data entered here will be used in calculations on Steps 5 and 6. Please consult those sections for details on the calculations. For a general discussion on Table B, please see the *User’s Manual*.

Figure 7: Step 4 Main Input sheet, upper part.

Table A: Metrics (Yellow cells: Enter data, remaining data from the AHU, Equip, and RC) sheets (color coded).

Metric	Definition	Measured	Unit
ΔT_{room}	Typical (surface weighted) AHU temperature drop	55.3	F or C
ΔT_{rack}	Typical (surface weighted) equipment temperature rise	55.3	F or C
Q_{room}	Total AHU airflow	100000	cfm or m³/h
Q_{rack}	Total equipment airflow	100000	cfm or m³/h
RTI	Return Temperature Index ($\Delta T_{room}/\Delta T_{rack} + Q_{room}/Q_{rack}$)	65.3	%
RCI_{room}	Rack Cooling Index: Measure of absence of over-temperatures	95.3	%
RCI_{rack}	Rack Cooling Index: Measure of absence of under-temperatures	95.3	%
$\Delta T_{room, min}$	Typical (surface weighted) AHU supply air temperature	55	F or C
$\Delta T_{rack, min}$	Typical (surface weighted) AHU supply air temperature	55	F or C
$\Delta T_{room, max}$	Maximum difference between AHU supply air temperatures	6.6	F or C

* AHU 3 has priority over AHU 2

Table B: Questions (Yellow cells: Enter data).

Question	Current	Target
Primary Input (Impact on energy estimates if raised floor cooling, and recommended Actions)		
1. Recommended IT equipment intake temperature range (statement of reliability)	ASHRAE/NEBS	Wide
2. Allowable IT equipment intake temperature range (statement of functionality)	ASHRAE/NEBS	ASHRAE 41
3. Aisle containment quality/implementation?	LOW	HIGH
4. Blanking panels in and between racks quality/implementation?	MID	MID
5. Floor leakage quality/implementation (set to "high" if not raised floor cooling?)	MID	MID
6. Tile/diffuser placement quality/implementation?	MID	MID
7. EC-Class (equipment ventilation protocol) quality/implementation?	MID	HIGH
8. Controls sophistication (CAV/VAV with IAT sensing)?	LOW	HIGH
9. AHU modular/other distribution quality/implementation (set to "high" if not raised floor cooling?)	LOW	HIGH
10. Cable/pipe management in supply air path quality/implementation?	LOW	HIGH
Secondary Input (Impact on recommended Actions only)		
11. What is the clear ceiling in feet (or m) (visible floor to visible ceiling)?	9	
12. Is there a dropped ceiling (not necessarily used as airflow plenum)?	Yes	
13. Is the IT equipment arranged in straight rows?	No	
14. Are there cosmetic doors on the equipment racks?	Yes	
15. How many AHUs are operating under normal conditions (exclude stand-by units)?	2	Also Primary Input
16. Do some areas have load densities that are 2-4 times the average?	Yes	
17. Is there any supplemental cooling (liquid and/or air solution)?		
18. Which is the predominant air supply path?	Floor Plenum	
19. Plenum height in feet (or m)?	2	
20. Floor plenum static pressure in in. of water (or Pa)?	<0.05 (or <7)	
21. Which is the predominant air return path?	Ceiling Plenum	
22. Ceiling plenum height in feet (or m)?	1	
23. Where are cables/pipes located?	Floor Plenum	
24. Central (built-up) or local (CRAC/H) air handling?	Local on floor	
25. Do CRAC/H have centralized (networked) or distributed controls?	Distributed	
26. Have temperature (and humidity) sensors been calibrated during the past 12 months?	No	
27. Is the air-delivery system balanced to ensure correct airflow rates?	Yes	
Management Practices Input (Impact on recommended Management Actions only)		
28. Is there a sensor calibration program in place?	No	
29. Is there a floor plenum cable-mining program in place?	No	
30. Is there a tile/diffuser-placement program in place?	No	
31. Is there a supply plenum-tightness (sealing leaks) program in place?	No	
32. Is there a return plenum-tightness (sealing leaks) program in place?	No	
33. Is there a rack- and row-tightness (blanking panels) program in place?	No	
34. Is there an air-balancing (proper airflow distribution) program in place?	No	

Table A includes calculated metrics from Steps 1-3 (color coded).
 Rack Cooling Index (RCI)TM, Ideal=100%, Poor (often considered) <90%
 Return Temperature Index (RTI)TM, Balanced=100%, By-Pass=100%, Recirc=100%
 *Target refers to realistic Target architecture/controls for raised floor cooling.
 Questions 1-22 are considered the key factors for Air Management.
 Notes: Grouped out data for internal use only.

Figure 8: Step 4 Main Input sheet, lower part.

Table B: Questions (Yellow cells: Enter data).

Question	Current	Target
Primary Input (Impact on energy estimates if raised floor cooling, and recommended Actions)		
1. Recommended IT equipment intake temperature range (statement of reliability)	ASHRAE/NEBS	Wide
2. Allowable IT equipment intake temperature range (statement of functionality)	ASHRAE/NEBS	ASHRAE 41
3. Aisle containment quality/implementation?	LOW	HIGH
4. Blanking panels in and between racks quality/implementation?	MID	MID
5. Floor leakage quality/implementation (set to "high" if not raised floor cooling?)	MID	MID
6. Tile/diffuser placement quality/implementation?	MID	MID
7. EC-Class (equipment ventilation protocol) quality/implementation?	MID	HIGH
8. Controls sophistication (CAV/VAV with IAT sensing)?	LOW	HIGH
9. AHU modular/other distribution quality/implementation (set to "high" if not raised floor cooling?)	LOW	HIGH
10. Cable/pipe management in supply air path quality/implementation?	LOW	HIGH
Secondary Input (Impact on recommended Actions only)		
11. What is the clear ceiling in feet (or m) (visible floor to visible ceiling)?	9	
12. Is there a dropped ceiling (not necessarily used as airflow plenum)?	Yes	
13. Is the IT equipment arranged in straight rows?	No	
14. Are there cosmetic doors on the equipment racks?	Yes	
15. How many AHUs are operating under normal conditions (exclude stand-by units)?	2	Also Primary Input
16. Do some areas have load densities that are 2-4 times the average?	Yes	
17. Is there any supplemental cooling (liquid and/or air solution)?		
18. Which is the predominant air supply path?	Floor Plenum	
19. Plenum height in feet (or m)?	2	
20. Floor plenum static pressure in in. of water (or Pa)?	<0.05 (or <7)	
21. Which is the predominant air return path?	Ceiling Plenum	
22. Ceiling plenum height in feet (or m)?	1	
23. Where are cables/pipes located?	Floor Plenum	
24. Central (built-up) or local (CRAC/H) air handling?	Local on floor	
25. Do CRAC/H have centralized (networked) or distributed controls?	Distributed	
26. Have temperature (and humidity) sensors been calibrated during the past 12 months?	No	
27. Is the air-delivery system balanced to ensure correct airflow rates?	Yes	
Management Practices Input (Impact on recommended Management Actions only)		
28. Is there a sensor calibration program in place?	No	
29. Is there a floor plenum cable-mining program in place?	No	
30. Is there a tile/diffuser-placement program in place?	No	
31. Is there a supply plenum-tightness (sealing leaks) program in place?	No	
32. Is there a return plenum-tightness (sealing leaks) program in place?	No	
33. Is there a rack- and row-tightness (blanking panels) program in place?	No	
34. Is there an air-balancing (proper airflow distribution) program in place?	No	

Step 5 Main Results

“Step 5 Main Results” is the first of two output sheets.

Table 1 lists numerical output based on user input on the previous sheets (Figure 9).

There are four table columns:

- Measured: Measured data (Step 4, Table A) with Current architecture/controls (Step 4, Table B, Questions 1-10).
- Commissioned: Achievable through commissioning with Current architecture/controls (Step 4, Table B, Questions 1 and 3-10). SAT and 100/RTI are fetched from Lookup tables (Figure 12). RAT is based on SAT, RTI, and measured ΔT_{Equip} .
- Retrofitted: Achievable through retrofit with Target architecture/controls (Step 4, Table B, Questions 1 and 3-10). SAT and 100/RTI are fetched from Lookup tables (Figure 12). RAT is based on SAT, RTI, and measured ΔT_{Equip} (i.e., no change to the equipment).
- State-of-the-Art: Achievable with State-of-the-Art architecture/controls. SAT is based on max Target recommended intake temperature. RAT is based on SAT and measured ΔT_{Equip} (i.e., no change to the equipment).

The Commissioned and Retrofitted columns are valid for raised-floor cooling only (Step 4, Table B, Question 18 = Floor Plenum). Cells may be empty if insufficient data have been provided in Steps 1-3.

Calculated data (white cells):

There are fifteen (15) cells in Table 1:

- 100/RTI [-]: Total AHU Airflow/Total Equipment Airflow ($V_{\text{AHU}}/V_{\text{Equip}}$) [-]
 - Measured: 100/("RTI" Step 4, Table A)
 - Commissioned: Fetches data from Lookup tables based on user selection in Step 4 for questions 1 and 3-10 in column Current. See Lookup section for the significance of the Lookup tables and calculation details including CAV controls and RAT sensing.
 - Retrofitted: Fetches data in Lookup tables based on user selection in Step 4 for questions 1 and 3-10 in column Target. See Lookup sheet for the significance of the Lookup tables and calculation details including CAV controls and RAT sensing.
 - State-of-the-Art: This entry is assigned 1.00 (ideal).
- SAT [°F or °C]: Typical (airflow weighted) AHU Supply Air Temperature [°F or °C]
 - Measured: ("SAT" Step 4, Table A)
 - Commissioned: Fetches data in Lookup tables based on user selection in Step 4 for questions 1 and 3-10 in columns Current. See Lookup section for the significance of the Lookup tables and calculation details.
 - Retrofitted: Fetches data in Lookup tables based on user selection in Step 4 for questions 1 and 3-10 in columns Target. See Lookup sheet for the significance of the Lookup tables and calculation details.
 - State-of-the-Art: Max Target recommended IT-equipment intake temperature (Step 4) – 2.0 [°F] or 1.1 [°C] (a small margin is assumed).

- RAT [°F or °C]: Typical (airflow weighted) AHU Return Air Temperature [°F or °C]
 - Measured:
 - "SAT" + ("ΔT_{AHU}" Step 4)
 - Commissioned:
 - $[(\text{"RTI"}/100) * (\text{"SAT"} + (\text{"ΔT}_{\text{Equip}} \text{ Step 4}))] + [(1 - \text{"RTI"}/100) * \text{"SAT"}]$
 - Retrofitted:
 - $[(\text{"RTI"}/100) * (\text{"SAT"} + (\text{"ΔT}_{\text{Equip}} \text{ Step 4}))] + [(1 - \text{"RTI"}/100) * \text{"SAT"}]$
 - State-of-the-Art:
 - "SAT" + ("ΔT_{Equip}" Step 4)
- RCI_{HI} [%]: Rack Cooling Index (RCI)[®] "HI" [%]; measure of absence of over-temperatures
 - "RCI_{HI}" Step 3; value depends on user selection in Step 4 for questions 1 and 2 in column Current.
- RCI_{LO} [%]: Rack Cooling Index (RCI)[®] "LO" [%]; measure of absence of under-temperatures
 - "RCI_{LO}" Step 3; value depends on user selection in Step 4 for questions 1 and 2 in column Current.
- V_{AHU} [cfm or m³/s]: Total Air-Handler Unit Airflow [cfm or m³/s]
 - "V_{AHU}" Step 4

The data in Table 1 are used for estimating the percentage savings for fan energy and chiller energy in Step 6 Energy Results. Since the Tool is using discrete Lookup tables (Figure 12) for calculating the numerical output for the Commissioned and Retrofitted conditions, the results may not change if the input is only marginally changed.

The lookup values for RTI for the Commissioned and Retrofitted conditions assumes a built-in economizer—if any. A separate air-side economizer could result in higher (worse) 100/RTI values than those shown in Table 1.

Table 2 lists recommended Actions (Figure 10) based on user input on the previous sheets (mainly Table B in Step 4 Main Input) and the self-explanatory rules outlined on the last sheet of the Tool: Action Rules. Table 2 has three sections:

- Actions for realizing Commissioned conditions in Table 1 (Actions 1-10)
- Actions for realizing Retrofitted or State-of-the-Art conditions in Table 1 (Actions 11-37)
- Management Practices (Actions 38-44).

Table B in Step 4 Main Input also has three sections:

- Primary Input (impact on Energy estimates, Table 1 in Step 5 Main Results—if raised-floor cooling—and recommended Actions, Table 2 on Step 5 Main Results). Questions 1 and 2 for Current ranges will impact the numerical value of the RCI values calculated in Step 3 RCI.
- Secondary Input (impact on Recommended Actions only, Table 2 on Step 5 Main Results).
- Management Practices Input (impact on recommended Management Actions only, Table 2 on Step 5 Main Results, Actions 38-44).

Not applicable Actions are indicated by N/A in Table 2. By implementing recommended Actions (by revisiting user data input and/or question responses) further Actions may be provided.

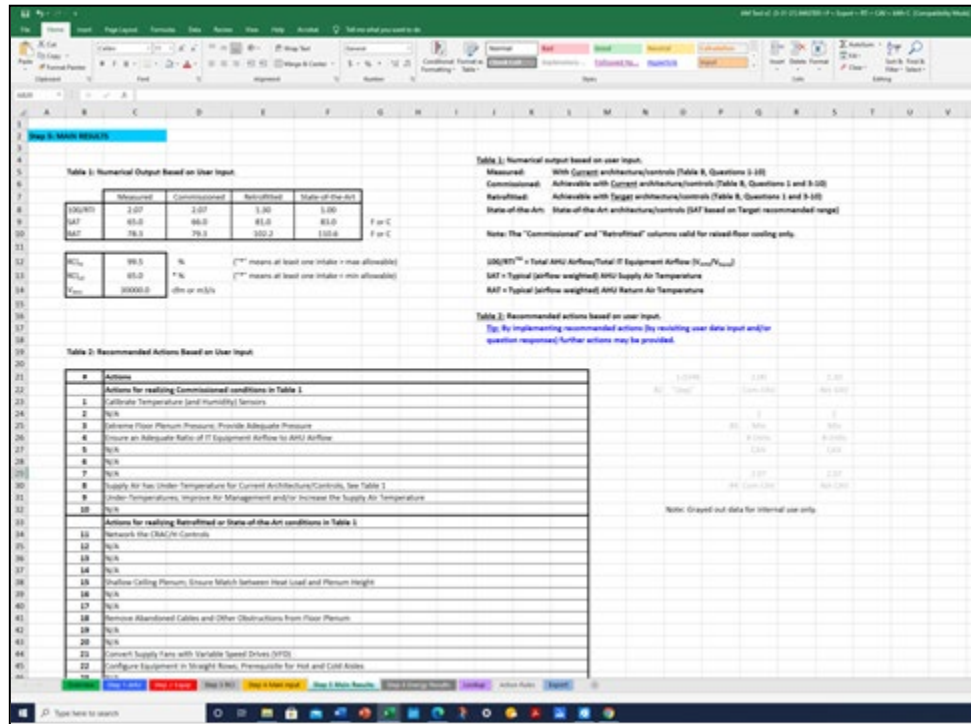


Figure 9: Step 5 Main Results sheet, upper part.

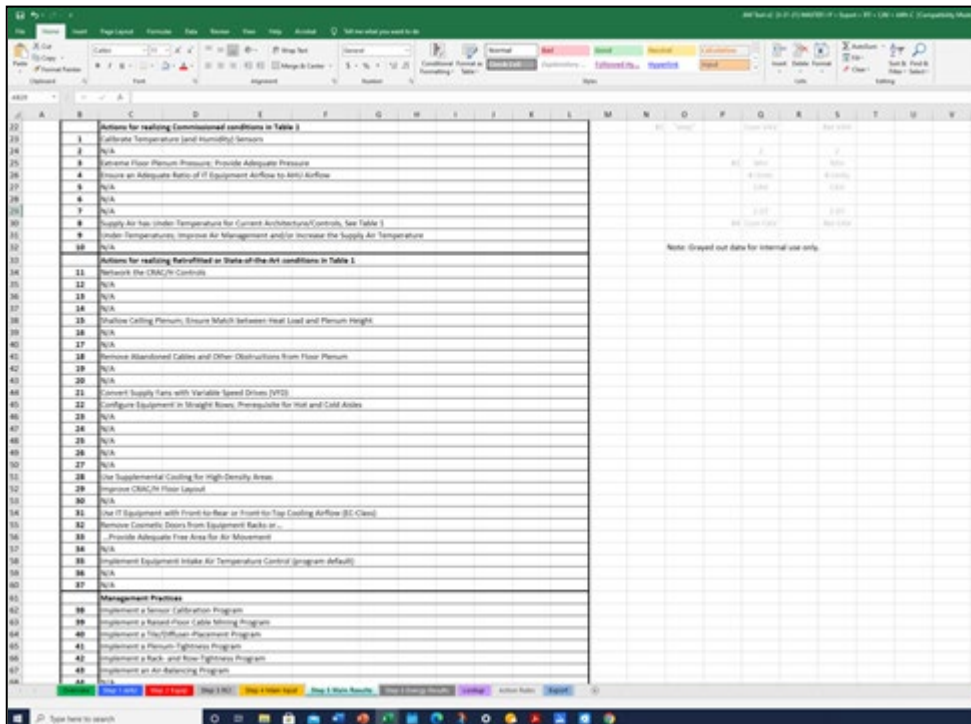


Figure 10: Step 5 Main Results sheet, lower part.

Step 6 Energy Results

“Step 6 Energy Results” is the second of two output sheets. This sheet contains % energy reduction, kWh reduction, and associated \$ and carbon (CO₂) savings for supply fans and chillers. Simple payback periods are also provided based on entered implementation costs. All other results can be found in Step 5 Main Results.

The two bar charts are based on Table 1 in Step 5 Main Results. Since the Tool is using discrete lookup tables for calculating the numerical output for the Commissioned and Retrofitted conditions, the percentage savings may not change if the input is only marginally changed.

The Measured bars are the reference (100%) and values above 100% for the other bars will not be displayed. Obviously, this is a situation that should be avoided—the goal is to decrease the energy demand, not increase it. The Commissioned and Retrofitted bars are valid for raised-floor cooling only (selected in Step 4 Main Input, Table B, and Question 18 = Floor Plenum). These two bars will not be displayed for other selections of Question 18 (Ceiling Plenum and Overhead Ducting).

Calculated data (bar charts):

- Fan Energy [%]
 - Measured: By definition 100% (reference)
 - Commissioned:
 - CAV; turning units off: $[(\text{"100/RTI Commissioned"} / \text{"100/RTI Measured"})^1] * 100$
 - VAV; turning all units down: $[(\text{"100/RTI Commissioned"} / \text{"100/RTI Measured"})^e] * 100$
 - Retrofitted:
 - CAV; turning units off: $[(\text{"100/RTI Retrofitted"} / \text{"100/RTI Measured"})^1] * 100$
 - VAV; turning all units down: $[(\text{"100/RTI Retrofitted"} / \text{"100/RTI Measured"})^e] * 100$
 - State-of-the-Art:
 - VAV assumed; turning all units down: $[(\text{"100/RTI State-of-the-Art"} / \text{"100/RTI Measured"})^e] * 100$

The exponent “e” in the expressions above is the value entered in the “Select Exponent” box immediately to the right of the fan energy bar chart. The permitted range is 2-3. An exponent of 2 represents fully laminar airflow whereas an exponent of 3 represents fully turbulent airflow. Since the majority of the flow resistance is turbulent in data centers, an exponent of 2.8 can often be used.

For the Commissioned and Retrofitted cases, CAV system or VAV systems are determined in Step 4 Main Input, Table B, and Question 8. Selecting “Low” will result in VAV, whereas “Mid” or “High” will result in CAV.

The fan-energy savings are not altered by a built-in air-side economizer. With a separate air-side economizer, however, the fan savings for the Commissioned and Retrofitted cases could be overestimated since the lookup values for RTI assumes a built-in air-side economizer—if any.

With adequate air management, the reduction in fan energy is often very large due to the fact that the fan energy varies close to the cube of the airflow. It is not uncommon with 70-80% savings.

- Chiller Energy [%]
 - Measured: By definition 100% (reference)
 - Commissioned: $100 - [f * ("SAT \text{ Commissioned}" - "SAT \text{ Measured}")]$
 - Retrofitted: $100 - [f * ("SAT \text{ Retrofitted}" - "SAT \text{ Measured}")]$
 - State-of-the-Art: $100 - [f * ("SAT \text{ State-of-the-Art}" - "SAT \text{ Measured}")]$

The chiller energy reduction depends on the supply air temperature (SAT) as a percentage saving per degree increase. For data center applications, a factor between 1 and 3 (I-P) or 2 and 5 (SI) is common. The factor “f” in the expressions above is the value entered in the “Select Factor” box immediately to the right of the chiller energy bar chart.

The chiller-energy savings only takes into account the increase in supply air temperature. Additional savings are due to higher utilization of an air-side economizer—if present. The associated savings depend on factors not covered in the Tool. Note also that higher supply air temperatures may result in higher IT-equipment airflows and, in turn, higher equipment electrical costs.

The annual energy (kWh/year) and associated annual cost (\$/year) for operating supply fans and chillers are based on the percentage chart values, the Measured Annual Fan/Chiller Energy inputs, and the Electric Cost input. Note that the Electric Cost input is in \$/kWh for both I-P and SI units.

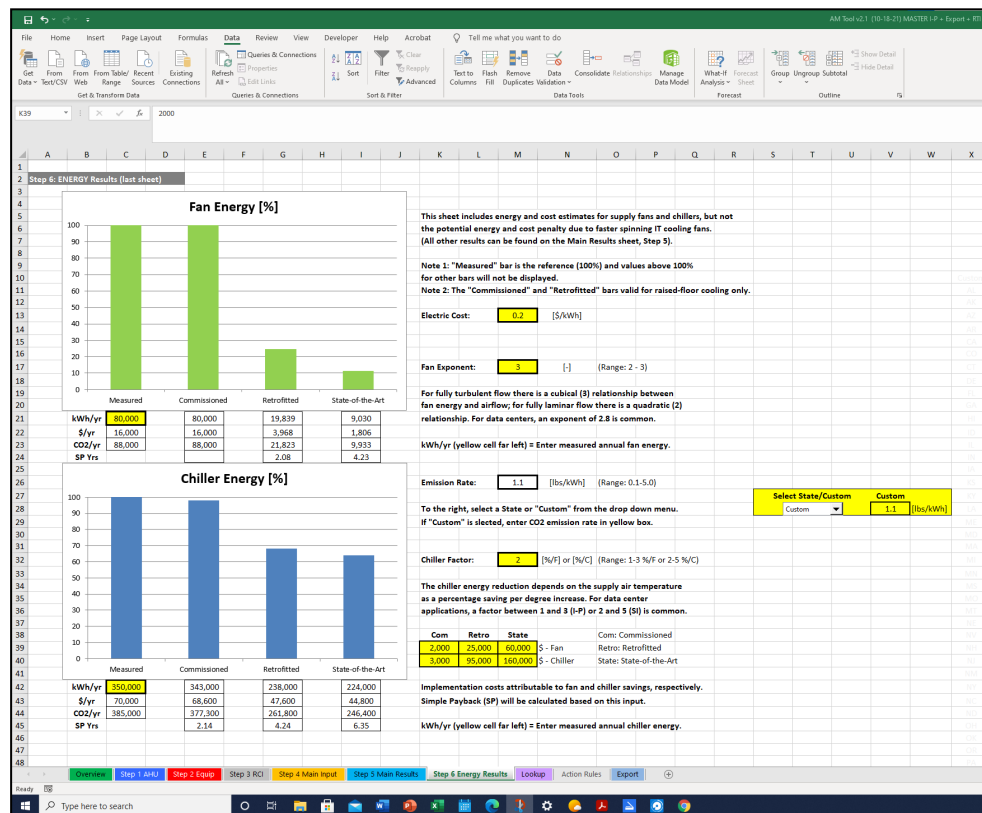


Figure 11: Step 6 Energy Results sheet.

Lookup

This sheet is initially hidden since there are no user inputs or user outputs. If the sheet is made visible, please do not enter or change data. The following text discusses the significance of the lookup tables and some calculation details.

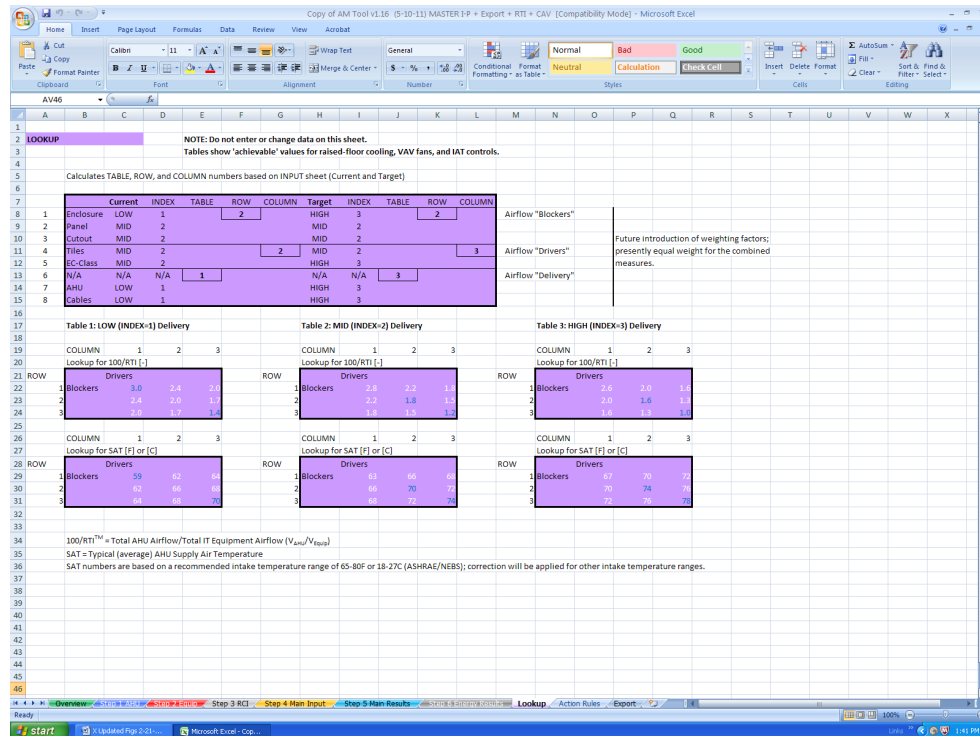


Figure 12: Lookup sheet.

The top table is a pre-calculation table whereas the remaining six smaller tables are the actual lookup tables. These tables are partially based on a study by Pacific Gas and Electric Company (PG&E 2010). The mechanics of looking up data are as follows:

- Each of the eight measures in Step 4 (Questions 3-10) except measure 6 Controls Sophistication (CAV or VAV) is assigned a number of 1, 2, or 3 depending on user selection: LOW=1, MID=2, and HIGH=3. The upper table echoes the selections and the assigned numbers for all measures as selected under Current and Target. Measure 6 is handled separately. The lookup tables depict "achievable" values assuming VAV fans with Intake Air Temperature (IAT) sensing. The table airflows (100/RTI) will be modified if CAV fans were selected on 4 Main Input, Question 8. The program then determines the average size of the air handlers and selects the nearest larger multiple of units required to meet the table values. This may allow units to be shut down or additional units may be needed.

Location and size distribution of the air handlers may require increased airflow compared to the calculated value. Return Air Temperature (RAT) sensing may also require post-processing. RAT sensing is less accurate than IAT sensing and the level of accuracy depends on the calibration with the intake air temperatures.

- 2) The top table on the Lookup sheet calculates an average number of 1, 2, or 3 for each grouping of Airflow Blockers (Enclosure, Cutout, and Panel), Airflow Drivers (Tiles and EC-Class), and Airflow Delivery (AHU, and Cables) for both Current and Target conditions.
- 3) When the grouping numbers have been calculated, the corresponding data are fetched from the six smaller lookup tables through an INDEX function. The three SAT tables are based on a recommended intake temperature range of 65°-80°F or 18°-27°C; a correction will be applied for other ranges. The table data were established by industry experts and CFD simulations. The groupings do not imply that certain groupings of measured are preferred but simply a way of organizing the tables.

Action Rules

This last sheet is initially hidden since it does not contain any user inputs or user outputs. The following single paragraph briefly describes the significance of the action rules detailed in the table on this sheet. Please open the Tool and select tab Action Rules to view the sheet (after making the sheet visible—if hidden).

The Action Rules are rule-sets for triggering certain Actions (recommendations) in Step 5 Main Results, Table 2 based on user input, mainly Table B in Step 4 Main Input, and the rather self-explanatory rule-sets on this sheet. Across the top of the spreadsheet, the Questions from Step 4 Main Input are listed as table columns. The rows in the table represent the resulting Actions (recommendations). In the body of the table are the actual rules or the conditions that trigger Actions.

Export

This last sheet is also initially hidden. The purpose of this sheet is to summarize output that may be used for post-processing, for example in whole-building simulation packages.

The table cells are color coded per the originating sheet (tab) color. The majority of the data come from Table A on Step 4 Main Input (orange) and Table 1 on Step 5 Main Results (blue).

	Measured	Commissioned	Retrofitted	State-of-the-Art
Floor Area	No Data	No Data	No Data	No Data
AHU/Rack Power [W]	126,595	126,595	126,595	126,595
Average Rack Inlet Temperature [F or C]	65.6	No Data	No Data	No Data
Average AHU Temperature drop [F or C]	13.3	13.3	21.2	27.6
Average equipment temperature drop [F or C]	27.6	27.6	27.6	27.6
Total AHU airflow [cfm or m ³ /s]	30,000.0	30,000.0	18,848.0	14,498.4
Total equipment airflow [cfm or m ³ /s]	14,498.4	14,498.4	14,498.4	14,498.4
100/RTI [-]	3.07	3.07	1.30	1.90
AHU Supply Temperature [F or C]	65.0	66.0	81.0	83.0
AHU Return Temperature [F or C]	78.3	79.3	102.2	110.6
Rack Cooling Index [IC _{RA}] [W]	99.5	99.0	99.0	99.0

Figure 13: Export sheet.

ABBREVIATIONS AND ACRONYMS

ΔT_{AHU}	Typical (airflow weighted) AHU temperature drop [$^{\circ}\text{F}$ or $^{\circ}\text{C}$]
ΔT_{Equip}	Typical (airflow weighted) equipment temperature rise [$^{\circ}\text{F}$ or $^{\circ}\text{C}$]
AHU	Air-Handler Unit
AM	Air Management
By-pass	Cool air that by passes the electronic equipment
Commissioned	Achievable with Current architecture/controls
CRAC	Computer Room Air Conditioner
CRAH	Computer Room Air Handlers
Current	Current architecture/controls in data center
DC Pro	DOE Data Center Profiling Tool
DOE	U.S. Department of Energy
DT	Temperature differential across Equipment [$^{\circ}\text{F}$ or $^{\circ}\text{C}$]
Equip	Equipment (IT and Electrical)
HVAC	Heating, Ventilating, and Air-Conditioning
IAT max	Typical (not extreme) maximum IT-equipment intake temperature [$^{\circ}\text{F}$ or $^{\circ}\text{C}$]
IAT min	Typical (not extreme) minimum IT-equipment intake temperature [$^{\circ}\text{F}$ or $^{\circ}\text{C}$]
Measured	Measured data with Current architecture/controls
P	Power [W] or [kW]
RAT	Return air temperature [$^{\circ}\text{F}$ or $^{\circ}\text{C}$]
RCI	Rack Cooling Index (RCI) [®] [%]
RCI _{HI}	Rack Cooling Index (RCI) [®] “HI” [%]; Measure of absence of over-temperatures
RCI _{LO}	Rack Cooling Index (RCI) [®] “LO” [%]; Measure of absence of under-temperatures
Recirculation	Hot equipment exhaust re-circulates back to the equipment intakes
Retrofitted	Achievable with Target architecture/controls

RTI	Return Temperature Index (RTI) TM [%]; $\Delta T_{AHU}/\Delta T_{Equip} = V_{Equip}/V_{AHU} (x100)$
SAT	Typical (airflow weighted) AHU supply air temperature [°F or °C]
ΔSAT	Maximum difference between AHU supply air temperatures [°F or °C]
State-of-the-Art	State-of-the-Art architecture/controls
Target	Realistic target architecture/controls for raised-floor cooling
Ton	Ton Cooling = 3.52 kW
U	Number of Equipment Units [-]
V_{AHU}	Total Air-Handler Unit airflow [cfm or m ³ /s]
V_{Equip}	Total equipment airflow [cfm or m ³ /s]

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