Power Knot LLC

501 Valley Way

Milpitas CA 95035

USA

+1-408-889-8433

www.powerknot.com

COPs, EERs, and SEERs

How Efficient is Your Air Conditioning System?

1 Introduction

This note discusses performances of air conditioning systems, including heat pumps and chillers. It describes the efficiencies of systems so you can estimate how much energy a system may use. The discussion applies equally to residential, commercial, and industrial systems.

When we talk about the size of an air conditioning system (whether by tons of cooling, BTU/h, or kW), we are specifying the cooling capacity (power) of the system. The actual electrical power used to operate such a system is less. As described in this document, the electrical power used is one half to one third (or less) of the cooling power.[1]

In the US, the Department of Energy (DoE) set standards for the minimum performance of residential central air conditioners and heat pumps and this document lists some of those requirements.

2 Coefficient of Performance, COP

The COP is a measure of the amount of power input to a system compared to the amount of power output by that system:[2]

$$\text{COP} = \frac{\text{power output}}{\text{power input}} \qquad \text{(Eq 1)}$$

The COP is therefore a measurement of efficiency; the higher the number, the more efficient the system is. The COP is dimensionless because the input power and output power are measured in Watt. The COP is also an instantaneous measurement in that the units are power which can be measured at one point in time.

Consider a simple electric heater. All of the electricity that is input to the unit is converted to heat. There is no waste and the power output (in heat) equals the power input (in electricity), so the COP is one. The COP can be used to describe any system, not just heating and cooling.

An air conditioning system uses power to move heat from one place to another place. When cooling, the air conditioning system is moving heat from the space being cooled (usually a room), to somewhere it is

1. It is possible to run air conditioning systems using gas or other power sources. While some parts of this discussion apply equally to such systems, the focus of this document is on systems driven by electrical power.
2. It is important to distinguish between “energy” and “power.” Energy is the amount of work that is done and is measured in Joule (J) or British thermal units (BTU). Power is work done in unit time (or the rate of doing work) and is measured in W (W=J/s) or BTU/h.

unwanted (usually outside). A heat pump uses the same principles, but it is moving heat from outside (the cold side) to the space being heated inside (the living space).

The maximum theoretical COP for an air conditioning system is expressed by Carnot's theorem, reduced to the following equation:

$$OP_{maximum} = \frac{T_C}{T_H - T} \quad \text{(Eq 2)}$$

Where T_C is the cold temperature and T_H is the hot temperature. For space cooling, the cold temperature is inside the space; for space heating, the cold temperature is outside. All temperatures are expressed in Kelvin. To convert from °C to Kelvin, add 273.15. To convert from °F to °C, subtract 32, multiply by 5 and divide by 9.

As you can see from equation 2, as the difference between the hot temperature and the cold temperature increases, the COP becomes lower, and vice versa. This means that an air conditioning system is more efficient when the room temperature is closer to the outside temperature and will use more power when there is a larger difference in these temperatures.

As an example, consider the maximum theoretical efficiency of an air conditioning system that is cooling a room to 23°C (73.4°F). If the outside air temperature is 32°C (89.6°F), the theoretical maximum efficiency is:

$$COP_{maximum} = \frac{T_C}{T_H - T_C} = \frac{(23 + 273.15)}{(32 + 273.15) - (23 + 273.15)} = 32.9 \quad \text{(Eq 3)}$$

Typical COP values for air conditioning and heat pump systems are in the range 2 to 4, or about a tenth of the theoretical maximum. However, this helps to explain where the power is used in such a system. Consider the heat pump application shown in figure 1.

The heat pump takes power from the environment and uses electrical power to move that power to the inside space. More power is put into the house than used in electricity.[1] The COP of this system is 4 (power into the house ÷ power consumed). Observe that the electrical power consumed goes into the building. In practice some is expended as heat outside the building, so the actual COP will be slightly less than 4.

An air conditioner operates in the same way, but it is removing power from the space. Consider the figure in reverse where 1 kW is used to move 3 kW of power from the space. The air conditioner puts 4 kW of power into the environment and this power must be dissipated by the condenser. The air conditioning unit is using more power than is being consumed in electricity. However, in this case, all the power used to operate the air conditioning unit is dissipated outside and has no effect on the power removed from the space. Hence, the COP is equal to 3.

1. The figure uses the term "heat." Heat is energy, not power, but is used here to aid in the understanding.

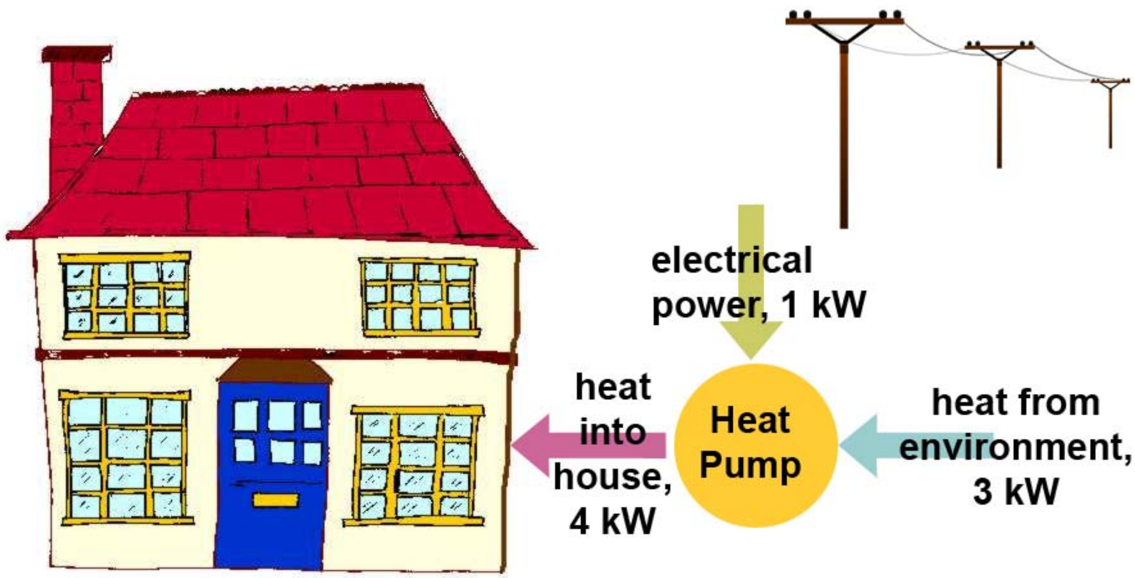

Figure 1. Example of operation of a heat pump

3 Energy Efficiency Ratio, EER

The EER is the ratio of output cooling energy (in BTU) to electrical input energy (in Watt-hour).

$$\text{EER} = \frac{\text{output cooling energy in BTU}}{\text{input electrical energy in Wh}} \qquad \text{(Eq 4)}$$

The units are therefore $BTU/W/h$ or more formally $BTU \cdot W^{-1} \cdot h^{-1}$.

The bizarre units of measurement originated in the US to measure the efficiency of an air conditioning system in a steady state. The units are therefore not dimensionless and EER can be measured only over time. Typically, with the system stable, one can measure the energy used over an hour period. One measures the amount of cooling the system has performed during that time.

Many writers erroneously consider the EER to be a ratio of power, not energy:

$$\text{EER}_{\text{erroneous}} = \frac{\text{output cooling power in BTU/h}}{\text{input electrical power in W}} \qquad \text{(Eq 5)}$$

The units are the same, but now we are dividing the power of the air conditioning unit (in BTU/h) by the power to operate it (in Watt). Although incorrect, this view does have the advantage of allowing us to easily estimate the power used for a certain size of air conditioning unit.

As an example, consider an air conditioning unit that is five tons and has an EER of 11.6.[1] If we want to find out how much power is used we rewrite equation 5:

$$\text{input electrical power} = \frac{\text{output cooling power in BTU/h}}{\text{EER}} = \frac{5 \times 12000}{11.6} = 5.17\ \text{kW} \qquad \text{(Eq 6)}$$

Where the multiplication by 12,000 converts tons of air conditioning to BTU/h.

The EER can be specified only at a specific delta temperature (between inside and outside the space being cooled), because as we see from equation 2, the efficiency changes with this delta temperature. The EER is usually specified under the conditions shown in table 1.

	Dry bulb temperature	**Wet bulb temperature**	**Relative humidity**	**Dew Point**
Outdoor conditions	95°F (35°C)	75°F (24°C)	40%	67°F (19°C)
Indoor conditions	80°F (27°C)	67°F (19°C)	51%	60°F (16°C)

Table 1. Usual test conditions to evaluate EER

To convert EER to COP, we need to accommodate for the units used. We convert the BTU energy and the electrical input energy to a common energy unit, namely Joule.[2] One BTU equals 1055 J. One Wh equals 3600 Ws or 3600 J. So:

$$\text{COP} = \frac{\text{output cooling energy}}{\text{input electrical energy}} = \text{EER BTU/(Wh)} \times \frac{1055\text{J/BTU}}{3600\text{J/(Wh)}} = \text{EER} \times 0.293 \qquad \text{(Eq 7)}$$

Alternatively:

$$\text{EER} = \text{COP} \times 3.41 \qquad \text{(Eq 8)}$$

4 Seasonal Energy Efficiency Ratio, SEER

As with EER, the SEER is the ratio of output cooling energy (in BTU) to electrical input energy (in Watt-hour). However the SEER is a representative measurement of how the system behaves over a season where the outdoor temperature varies:

$$\text{SEER} = \frac{\text{output cooling energy in BTU over a season}}{\text{input electrical energy in Wh during the same season}} \qquad \text{(Eq 9)}$$

1. To understand the meaning of a ton of air conditioning, please review Power Knot's application note on this topic available at www.powerknot.com.
2. The symbol for Joule is J. One Joule is equal to one Watt-second (Ws).

The US DoE defined the formula to be used to calculate SEER values for residential air conditioning systems of less than 65,000 BTU/h (19 kW). The manufacturer makes EER or COP measurements at various values for indoor and outdoor temperature and then computes the SEER. The result is one number that may guide a prospective purchaser or owner of a system to compare one unit with another unit.[1]

As an example, consider a five ton unit (60,000 BTU/h) that runs on average eight hours a day during the cooling season.[2] At the ends of the season, the system may run only four hours a day but at the peak of the season, it is running 14 hours a day. Assume the cooling season is 180 days (about six months). Again, assume that on average throughout the season, the unit runs at two thirds of its capacity. The cooling energy is:

$$\text{cooling energy in season} = 60000\ \text{BTU/h} \times \frac{2}{3} \times 8\ \text{h/day} \times 180\ \text{days} = 57.6 \times 10^{6}\ \text{BTU} \qquad \text{(Eq 10)}$$

If the system has a SEER of 13, the total electrical energy used is:

$$\text{electrical energy in season} = \frac{57.6 \times 10^{6}}{13} = 4.43\ \text{MWh} \qquad \text{(Eq 11)}$$

If the cost of electricity is 17 ¢ per kWh, the cost to run this air conditioning unit during the season is:

$$\text{cost to operate the a/c unit in the season} = 4.43\ \text{MWh} \times \$0.17/\text{kWh} = \$753 \qquad \text{(Eq 12)}$$

The EER is usually specified under the conditions shown in table 1. The SEER is averaged over a range of temperatures that are less than or equal to this, including one test where the outside temperature is 82°F (28°C) and the inside temperature is 80°F (27°C). We know that as the delta temperature goes down, the efficiency goes up, so therefore the SEER is greater than the EER (typically by about 15% to 35%). One formula, to convert between the two was proposed by a student in a master's thesis as follows:[3]

$$\text{EER} = 1.12 \times \text{SEER} - 0.02 \times \text{SEER}^{2} \qquad \text{(Eq 13)}$$

Therefore:

$$\text{SEER} = \frac{1.12 - \sqrt{1.2544 - 0.08 \times \text{EER}}}{0.04} \qquad \text{(Eq 14)}$$

For example, if EER is 12, the estimated SEER is 14.4, calculated as follows:

$$\text{SEER} = \frac{1.12 - \sqrt{1.2544 - 0.08 \times 12}}{0.04} = 14.4 \qquad \text{(Eq 15)}$$

1. Again, ostensibly, a system with a higher SEER will consume less energy than a system with a lower SEER.
2. The cooling season is typically summer, but the US DoE specifically uses the term "cooling season."
3. This formula seems to have been widely accepted, but this author cannot find the original document. It is referenced in a US DoE document titled Building America House Simulation Protocols, June 2010 and attributed to Wassmer (2003).

This implies SEER is 20% more, but in practice the value may be larger.[1] Also, because the conditions to calculate the SEER are fixed, they may differ widely from where the air conditioning unit is actually installed where temperatures and operating parameters vary significantly. Therefore, the actual ratio observed in practice may differ widely from the published SEER, making it difficult to accurately estimate the energy to run the system during a season.

In the US, the DoE specifies the minimum values for SEER as shown in table 2. The law was changed in January 2006 and the table lists the old and new standards.

	1994 to 2006	After January 2006
Split systems	10	13
Packaged systems	9.7	13

Table 2. Minimum SEER standards for new residential installations in the USA

A split system is one where the evaporator and condenser are in physically different places. The compressor is usually housed with the condenser and these are in one package that is usually installed outside or on a roof. The metering device (expansion device) is adjacent to the evaporator and installed inside the space where the air used to cool the space can flow.

A packaged system has all four major components (evaporator, condenser, metering device, and evaporator) in a single unit that is usually placed outside. Air ducts transport the supply and return air to the unit.

Using equation 9, we see that a unit that is rated at SEER of 13 is 30% more efficient than a unit rated at SEER 10.

5 Heating Seasonal Performance Factor (HSPF)

Like SEER, this is a measurement of the efficiency of a system and the units are the same (BTU/h divided by Watt). However, this measures the efficiency of the system in heating mode, not cooling mode. Therefore it applies only to heat pumps or reversible air conditioning units and not to units that only cool a space. A variant of equation 7 on page 4 applies:

$$\text{COP} = \frac{\text{output heating energy}}{\text{input electrical energy}} = \text{HSPF} \times 0.293 \qquad \text{(Eq 16)}$$

As with COP, EER, and SEER, the higher the number of HSPF the greater the efficiency.

In the US, the DoE specifies the minimum values for HSPF as shown in table 3. The law was changed in January 2006 and the table lists the old and new standards.

For example, Assume a system has an HSPF of 8. Then from equation 16, the COP is 2.3. This means that 2.3 times the amount of heat is put into the space than is consumed in electricity. Put another way, for every 1 kWh of electrical energy used by the heat pump, 2.3 kWh of heat energy is input to the space.

1. If you are evaluating two different air conditioning systems, compare the EER of one to the EER of the other, or compare the SEER of one to the SEER of the other. It is not valid to compare the EER of one unit with the SEER of another unit.

	1994 to 2006	After January 2006
Split systems	6.8	7.7
Packaged systems	6.6	7.7

Table 3. Minimum HSPF standards for new residential installations in the USA

6 Kilo-Watt per Ton (kW/ton)

The efficiencies of large industrial air conditioner systems, especially chillers, are given in kW/ton to specify the amount of electrical power that is required for a certain power of cooling. In this case, a smaller value represents a more efficient system. However, as we have seen, to be valid, this number must be reported at various operating conditions, especially the indoor and outdoor temperatures, and the difference between chilled water return and chilled water supply.

You can convert kW/ton to COP as follows:

$$\text{COP} = \frac{\text{power output in W}}{\text{power input in W}} = \frac{3.517}{\text{kW/ton}} \qquad \text{(Eq 17)}$$

Because a ton of refrigeration is equivalent to 3.517 kW.

For example, if a chiller has a rating of 1.8 kW/ton, then using equation 17, the COP is 1.95. Therefore, for every 1 kW of power consumed by the chiller, it will provide 1.99 kW of cooling in the space.

7 Horse Power

Another unit in use in the US is the horse power (HP). This is a unit of power and typically is used to specify the size of motors. It may also be used to specify the input power of an air conditioning system. One HP is approximately 746 W.

8 Energy Star

In the US, Energy Star is the Environmental Protection Agency's (EPA's) indication for products that have high energy efficiency. it makes it easy for consumers to identify and purchase products that have higher energy efficiency than those products without such designation.

Systems under 65,000 BTU/h (19 kW) can earn the Energy Star symbol by meeting the minimum efficiency ratings listed in table 4. The numbers in parentheses are those values that must be met to qualify for a Federal tax credit. The ratings for HSPF apply only to systems that combine a heat pump.

ENERGY STAR

	EER	SEER	HSPF
Split systems	12 (≥12.5)	14.5 (≥15)	8.2 (≥8.5)
Packaged systems	11 (≥12)	14 (≥14)	8 (≥8)

Table 4. Energy Star ratings for air-source heat pumps and central air conditioners

9 References

Details about Energy Star (US EPA) are here:

http://www.energystar.gov

The DoE web site with many references for residential systems is:

http://www1.eere.energy.gov/buildings/appliance_standards/residential/central_ac_hp.html

The document 10 CFR Part 430, titled “Energy Conservation Program for Consumer Products: Test Procedure for Residential Central Air Conditioners and Heat Pumps; Final Rule,” October 2007 describes the test procedures to used to evaluate EER, SEER, and HSPF.

It is interesting to read the discussion regarding the introduction of these news rules. Two subjects were broached that were not included in the new rules:

- Setting a minimum EER. It was proposed that the minimum EER should be set at 11.6. However, it was concluded that specifying the minimum SEER was a good way of ensuring the efficiencies required.
- Mandating the use of a thermal expansion valve (TXV) for all systems. Previously, fixed orifices were permitted for the metering device; the DoE concluded that the TXV can make a system 11% more efficient. However, it was eventually decided that the DoE should not dictate the technology used, so the mandate was dropped. In practice, however, most manufacturers adopted the use of a TXV to improve the efficiency of the systems they manufacture.

Also, when the new standards were proposed, two of the largest US manufacturers of these systems opposed the rules.

The values for EER, SEER, and HSPF are specified in Standard 210/240 by the Air-Conditioning, Heating and Refrigeration Institute (AHRI) “2008 Standard for Performance Rating of Unitary Air-Conditioning and Air-Source Heat Pump Equipment.” You can freely access this document here:

http://www.ahrinet.org/Content/FindaStandard_218.aspx

The DoE also refers to Standard 90.1-2010 by the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) “Energy Standard for Buildings Except Low-Rise Residential Buildings.” You can buy this document ($125 USD at the time of this document) here:

http://www.techstreet.com/standards/ASHRAE/90_1_2010_I_P_?product_id=1739526

The ASHRAE web site is:

http://www.ashrae.org/

10 Summary of Performance Requirements

The following tables list the minimum performance standards that must be met for new installations of air conditioning systems in the US as of the date of this document. This is not an exhaustive or comprehensive list and the requirements change as technology improves.

Type	Size of System (Cooling Power)			Minimum Efficiency		Input power, kW[a]
	BTU/h	kW[b]	Tons[c]	EER, SEER	COP[d]	
Through the wall air cooled air conditioner	<30,000	<8.8	<2.5	SEER 12	3.1	<2.8
Small duct, high velocity air cooled air conditioner	<65,000	<19	<5.4	SEER 10	2.7	<7.1
Other air cooled air conditioners	<65,000	<19	<5.4	SEER 13	3.3	<5.8
Other air cooled air conditioners	65k ~ 135k	19 ~ 40	5.4 ~ 11.3	SEER 11.2	2.9	6.5 ~ 13.5
Other air cooled air conditioners	135k ~ 240k	40 ~ 70	11.3 ~ 20	SEER 11	2.9	13.6 ~ 24.3
Other air cooled air conditioners	240k ~ 760k	70 ~ 223	20 ~ 63	SEER 10	2.7	26.1 ~ 82.5
Other air cooled air conditioners	>760,000	>223 kW	>63	SEER 9.7	2.6	>84.7
Water cooled air conditioners	<65,000	<19	<5.4	EER 12.1	3.6	<5.4
Water cooled air conditioners	65k ~ 135k	19 ~ 40	5.4 ~ 11.3	EER 11.5	3.4	5.7 ~ 11.7
Water cooled air conditioners	>135,000	>40	>11.3	EER 11	3.2	>12.2

Table 5. Selective sample of minimum efficiencies of air conditioning systems in the US

a. Input power is derived using equation 1 on page 1.

b. 1,000 BTU/h = 293.1 W.

c. 1 ton of cooling power = 12,000 BTU/h.

d. COP values are obtained using equation 7 on page 4 and equation 13 on page 5. These are approximate conversions and apply only at the conditions under which SEER or EER is specified.

You can see from the table that the input power in W is approximately equal the cooling capacity in BTU/h divided by ten. This is a very approximate guide that allows you estimate the size of current clamps that you may need if you want to monitor such a system.

The table also allows you to calculate kW/ton. Either divide the input power in kW by the size of the system in tons or use equation 17. For example consider a water cooled air conditioner of greater than 135,000 BTU/h (the last row). The cooling is 11.3 tons. The kW/ton is 12.2 ÷ 11.3 = 1.1. Alternatively, using equation 17:

$$\text{Efficiency in kW/ton} = \frac{3.517}{\text{COP}} = \frac{3.517}{3.2} = 1.1 \qquad \text{(Eq 18)}$$

11 Conclusion

The efficiency of air conditioning systems changes with operating conditions. Various ratios can provide a guidance on efficiency. For residential systems, the specifications for SEER are well documented, but not necessarily applicable for your climate. For commercial systems, an EER also allows you to compare various systems and to approximate electricity usage. With each number, however, these figures only give a guidance to the power you will use in practice. Because suppliers will optimize their systems to give the best performance at the specific test conditions, you need to proceed with caution in evaluating competing systems – *caveat emptor!*

A SEER of 13 can be approximated as an EER of 11.2 (using equation 13 on page 5), or a COP of 3.6 (using equation 8 on page 4). The theoretical maximum COP for a difference of 2°F is about 100 (using equation 2 on page 2), or 25 times more efficient. While there are now residential systems on the market that have a SEER of over 20, most commercial and industrial systems have efficiencies far below this.

The point not addressed in this article is that no matter how efficient the system is once it is installed, its performance degrades in time due to oil fouling. A newly installed SEER 13 unit can be a SEER 11 unit in a few years. Power Knot can help to restore such a system or even make it perform better than new.