Evaporative cooling of a home vs. refrigerated air: lower economic cost, vastly greater water use

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Everyone who has used evaporative cooling in our usually dry climate knows that it's much cheaper in monetary terms than running refrigerated air. Our electric bill rises from about $36-38 per month in our March and April bills (February and March usage) to about $73 in August (July usage). Friends who have refrigerated air ("AC") spend as much as $300 per month, but I'd attribute about $200 of that to AC use, since most people use home lighting much more profligately than we do, leaving lights on in most rooms in the morning and evening. Our home is only about 2/3 the size of more recently-built homes, so let's call it about $54 to use evaporative cooling (EC) in a modern home vs. $200 for AC in the same size of home. The cost advantage for EC is fourfold!

What about water use? EC needs direct water use at the home. AC needs water use for cooling at the electric power plant, which is nontrivial. Let's compare these.

Spoiler alert: the following analysis indicates that:
* EC uses about 18 times as much water as does AC, and it accounts for about a doubling of residential water use during its operation, per household
* AC costs about $39 per gigajoule (GJ) of electric power. EC uses some electric power for the blower, but its predominant energy use is the evaporation of water. Water is dirt cheap currently, so that the cost of household water use per GJ of evaporative cooling is a measly $0.21. That is, electric power at the wall socket costs about 185 times more than the "power" of water for the same energy transfer
* This ratio is much larger than the monetary cost differential, where AC costs about 4 times more. This is because AC is at least 18 times more efficient in applying energy inputs to net cooling:
    * AC transfers about 3 J of energy from home to the condenser (heat rejection to outside air) for each J of electrical energy input. One says that AC has a coefficient of performance of 3.
    * EC is inefficient in transferring the cooling of the air to the cooling of the home. There is a flow of cooled air out of the home, which carries the majority of cooling effort out. I made a crude estimate that the temperature of the rejected (outflowing) air is at about ¾ of the way down from home air temperature – that is, about ¾ of the cooling effort leaves with the exhausted cool air. (Example: outside air is at 40°C; EC cools it to 28°C, or by 12°C; air flows out of the house at vents at 31°C; 9 out of 12 degrees of cooling are wasted.)Also, the water flow to the evaporative cooler needs to be as much as 50% higher than the evaporation rate (water is bled off or bypassed), so that salts don't build up on the cooler pads. So, an EC uses perhaps 6 times as much water as would be needed if all the cooling from evaporating water would stay in the home.
* This is an interesting tradeoff:
    * EC: much less contribution to climate change from power plant emissions of greenhouse gases to run the system
    * AC: much less water use in a water-limited area
    * Water for residential use is far too cheap, by world standards – we flush our toilets with drinking-quality water, for example. It should only be cheap for direct human consumption. There's much discussion currently about how to reduce the use of high-quality water, which is increasingly in short supply, for purposes other than direct human consumption (drinking, cooking). The use of graywater systems, toilet-to-tap systems, and two-tier pricing are among

options being considered for an increasingly water-stressed world (and water-stressed local area).
* EC isn't causing a crisis in water use but it contributes to water supply problems (and the diversion of water from ecological functions at water sources). The solutions for using lower-quality water will help in overall water use.
* I don't see an easy way to use much lower-quality water in evaporative coolers without the risk of health problems, such as increasing the risk of, say, Legionnaire's disease in coolers using inadequately sanitized water. One way to greatly reduce water use in an EC sytem is to capture the cooling in exhaust air, using a heat exchanger: cooled air leaving the home absorbs heat from incoming air, best being done at the inlet to the cooler (see sections 7 and 8). No one is doing this, at least not in the US, and the incentives to do it are minimal.

OK, to the calculations:

1. Water use by an evaporative cooler: does the energy balance work out correctly?

I measured the increase in water vapor content of EC air, relative to inlet air at outdoor temperature, and I tested that the heat of vaporization of that much water matched the decrease in sensible heat content of the air. This is a test that I have the physics right.

June 4, 2016, Las Cruces:

Summary:

The EC added 0.267 moles of water (4.8 g) per cubic meter of air. (That looks too precise, right? I'm carrying 1 more significant figure than is merited by the individual measurements, to minimize rounding errors *en route* to a final answer.) Evaporating that much water takes about 11,700 J of energy, taken from the sensible heat of the air. The air temperature, from outside to EC vent, dropped by 10.4°C. With the heat capacity of air (C_P) at our atmospheric pressure, a bit over 1100 J per cubic meter per degree, the drop in sensible heat content of a cubic meter is about 11,400 J. Nice agreement.

Details:

Inlet air (outside air) is at 34.4°C, measured with a thermocouple thermometer and verified with a more distant high-resolution weather station. Its water vapor content can be expressed as a partial pressure of water vapor of 869 pascals (Pa) in metric units. You can convert this to the mass of water in each volume of air, as well as to the percent of molecules that are water (it's about 1% at our atmospheric pressure of 88.500 Pa). Here's the calculation:

> First, to get the vapor pressure of water, e_{air}, I used the dew point temperature reported by the weather station, 4.9°C. The value of e_{air} for pure water depends only upon the temperature. A convenient and very accurate approximation is Murray's formula, where T is in Celsius:
>
> $$e_{air} = 610.8\,Pa \exp\left(\frac{17.269\,T}{237.2+T}\right)$$
>
> Plugging in T=34.4°C, one gets 869 Pa.

To get the content as moles or mass per unit volume, we use the ideal gas law, PV=nRT, where P is the pressure of any gas (air, or just the water vapor in it), V is the volume being considered, *n* is the number of moles of the gas, R is the universal gas constant of 8.314 J mol^{-1} K^{-1}, and T is the absolute temperature relative to absolute zero, or (Celsius temperature) + 273.16 K.

We want the number of moles of water per volume of air:

$$\frac{n}{V}=\frac{P}{RT}=\frac{869\,Pa}{(8.314\,J\,mol^{-1}K^{-1})(34.4+273.2)K}$$
$$=0.340\,mol\,m^{-3}$$

All the units cleared up nicely, as happens when one uses metric (SI) units; e.g., a pascal is a joule per cubic meter.

Repeating this calculation for the EC outlet air, which is at 24°C and a dew point of 13°C, we get a partial pressure of 1498 Pa and a molar content of 0.606 mol m^{-3}. This is a gain of 0.267 mol m^{-3}, as just noted.

I don't have a weather station that gives me that dew point or the vapor pressure. I have access to weather data at our school in Mesilla from a networked weather station, where the weather is consistently nearly identical to that at our house when I make a "campaign" of measurement at our house. That station reported the same air temperature as the thermocouple thermometer (averaging the readings of the latter over about a minute; it does vary as eddies of air roll over the landscape).

2. How much thermal energy (in fuel) is used at the power plant to provide a given amount of heat energy transferred from home to outside air, when AC is used?

OK, we're going to used energy units throughout.

First, note that refrigerators transfer more energy as heat from cooled location to heat-rejection location than the amount of work done by the compressor. This is an interesting concept and a reality, which anyone can look up. One says that a refrigerator (such as in an AC unit) has a coefficient of performance greater than 1 – commonly, about 3. One J of energy put in as work running the compressor transfers about 3 J out the cool house to the hotter air outside. This doesn't violate thermodynamics. Quite the reverse – a refrigerator is like a heat engine (e.g., combustion engine) run backwards, using work to move heat instead of heat to generate work.

Second, a utility power plant uses about 2.5 J of fuel energy (enthalpy) to create 1 J of electrical energy. That is, the efficiency is about 40% on a so-called first-law of thermodynamics basis.

Then, one J of heat removed from a house takes about 0.83 J of fuel energy consumed at the power plant.

3. How much water is used in cooling the power plant for each unit of electrical energy generated?

A common figure for power plants is that they use about 400 gallons of water per megawatt-hour of electrical energy produced. Let's put that into metric units:

$$\frac{mass\ of\ water}{J_e} = \frac{400\,gal}{MWh} * \frac{3.8L}{gal} * \frac{1MW}{(10^6 J\,s^{-1})} * \frac{1h}{3.6x10^3 s)}$$
$$= 4.2x10^{-7}\,L\,J_e^{-1}$$

The three multipliers, such as 3.8 L/gal, are factors that all equal 1; they only change the units. The answer is read as that it takes 4.2x10^{-7} liters of water (0.42 microliters, about 1/60 of a drop) to generate one joule of electrical energy.

4. Let's look at this on an energy basis again, using the energy to evaporate water

It takes about 2.44 million joules to evaporate one liter of water. Multiplying this by the water used per joule of electrical energy, we get

$$\frac{Energy\ of\ vaporization}{Electrical\ energy} = (4.2x10^{-7}\ L\,J_e^{-1})(2.44x10^6\,J\,L^{-1})$$
$$= 1.03\,J_{evap}J_e^{-1}$$

Very amusing. It takes almost exactly as much energy in vaporizing water as the electrical energy produced. This is not so surprising in the end: at a thermal efficiency of 40%, there's 1.5 J of waste heat per J of electrical energy. So, about 2/3 of that is dissipated by evaporating water and the rest by adding sensible heat to the air.

Another interesting note: the water use is quoted for so-called wet cooling towers, where the cooling water is completely evaporated. There are also once-through cooling systems, where liquid water flows in, gets heated but not evaporated, and is discharged to the source body of water, such as a river. I did an interesting calculation in another document. There, I calculated that the warmed water is subject to higher evaporation that is essentially identical to the evaporation in a wet cooling tower. Ask me about it if you're interested.

5. How about evaporative coolers? Are they really using only as much evaporative energy as they deliver to the house as cooling?

Quick answer: No. They use about 6 times more, in a rough calculation!

Unlike an AC system, an EC blows cooled air out of the house, not recirculating it to retain the cooled air. That's why there are vents in the ceiling, so that even with the windows and doors closed there is a way that cooled air can be pushed into the home...and out to the outside air at the end of its journey. Going back to the first part of this document, I made a crude estimate that the air exiting the house is still cooled to ¾ as much as when it entered the house. This is very rough; it's hard to find the air exits and measure the temperature. This means that at least ¾ of the cooling is lost, or that an EC has to provide 4 J of evaporative cooling for every 1 J of cooling that counteracts heat entry into the home (conduction from walls, roof, floor; sunlight entering at windows).

There's yet more loss of water in the bleeder or bypass flow. Everyone who has operated an EC knows that one has to bleed off a goodly amount of water to prevent calcium salts from building up and blocking air flow over the cooler pads. Here's a simple scenario: our water has lots of calcium compounds such as calcium carbonate and calcium sulfate that are only moderately soluble in water. If their limit of solubility is about three times their concentration in our water, then if we evaporate the water to 1/3 its original amount we will triple their concentrations in the remaining water and reach the

limit of solubility; the compounds will precipitate on our cooler pads. To avoid this problem in this scenario, we have to bleed off about half as much water as actually gets evaporated on the pads: 1 g of water gets evaporated and 0.5 g gets pumped out. For every 1.5 grams of water used, 0.5 grams of sump water get dumped at 3 times the concentration
of the incoming water.

We're now up to consuming 6 times as much water as is effective in evaporatively cooling the house. Compare this to the AC system, where 1 J of evaporative energy was used to create 1 J of electrical energy and that 1 J of electrical energy moved 3 J of heat out of the house. Thus, EC used 6 * 3 = 18 times as much water as does AC for the same amount of cooling, by my rough estimate of air flows!

6. So, why is AC so much more expensive to operate than EC?

Quick answer: water is really cheap, per volume and especially per unit of energy that it can carry away by evaporation.

Cost of water: we pay about $2 per 1,000 of water. Let's convert that 1,000 gal to the amount of heat it can carry away by evaporating:

$$\frac{\text{Cost}}{J_{evap}} = \frac{\$2}{10^3\,gal} * \frac{1gal}{3.8L} * \frac{1L}{2.44x10^6\,J_{evap}}$$
$$= \$2.1x10^{-10}\,J_{evap}{}^{-1}$$

That is, it costs about 0.21 nanodollars per J!

Cost of electric power for AC: we pay about 14 cents per kWh. Let's convert this to per joule:

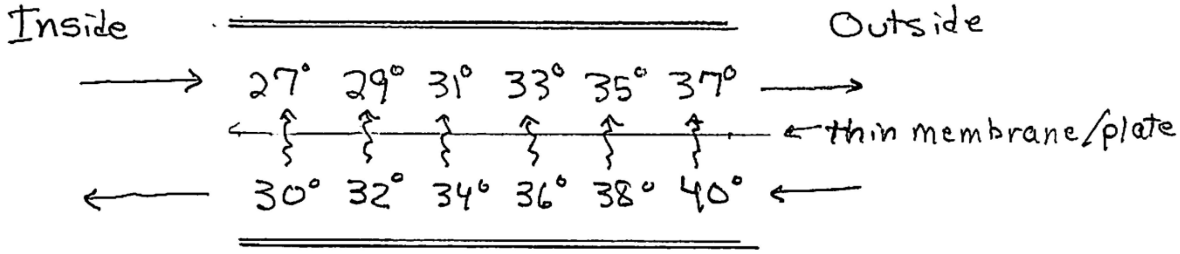
$$\frac{\text{Cost}}{J_{power}} = \frac{\$0.14}{kWh} * \frac{1kW}{10^3\,J\,s^{-1}} * \frac{1h}{3.6x10^3\,s}$$
$$= \$3.9x10^{-8}\,J^{-1}$$

This is about 39 nanodollars per J, or 185 times more than the cost of water per joule of evaporation. Electrical energy is much higher quality energy; it has more free energy content (a topic not pursued here), and its voltage and frequency are tightly controlled for many purposes.

Of course, AC is not 185 times more expensive. I estimated earlier that a joule of energy in evaporating water in an EC is about 1/18th as effective as a joule of electrical energy used in an AC. This reduces the cost ratio to 185/18 or about 10-fold higher for AC than for EC. It's really about 4-fold higher, so there is an estimate somewhere that's not accurate. A likely place is in the fraction of cooling effort lost in an EC as cooled air is pumped out all the time. If 90% is lost, then the ratio of monetary cost is 4-fold.

7. How could the water- inefficiency of an EC be ameliorated?

A proven way to preserve heating and cooling effort is with a heat exchanger in so-called counter-current flow. Here's a diagram showing how outflowing cooled air can chill the incoming warm air from outdoors (obviously, the two mass flow rates have to be the same so that air doesn't accumulate or get depleted in the house):

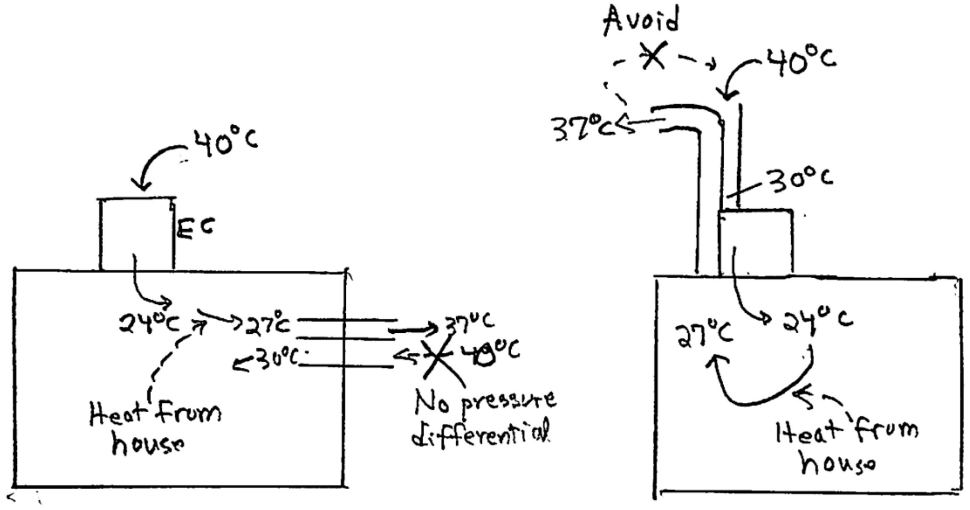


At each point along the heat exchanger, there is here a 3°C temperature difference pushing heat (wiggly arrows) across the thin membrane (highly conductive for heat), out of the incoming air and into the outgoing air. The flow must occur in narrow tubes or channels so that heat transfer is effective; consequently, many channels are stacked in a large array, perhaps 100 x 100 tubes across the face of the heat exchanger, each tube being less than a cm in cross-section (not too small, or the drag on the air flow requires too much power in the blower).

The result, in this scenario, is that the incoming air is at 30°C, not 40° C. To reach the 24°C vent temperature, it only has to be cooled by 6°C, not 16°C, saving of almost 2/3 on cooling effort.

There are many examples of counter-current flow for thermal efficiency and heat retention or transfer in the biological world. Our nasal cavities are one; in cold weather, we warm incoming air, starting at the cold tips of our noses, grading into warm interior parts of our respiratory system. In very hot weather, we do the reverse, cooling the incoming air (and not just by heat exchange but also by evaporating water from our mucous membranes, our own EC system). There are animals with more remarkable countercurrent heat exchangers, notably the *rete mirabile* of wading birds. In cold water, their flow of warm blood down to their lower legs and feet exchanges heat with blood returning from their legs and feet. That way, they lose only a small part of the heat in the blood circulating to their legs and feet.

How could this be implemented in an EC system? We can't just put a heat exchanger somewhere on the walls or the roof, separate from the evaporative cooler; there would be no pressure driving air into the heat exchanger:



So, the heat exchanger has to be stacked onto the EC, as in the right-hand figure. The exhaust air from the house needs to be directed away from the intake of the EC; recycled air is humid, so that it reduces the cooling achievable in the EC.

This imposes different operating conditions on the EC. Without the heat exchanger, air is coming in at 40°C, with a high driving force for evaporating water, contributed by air that's 16°C hotter than the exit temperature. With the heat exchanger, there's a lower driving force, with air reaching the cooling pads at only 30°C. The driving force is lower, but so is the inlet air temperature. The new vent temperature will be lower; the EC will need to run at a lower rate, on average, saving both water and the electrical energy to run the lower. A rough calculation is in section 8 below.

Adding a heat exchanger adds cost to an EC system. With water so cheap and blower power demand rather modest, there's no significant incentive to save water this way. I know of no installation of a heat exchanger on top of an evaporative cooler. It will only happen with changes in water pricing or in absolute water availability. In the US, this is unlikely. In other areas using EC, such as the Middle East, the odds are different.

8. A rough calculation of the lowered vent temperature of an evaporative cooler with its inlet air cooled by a heat exchanger

This is a follow-on to the preceding section. It's quite a rough estimate, as I don't know the real dynamics of heat transfer in an EC. My statement of operating conditions and my premises are:

* Air enters at a temperature T_{in} and a partial pressure of water vapor e_{in}.
* The cooling pad reaches a steady-state temperature T_{pad}, with a corresponding partial pressure of water vapor equal to the saturated vapor pressure at the temperature T_{pad}, or $e_{sat}(T_{pad})$. This is readily calculated. This is solid physics.
* The rate of evaporation of water into the air stream is proportional to the difference in vapor pressure between the incoming air and that of the pad. Thus, the gain in vapor pressure from incoming air to vent air is $k*(e_{sat}(T_{pad})-e_{in})$. This is also good physics, provided that the air is thoroughly mixed, not having a fraction bypassing the cooling.
* The final temperature of the vent air is the same as the temperature of the cooling pad. This assumes that the air is thoroughly mixed, not having fraction bypassing the pad, and that heat transfer between the pad and the air is very efficient. This is a weak point in the model. Heat and vapor transfer are both limited by the same processes in the boundary layer from pad to air stream. I could tighten this up later. The current estimate may overestimate the cooling.
* The cooling, as the drop in temperature from inlet to vent air, is proportional to the amount of water evaporated, thus, proportional to the gain in vapor pressure. This is solid physics.

Then, we have

$$Cooling = T_{in} - T_{pad} = k[e_{sat}(T_{pad}) - e_{in}]$$

Here, *k* is a constant of proportionality dependent upon the physical layout of the cooler pad (thickness, diameter of pores, etc.). We can solve for its value, knowing the values of all the other quantities in the original case with the EC running without a heat exchanger. For the case of Las Cruces on 4 June 2016, we had T_{in}=34.4°C, e_{in}=869 Pa, $T_{pad}=T_{out}$=24° (and e_{out} = 1498 Pa, but its value is not needed – it simply determines the evaporation rate, which is proportional to the cooling amount). We can solve this as

$$34.4-24=k[2985-869]=10.4$$

$$\rightarrow k=10.4/2116=0.0049$$

The units of *k* are degrees per pascal (K Pa^{-1}), and they are essentially the inverse of the rate of rise of water vapor pressure per degree of temperature.

I'll now assume that the outgoing air is at the measured room temperature, about 27°C, and, further, that the heat exchanger enforces a 3°C temperature difference between the incoming and outgoing air streams at both ends. Thus, the new incoming air is 3°C warmer than the outgoing room air, or 30°C. I then make guesses for T_{pad} until I solve the equation with the new value of T_{in} (and the old value of e_{in}; heat exchange doesn't change the water vapor content of the air).

The result is that T_{pad} = 21.6°. This is 2.4°C lower than without the heat exchanger.

Assuming that the "old" EC without a heat exchanger had to run full time, the new EC with the heat exchanger produces colder air and only needs to run part time to maintain the same home air temperature. The old EC pumped in air that was 3°C colder than the home air temperature, in order to balance the heat inputs. The new EC pumps in air that is 5.4°C colder than the room air, so that, in operation, it delivers 5.4/3 = 1.8 times as much cooling. Taking the heat inputs as unchanged (given the same room temperature, same walls, roof, floor), the new EC should run a fraction 1/1.8 of the time to maintain the same room air temperature. This is a savings in energy to run the blower, which is modest. A better setup is, of course, to run a smaller pad and smaller blower, saving capital cost of the EC. This also keeps the system running rather than cycling on and off, which adds to calcium salt deposits on the pads as they sit and dry during off times.

More so, there's less water use. The air flow is 1/1.8 = 56% of what it was with the old EC. Also, the evaporation rate during operation is lower. The old rate was proportional to the difference in vapor pressure e_{sat}(24°C) – 869 Pa = 2985 Pa – 869 Pa = 2116 Pa. The new rate is proportional to e_{sat}(21.6°C) – 869 Pa = 2581 Pa -869 Pa = 1712 Pa. That new evaporation rate is a fraction 1712/2116 = 0.809 of the old rate. Multiply this by the fraction 1/1.8 that the EC now runs and the water use rate drops to a fraction 0.809/1.8 = 0.45, or 45%. This is a big savings in water use. With an even more effective heat exchanger, the saving would be larger.

9. Side notes

Life-cycle use of (mostly) fossil-fuel energy and water: it takes energy and water to make the physical AC and EC devices, with their contents of metals, plastics, and more. These expenditures tend to be a small fraction of the energy and water use in operation. I don't know of an accounting that has been done.