Using Yesterday's Waste Energy for Tomorrow's Heating

Electrification, Heat Pumps and Thermal Energy Storage

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"Electrification" has recently become a widely accepted road map toward the goal of a low-carbon future. The concept is easily understood in the transportation sector: cars using fossil fuels as their onboard energy source can never be carbon free. However, an electric car charged by a carbon-free source can be carbon free. When applied to buildings, one method is to envision stopping the flow of fossil fuels to them and having all energy come from the carbon-free grid of the future. Some skeptics believe it is a pipe dream to have a carbon-free electric grid, but certainly you can't have a carbon-free building if you are burning fossil fuels in them. Electrification will likely play a part in our low-carbon future, so understanding heat pumps, and thermal energy storage's relationship to them, will be critical.

After the architects have done their best to lower the energy loads in buildings, many HVAC engineers, given the challenge to heat a building without fossil fuels, will likely consider heat pumps. Whether the source is air, water, "ground" or some other source, the press for electrification will likely require the use of all sorts of heat pumps to help decarbonize the world's buildings. In big buildings that means big heat pumps. Because heat pumps are going to become critical to meeting carbon-neutral goals, we need to clearly understand the basics.

Energy in Everything

Most engineers understand that the term "heat pump" is a misnomer, mainly because "heat" is a relative term. Ask Google the definition of "heat," and you get "the quality of being hot, high temperature;" but "high" compared to what? As we learned in our science classes, there is thermal energy present at any temperature above absolute zero, which is –459°F (-273°C). Using Rankine or Kelvin as our temperature scales, absolute zero is 0°R or 0 K. Our natural body temperature is

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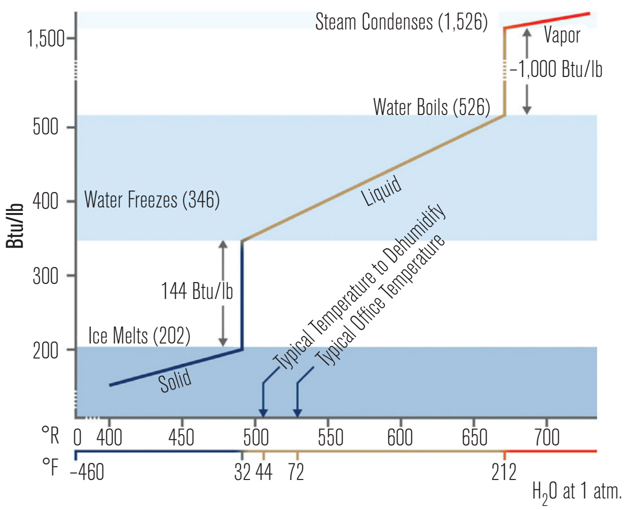
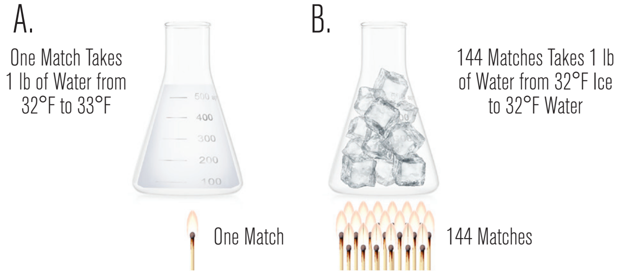
FIGURE 1 Energy in everything above absolute zero.



Water goes through a major phase change, storing lots of energy, at almost exactly the best temperature for human comfort conditioning.

FIGURE 2 Water's phase change (Btu).

One British thermal unit (Btu) is the amount of energy that will raise the temperature of 1 lb of water by 1°F.



558°R (98.6°F or 37°C), we like our buildings at 530°R (70°F or 21°C), we supply liquid to cool buildings at about 500°R, or 40°F (5°C). It's hard to imagine "cold" 40°F (5°C) water as having a lot of energy in it, but at 500°F (277°C) above absolute zero, it clearly does. "Cold" and "warm" are relative. *Figure 1* illustrates two types of energy in materials, sensible and latent. Sensible energy is the energy absorbed or released by a material as it changes temperature. In the case of H_2O it is about 0.5 Btu/lb (1.2 J/g) in the solid phase and 1.0 Btu/lb (2.3 J/g) in the liquid phase. Latent energy is the energy needed to change the phase of a material (solid to liquid or liquid to gas) without a change in temperature.

A more accurate naming of "heat pumps" is "energy pumps," because they extract energy from one temperature level and elevate (pump) it to a higher temperature level. And like water, energy naturally only flows "downhill" from a higher temperature to a lower temperature.

Big Chillers are Big Heat Pumps

Traditional heat pumps are reversible, so the heat exchangers can be used as condensers or evaporators, depending on which way you want the energy to go. Chillers are heat pumps; the only fundamental difference is that they only pump the energy in one direction, from an evaporator to condenser. As an example, in a heat pump used to heat a building, energy can be pumped from an outdoor airside evaporator to waterside condenser; to cool the space, this is reversed, so energy can be pumped from the indoor waterside evaporator to the outdoor condenser. The energy is pumped into or out of the space depending on the need.

Thermal Energy Storage

Society has stored thermal energy extensively for thousands of years. Many HVAC systems use ice or chilled water storage to cool buildings, but is freezing a tank of water really storing energy? The accurate answer is actually no. It's the reverse. To demonstrate, let's go back to basics. In *Figure 2a* you see 1 lb (0.5 kg) of liquid water at 32°F (0°C) and a wooden match burning beneath it.

It turns out that a wooden match, when burned completely, releases about 1 Btu (1055 J) worth of energy, so, by definition, the heat from one match can raise the temperature of a pound of water by 1°F (0.6°C). So, what happens when one has ice at 32°F (0°C)? H_2O goes through a phase change at this temperature. In *Figure 2b*, you see the same 1 lb (0.5 kg) of H_2O, but in solid phase, so imagine 16 one-ounce (28 g) ice cubes at 32°F (0°C). If you burn the 144 matches, and all that energy goes into the ice, all the ice will melt. So as odd as it sounds, melting ice is actually absorbing, and storing, massive amounts of energy. *Figure 3* shows the latent energy storage capacity of a typical thermal storage tank based on water's 144 Btu/lb (335 J/g).

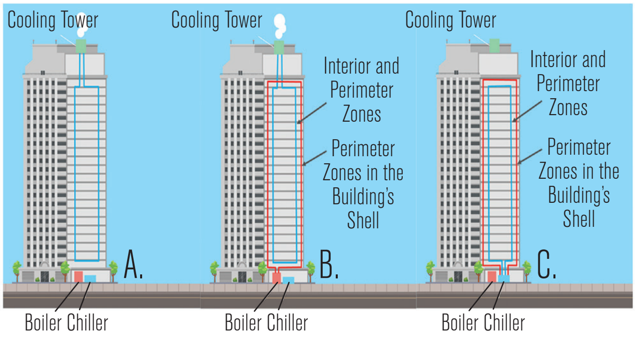
Changing ice to water is not the only way to store thermal energy in association with heat pumps. The most common way is to store it in the ground, with either deep vertical pipes in wells or horizontal fields of buried pipe used to convey the stored heat from above- to

FIGURE 3 Thermal energy storage tank capacity.

One Tank 8 ft 6 in. Tall by 7 ft 6 in. Diameter
1,655 Gal of Water = 13,786 lb
13,786 lb × 144 Btu/lb ~2,000,000 Btu
2,000,000 Btu = ~14 Gal of Fuel Oil
~20 Therms of Natural Gas
~2,000 lb of Steam
~160 Ton-Hours

One New York City Project has 44 Tanks
88,000,000 Btu
616 Gal of Fuel Oil ($1,835)
880 Therms ($1,056)
88 Mlb of Steam ($3,520)
~7,000 Ton-Hours

FIGURE 4 A. "Free" cooling with no coincident heating load. B. Simultaneous heating with boiler and "free cooling." C. Simultaneous heating and cooling with heat pump.



below ground or back. Because of the relatively low sensible heat capacity of the ground, this requires using a large mass of ground and having heat exchange tubing embedded throughout the ground mass. Another option is to put the energy in water, raising its temperature. Because no phase change is involved, either much more water or a very large temperature change would be needed, compared to using the phase change of H_2O as the storage approach.

Free Cooling is Wasting Energy (To the Atmosphere)

During the fall, winter and spring, most large buildings in northern climates use "free cooling" or "waterside economizer cycles" to cool the building's internal zones (*Figure 4a*), which have approximately the same cooling loads no matter the season. (And if you think about it, that makes perfect sense. If you are keeping the people in the perimeter zones comfortable, the internal zones do not experience a seasonal change.) So, this process of "free cooling" takes energy that is being emitted by people and electric devices inside the building and removes it from the air in the space by rejecting (wasting) it to the atmosphere via a cooling tower.

The energy logic of this process being "free" quickly breaks down when, on the same day you are rejecting thermal energy to the atmosphere, you are burning fossil fuels to add energy (heat) to the perimeter zones for portions of the day (*Figure 4b*). When this is evaluated considering the goal of electrification with big heat pumps in buildings to eliminate fossil fuel use, the practice seems illogical.

To meet simultaneous heating and cooling needs in a building, a heat pump can be used to simply pump the energy from one area to another. *Figure 4c* shows a simplified schematic of a building that has simultaneous heating and cooling needs and a standard chiller being used as an energy pump to move excess energy from the core zones to the perimeter zones. This is a very efficient cycle with high heating and cooling COPs, is all electric and is reducing fossil fuel use at the building.

Storing Yesterday's Waste Energy for Tomorrow's Heating

Using a free cooling cycle, by definition, is wasting energy by rejecting it to the atmosphere. This occurs when the daily heating and cooling loads are not simultaneous and balanced. Adding thermal storage to the system can minimize or eliminate this waste of energy in certain types of buildings, having a potential impact on its energy intensity. Thermal storage allows a system to save today's waste energy for tomorrow morning's heating needs.

Figure 5a depicts thermal storage integrated into a building's chiller system. To some it may look like standard piping of an ice storage system, but this system is capable of heating by making ice, and it may be hard to conceptualize. One way to think of the devices is as cells that store thermal energy that will have their

FIGURE 5A Winter cooling only mode (storing excess energy).

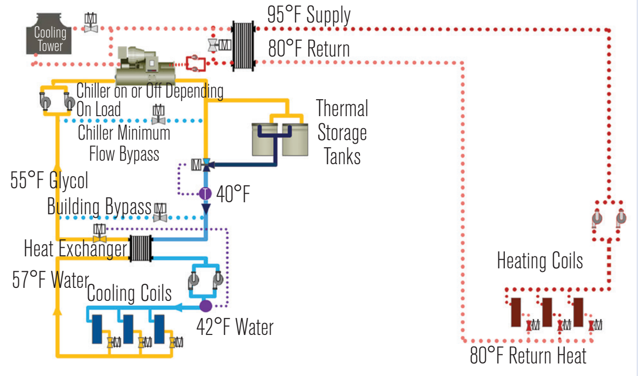
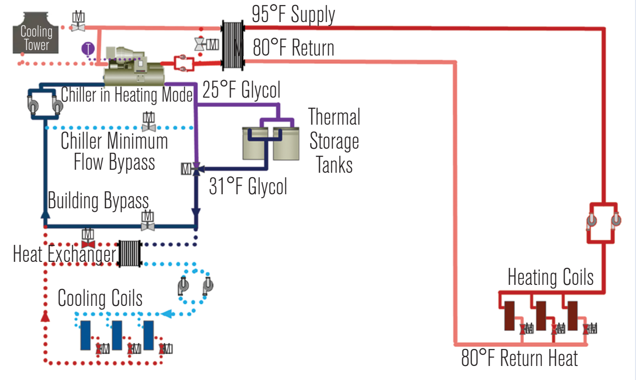


FIGURE 5B Heating with thermal storage (morning warm-up).



energy moved to a usable temperature level with a heat pump.

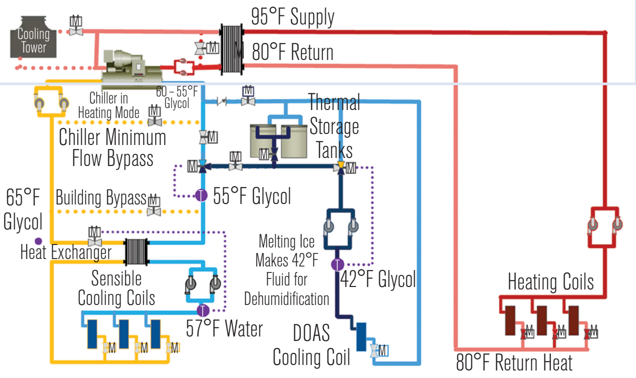
The thermal storage in the low-energy state (all ice) is ready to absorb excess energy, changing ice into water and storing the energy.

On winter afternoons, instead of releasing the building's waste heat to the atmosphere, it can be used to melt ice; in this way the energy is saved for tomorrow's energy needs. In the winter, the goal would be to have all the thermal storage in the high-energy state (all water) by the end of the business day. Each storage tank of water now represents millions of Btus ready to be pumped into the exterior zones of the building for morning warm-up by a standard (water-cooled) chiller at a heating COP of about 5.5 (*Figure 5b*). Removing the energy from the tank of water for heating the building will change the phase of the water to ice, which will be available for the following afternoon's cooling needs. Think of this system in heating mode as a storage source heat pump (SSHP). Your energy is extracted from water in the storage device.

When the building's core has excess energy (it's too warm) and the perimeter zones still need heat, simultaneous heating and cooling (*Figure 6*) by the heat pump (chiller) satisfies the building's load requirements. In smaller buildings, there may not be excess energy during this mode. But in many large buildings, by afternoon cooling will dominate the load requirements, so the winter cooling mode (melting ice and collecting excess energy) starts again.

Also in *Figure 6*, the air side has been modified and is now shown as a dedicated outdoor air system (DOAS), with the latent loads being addressed in the DOAS coils and the sensible loads in each zone's coils. The thermal storage supplies the cold (42°F [5.6°C]) solution to the DOAS coils to dehumidify the air. The chillers, handling just the sensible building load, run at extremely efficient conditions with a 55°F (13°C) supply liquid.

FIGURE 6 Simultaneous heating and cooling mode.



In the summer, when the building has no need for excess thermal energy, the chillers will run at night pumping as much energy out of the thermal storage as possible, rejecting the heat through the cooling tower, so that in the morning they are 100% ice, ready to absorb as much excess energy (heat) as possible during the peak periods, cooling the space and lowering energy costs.

Benefits

Many obvious and some not so obvious advantages exist to having thermal storage integrated into the HVAC systems. These include:

- Helps make electrification possible;
- Reduces carbon emissions;
- Reduces domestic water use;
- Reduces peak energy demand;
- Integrates vital energy storage into buildings;

- Raises source energy temperatures during design ambient conditions;
- Reduces outdoor footprint for outdoor heat pumps; and
- Comparable costs for heating.

Electrification

The current natural gas-based system is rather inefficient when compared to heat pumps: gas-fired boilers have a COP of 0.8, whereas the storage source heat pump (SSHP) system using the phase change of water as the source will be operating at a COP of above 5. (So, for 1 kWh of electrical energy going to the building, the heat pump can move four times that amount of energy from one level to another for a total heating COP of 5). Even factoring a source energy efficiency of the grid of 38%, the SSHP will be more than 200% to 250% more efficient than on-site boilers.

Lower Carbon Emissions

The use of a heat pump whenever simultaneous heating and cooling is needed should reduce carbon emissions. With standard emission numbers from NYC Local Law 97, a heat pump running at a COP of 5.45 has a CO_2 emission of 82 lb versus an 80% efficient gas boiler, which emits 370 lb (*Figure 7*). This is a 78% reduction in carbon on a source energy basis. And when the grid is carbon free, the SSHP emissions go to zero.

A question needing simulation is how much energy is normally wasted to the atmosphere when there are afternoon cooling needs on a cold winter day. This will vary greatly by project, but some things are pretty clear:

- In the early morning on cold winter days, a lot of heating is generally needed at a time when there are not likely to be simultaneous cooling loads in the unoccupied interior zones. So, having stored energy available at that time would be valuable, especially as we move toward electrification of entire cities. Fossil fuels are the "stored energy" of choice at the moment.
- In afternoons, lots of cooling is needed, particularly on the sunny side of an office tower with a glass façade.
- Finally, lots of usable thermal energy leaving a large building exists in the winter if all that has to be done to store it is melt ice. Think of all the energy in the exhaust air and used domestic water, which is above 32°F (0°C), that could be captured by melting ice.

FIGURE 7 Gas heating vs storage source heat pump.

One Thermal Storage Tank Capable of Holding 2,000,000 Btu

Gas – Boiler

- Assume 80% Combustion Efficiency and 5% Loss,* Site to Sources, of Natural Gas
- 2,400,000 Btu delivered to the Building/0.8/0.95=3.15 Million Btu
- 3.15 Million Btu=3,150 kBtu × 0.00005311 tCO_2e/kBtu*=0.167 Tonne CO_2=370 lb CO_2e

Electric – Storage Source Heat Pump

- 2,400,000 Btu Delivered to the Building
- Cooling COP=12/(kW/ton)/3.412
- Heating COP You Add 1.0 to Cooling COP
- 0.79 kW/ton Chiller Has Cooling COP of 4.45 and Heating COP of 5.45
- 2,400,000 Btu/5.45/3,414 Btu/kWh=129 kWh
- 129 kWh × 0.000288962 tCO_2e/kWh* =0.037 Tonne CO_2e=82 lb of CO_2e

82/370 = 78% Reduction in CO_2e

*tCO_2 conversion factors from NY LL97 document

An existing 2.2 million ft^2 (204 387 m^2) project in New York City uses 44 thermal storage tanks for cooling the building year-round, even in the dead of winter. After a few years of operation, the management[1] concluded that using the thermal storage to cool the building in the winter is actually less expensive than using their "free cooling" system. Even on the coldest days, they absorb all 88 million Btu (93 GJ) of energy (melting ice) that would have normally been rejected to the atmosphere with free cooling.

Figure 3 shows the thermal Btu equivalent of those 44 tanks in gallons of fuel oil, therms of natural gas, and pounds of steam (the approximate equivalent local cost of each different form of the energy is also included). On a carbon and cost basis these amounts seem significant enough not to just waste.

Reduces Domestic Water Use

Whenever a cooling tower runs, it loses water through evaporation. Looking back at *Figure 1*, when water goes from a liquid to a vapor it absorbs about 1,000 Btu/lb (2326 J/g), which lowers the temperature of the water left behind. Therefore, the 88 million Btu (93 GJ) in the example (*Figure 3*) that we did not "free cool" away in the cooling tower theoretically saved 88,000 lb (39 916 kg) of water or about 10,000 gallons (37 854 L). While the amount saved will vary depending on the exact wet-bulb temperatures, a green building can save a significant amount of domestic water each day.

Peak Energy Demand Reductions

For the past 30-plus years, thermal storage used for cooling buildings have been sold mainly to provide electric load flexibility to reduce summer peak electric demand, saving money (and source energy and possibly site energy) on electric bills. With the advent of electrification, winter morning warm-up will likely, if it isn't already, become a troublesome (peak) period for many electric grids. Having stored energy available could greatly reduce the amount of energy demand, compared to electric resistance heat, during morning warm-ups with heating COPs that are above 5.

A Clean Grid Needs Energy Storage in Buildings

The need for vast quantities of energy storage is pretty clear with a future grid based mainly on intermittent renewable resources. If you think about it, fossil fuels are forms of stored energy, which has made it easy to dispatch the energy when needed. Since almost no energy storage exists on the grid now, vast amounts of energy storage of all types will be needed to integrate large-scale renewables.

A recent WoodMackenzie[2] report says that by 2025 over eight gigawatts of energy storage will be installed and 25% of that will be "distributed" on the building's side of the electric meter. Two types of energy storage will likely end up in buildings: electric batteries and thermal storage. With the current costs of thermal storage being a quarter to a third the price of electric batteries, a good storage strategy for the customer will be to have electric batteries meet electric loads and thermal storage meet thermal loads. With the availability of thermal storage, using an electric battery to run a compressor to instantaneously cool something is a waste of money, energy and resources. Store the thermal energy instead.

Raises "Source" Energy Temperatures During Extreme Conditions

For decades, conventional air-source heat pumps have been used successfully for heating in the appropriate climate zones. These zones are mainly the temperate zones, because in cold climates the heat pumps drop dramatically in efficiency and capacity. An air-source heat pump running when it is 40°F (5°C) outside may have a COP of ~4.4 at 100% of its nominal capacity. That same heat pump with 14°F (–10°C) air has a ~COP of 2.8 and 40% less capacity (and this is without the defrost cycle factored in). The storage source heat pump system would have a constant source temperature of 32°F (0°C), no matter what the outside conditions are, so the efficiency (COP > 5) and the capacity of the chiller (heat pump) would be consistent and stay high.

TABLE 1 Heating energy costs.[a]

ENERGY SOURCE	UNITS	QUANTITY	APPROXIMATE COSTS
Natural Gas (Boiler)	Therms ($1.26)	12.5 Therms	$15
Fuel Oil (Boiler)	Gallons ($2.98)	9.0 Gal	$26
Steam (Con Ed)	Mlb ($40.00)	0.833 Mlb	$35
Electricity (Resistance)	kWh ($0.25 Incl. Demand)	292 kWh	$73
Electricity (Storage Source HP)	kWh ($0.25 Incl. Demand)	51 kWh	$13

[a] Prices are for general references only. Taken from different online sources (Bls.gov, Nyserda.com, ConEd.com) for New York 2018.

Reduces Outdoor Footprint for Air-Source Heat Pumps

Large outdoor air-source heat pumps need lots of room and lots of heat exchange coils for air to circulate so energy can be extracted or rejected to the ambient conditions. All these outdoor coils are exposed to dirt, dust and snow, which can play a major role in performance, especially snow in cold conditions. In contrast, thermal storage has massive amounts of heat exchange surface area in direct contact with the storage source (water) within the tank. No additional outdoor space is needed for the system other than the existing cooling towers, and no heat exchanger surface area is exposed to fouling in outdoor conditions.

Comparable Costs for Heating

Table 1 is a rough estimate of the costs in New York City for different types of energy sources based on 1 million Btu (1 GJ) delivered and used in the building. Steam and electric resistance are very expensive methods, especially when compared to the direct combustion of fossil fuels at the site. However, because of the high COP of the SSHP system, the cost of heating is comparable or possibly lower than fossil fuels, while meeting the goal of electrification of the building.

Conclusion: Be Thorough in Your Engineering Analysis

Electrification of buildings is a daunting task, and it will take lots of innovations and many types of systems to make it happen. But, just as the electric grid can be made carbon free, we, the heating and refrigeration experts, can make buildings carbon free. While the specific system described in this article applies primarily to large buildings in dense urban environments that have large winter cooling loads (similar to "legacy" commercial office buildings in New York) the integration of thermal storage can be helpful in many other situations.

For example, buildings that have excess solar energy available (whether thermal or PV) can benefit from storing it in thermal storage. And water storage tanks could also be used in a storage source heat pump system if the space is available. In suburban or rural areas, ground source heat pumps may be the better solution because of the land available for ground coils and wells. In all of these cases, wasting energy and water to the atmosphere through free cooling while consuming fossil fuel energy in the same 24-hour period to heat the space can be avoided by combining the use of heat pumps and thermal storage.

To the layperson, the term coefficient of performance seems incomprehensible, and the idea of putting in one unit of energy and getting out three to six times that energy seems beyond wishful thinking. But to an HVAC engineer, it is just plain thermodynamics. Likewise, getting energy to heat a building by turning cold water into ice may seem entirely backwards, but it is just plain thermodynamics. Very helpfully, Mother Nature has supplied an essentially free and drinkable material that can be used to store large amounts of energy at a temperature almost perfect to meet the comfort needs of people, and our ingenuity can enable us to do this without raising detrimental environmental issues. Water is indeed an excellent phase change material for helping solve some of the critical energy storage needs in moving toward a sustainable future.

References

1. Jerman, R. 2019. Chief Engineer, Royal Realty. Personal Conversation.

2. WoodMackenzie. 2020. "U.S. Energy Storage Monitor: 2019 Year-In-Review." ■

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