Design Brief: Time Independent Energy Recovery (TIER) Plant

December 29, 2020

Taylor Engineering has developed a new all electric HVAC design concept for large commercial and mixed-use buildings (e.g. ≥150,000 ft^2) that addresses key shortcomings with existing all-electric options related to energy efficiency, costs, and spatial requirements.

State of the Market

There are currently 3-primary options in the market for generating heat using electricity for large buildings:

- Air-source heat pumps, which generate hot water using heat extracted from ambient air via the vapor compression refrigeration cycle;
- Electric boilers, which rely on electric resistance heat to generate hot water; and
- Wire-to-air electric resistance coils, which are typically used at the zone level in terminal units such as VAV and fan-powered boxes.

Each of the above options is fraught with one or more major challenges related to equipment cost, spatial constraints, energy efficiency, and carbon emissions.

Air-source heat pumps are probably the most carbon-friendly option on the market since they can achieve heating coefficients of performance (COPh) above 2. In Santa Clara, CA where the design heating temperature is 29°F, one market leader's product yields a COPh of approximately 2.1 when generating 120°F water at design ambient. Air-source heat pumps are however very expensive per unit capacity and, because they use ambient air to extract heat, require multiple units with large footprints to generate heat at scale. We recently peer reviewed and subsequently took over the design of a 1.1MM sqft office campus where the original engineer used ten ASHPs, each with a footprint of 8'x32', to generate heat for the campus. On large high-rise projects, it can be nearly impossible to find sufficient roof space for ASHPs.

The use of multiple units in large installations necessitates costly piping and controls for each unit. Most, if not all, ASHPs on the market also require individual primary pumps *per unit*, adding further to first costs. ASHP plants are also likely to experience higher ongoing maintenance costs than other plant options because of the quantity of devices involved and the complexity of the equipment itself. Each ASHP typically has 4 to 6 scroll compressors, at least 2 refrigeration circuits, and multiple condenser fan motors, increasing the likelihood of some device failing or requiring service.

One apparent benefit of ASHP designs is that ASHPs can switch to cooling mode in the summer, thereby reducing the size of the cooling plant serving the same building and offsetting some of the first cost from the ASHPs. Unfortunately, ASHPs are not particularly efficient in cooling mode, commonly yielding EERs of around 10 (1.2 kW/ton) at AHRI conditions. Contrast this with a well-designed water-cooled chiller plant, which even after accounting for condenser water pumps and cooling towers, will operate at less than 0.65 kW/ton at design conditions. This reality makes it almost impossible to comply with current Title 24 when replacing water-cooled plant cooling capacity with ASHP capacity btu/h-for-btu/h. On one recent project where we used AHSPs, we were able to use part of the available ASHP capacity to provide 30% of the design cooling plant capacity, but no more, or else risk not complying with code, and also increasing energy costs.

The resistance based electric heating options, boilers and wire-to-air coils, do not present the same spatial or mechanical first cost challenges as ASHPs. Relative to ASHP plants, which are typically limited to supply temperatures of around 120°F, electric boilers can generate 160°F to 180°F like conventional natural gas boiler plants, and thus can benefit from the higher hot water delta-Ts and smaller pipe and pumps sizes resulting from this design strategy. The primary benefit of zone level electric resistance heating coils on the other hand is that they entirely eliminating parasitic pipe heat losses inherent to all water based designs, which preliminary research indicates can be as high the actual amount of heat needed to heat the space.

Both electric resistance design strategies are however limited by thermodynamics to a peak COP of 1. Consider further that the PG&E grid (for those practicing in Northern California) is not particularly clean in the early morning when heating systems peak, and it becomes clear that resistance heating options are likely to remain worse than natural gas boilers on a carbon basis in at least the near term. Electric resistance options can also present new challenges to electrical engineers by making buildings heating-peaking instead of cooling-peaking, although that is still unlikely in our mild bay area climate. Perhaps most importantly in California though, these options do not comply with current Title 24 prescriptively and it is all but impossible for them to comply on a performance basis unless a variance is granted by the Authority Having Jurisdiction.

The current market options therefore present owners with two mediocre options: either accept the spatial requirements and first cost adds inherent to ASHPs, or choose an electric resistance option that is unlikely to comply with code without a variance, and will yield worse carbon performance than a natural gas boiler plant for the foreseeable future.

Alternatives

An alternative to the existing paradigm would ideally take up less space than an ASHP heating plant, while bettering its efficiency too. A common approach to solving the efficiency problem is to use heat recovery chillers, but they only solve the efficiency problem on a *part time* basis and typically not when heating loads are the highest. Heat recovery chillers absorb heat from a chilled water loop and typically reject heat to a hot water loop. The *part time* qualifier arises because this scheme is only viable when there are simultaneous heating and cooling loads. When heating loads are high (e.g. on a cold winter day or during morning warm-up) there is typically little or no cooling load because airside economizers can provide all the cooling needed. For a well-designed office or school building in the Bay Area using ASHRAE Guideline 36 sequences, there is almost no simultaneous heating and cooling. However, when heat recovery is viable, heating can typically be done with a COPh of 4 to 5 when the chilled water supply temperature is ~42°F and the HWST is ~125°F.

The time dependency issue present with heat recovery chillers has been solved by some designers using geothermal systems, wherein heat absorbed from the building is rejected to the earth, and then heat needed to warm the building is pulled back out of the earth. This strategy is not without its own issues though as geothermal fields at scale are extremely expensive and prone to temperature degradation over time when the annualized heat rejection and absorption rates to/from the field are not reasonably balanced. Fields are invariably unbalanced in cooling dominated climates like California's, where the outcome is often that cooling towers are retrofit into the plant at some point after project completion once the field has degraded too significantly to be used for heat rejection.

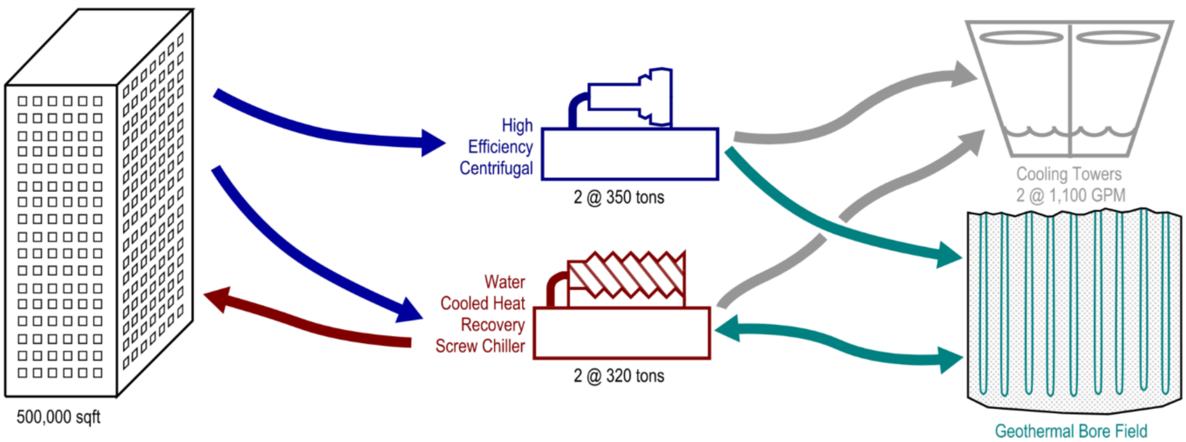

Figure 1. Direction of Heat Transfer with a Geothermal System

TIER

An optimal solution would allow the use of water-to-water chillers to perform heat recovery on a *time independent* basis as is done with a geothermal system, while avoiding the costs and temperature degradation inherent to the geothermal design. With this goal in mind, we developed the concept of a Time Independent Heat Recovery (TIER) Plant, which conceptually replaces the geo-field with a relatively small condenser water thermal energy storage (TES) tank.

The TIER plant takes heat rejected from cooling loads via high efficiency, low lift, centrifugal chillers and typically stores it in a TES tank at tepid temperatures between 60°F and 80°F, though excursions down to 40°F are allowed on peak heating days as is discussed subsequently. When energy is then needed for building heating, heat is extracted from the tank using water-to-water heat recovery chillers. In effect, the cooling chillers and heat recovery chillers are placed in a cascade configuration: the cooling chillers have a lift envelope of 40°F CHWST to 80°F CWRT, while the heat recovery chillers have a lift envelope of 60°F CWST to the active hot water supply temperature setpoint (e.g. 125°F).

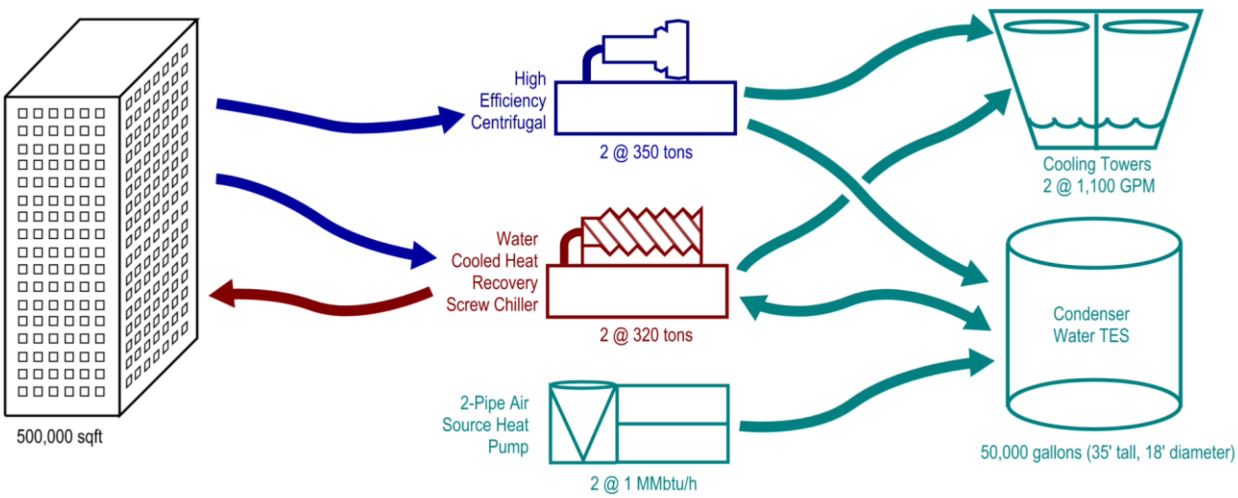

Figure 2. Direction of Heat Transfer with a TIER System

During most days in California's mild, highly populated climate zones, the energy recovered from cooling loads alone can satisfy heating loads. During the small fraction of the year when heat recovery alone cannot satisfy heating demand, ASHPs are used to charge the storage tank. Critically, because the storage tank allows load shifting, the amount of ASHP capacity required for this strategy is only a small percentage of the capacity required in a conventional ASHP plant. In the example 1.1MM sqft project mentioned previously, the number of air source heat pumps required for the project was reduced from 10 to 2 when the plant was redesigned using a TIER concept.

The TIER design is an innovative solution for a few critical reasons:

Spatial Requirements

While TES designs are often thought of as space intensive, the TIER solution is a space saver relative to an ASHP plant. This is because the stratified TIER tank is relatively small for a TES tank. In contrast to a conventional TES tank sized for design cooling day constraints, the TIER tank is sized for design heating day constraints, and design heating loads are significantly lower than design cooling loads in California's climate zones. Additionally, while a conventional TES tank's capacity is limited to the delta-T of the loads it serves (typically ~20°F to ~24°F for CHW tanks), the TIER tank serves as a source for heat recovery chillers, so it can have a much higher delta-T. While the tank is intended to operate with a 20°F delta-T between 60°F and 80°F on most days to minimize the lift overlap and thereby maximize efficiency in the cascading chiller configuration, on design heating days, the tank can cycle through one more time down from 60°F to 40°F. The overall delta-T with the TIER design is therefore 40°F, allowing for a compact tank.

A 500,000 sqft building in Santa Clara that might require five (5) ASHPs, each requiring 36'x16' when accounting for clearance zones, is instead likely to require only one (1) ASHP (though 2 smaller units might be provided for partial redundancy) and a 50,000 gallon, 35' tall, 18' diameter TES tank that could reasonably be located in a 3-story parking garage.

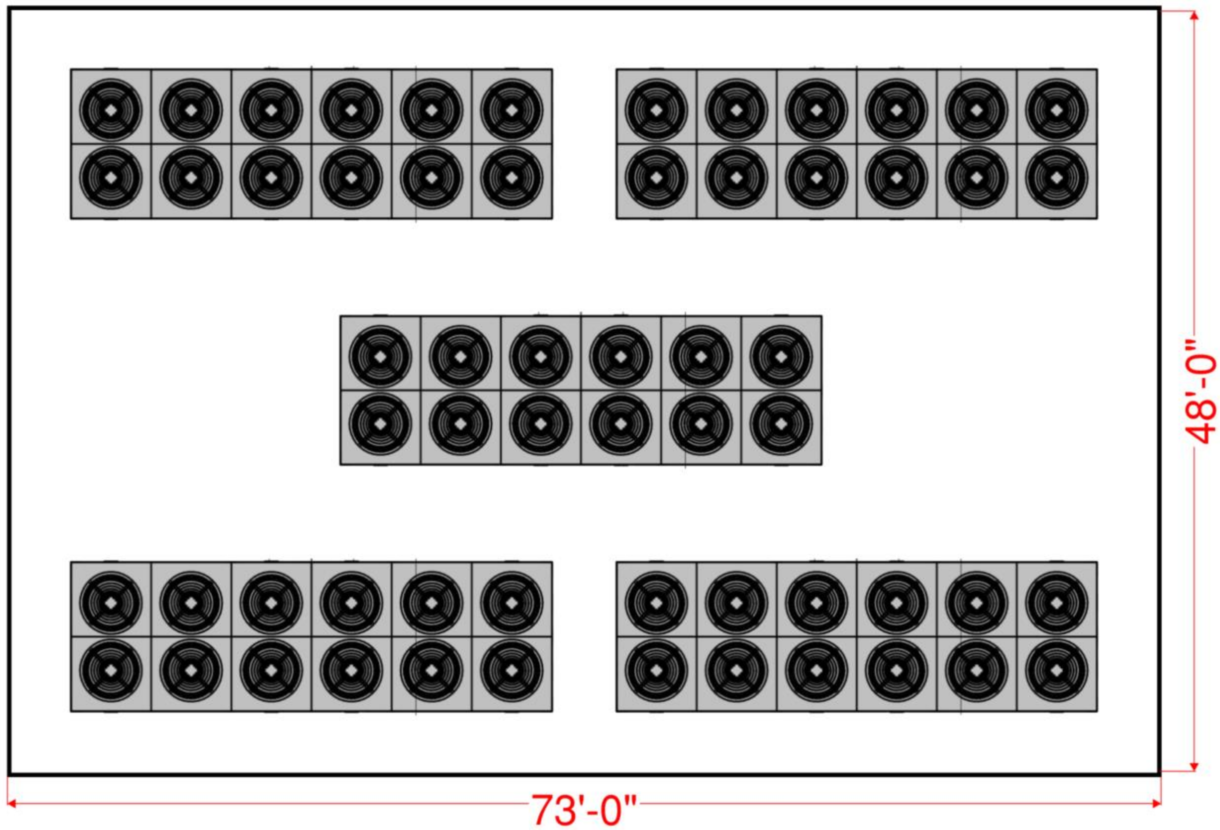

Figure 3. 500,000 sqft Building Conventional ASHP Farm

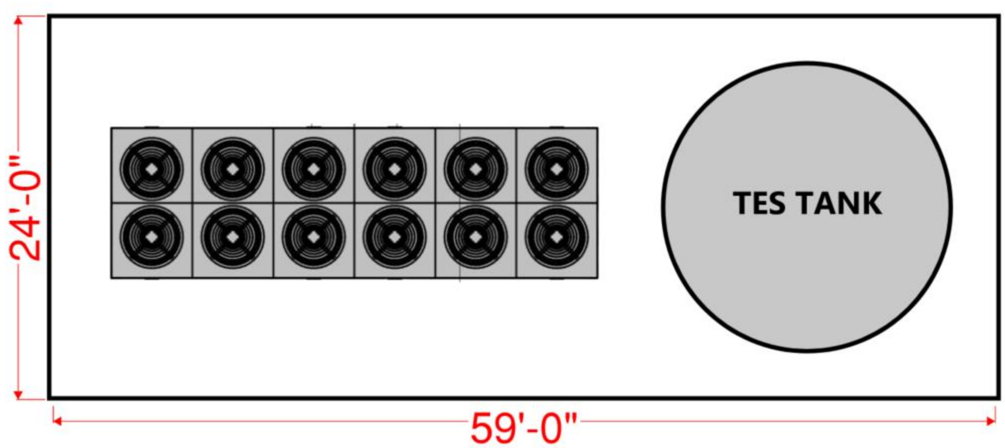

Figure 4. 500,000 sqft Building TIER TES Tank and ASHP Alternative

In high rise use cases we have evaluated thus far we have found the TES tank is smaller than that required for fire water storage, and we are in fact investigating using a fire water tank for dual purposes on a project at this time.

Efficiency

The TIER solution is significantly more energy efficient than a conventional ASHP plant. Consider first that the part load cooling efficiency of a typical variable speed centrifugal chiller that would be used to cool the building and charge the TES tank in a TIER design is on the order of 0.35 kW/ton; this corresponds to a COPh of 11. The COPh of heat recovery chillers boosting water from 60°F to 125°F would be approximately 5. The cascaded COPh is therefore roughly 3.7.

$$COPh_{Cascade} = \frac{1}{\frac{1}{COPh_{heat\ recovery\ chiller}} + \frac{1 - \frac{1}{COPh_{heat\ recovery\ chiller}}}{COPh_{cooling\ chiler}}}$$

Contrast this to the COPh of one representative ASHP product, which varies from 2.1 at design ambient conditions (32°F) to 3.1 under more mild ambient conditions (59°F) when supplying 120°F water. Perhaps most importantly, any cooling energy extracted from the building and stored in the TES tank for later or concurrent heating use is effectively free.

Note that on a design day, when the ASHPs are charging the TIER tank with tepid 80°F water, their COPh will increase to approximately 3.75, yielding a cascaded COP of 2.4. In other words, even on a design day when both the ASHPs and heat recovery chillers are operating, the TIER design will still yield superior energy efficiency.

Cost

TIER designs are cost effective. Because water-cooled chillers (typically 250 to 400-ton screw chillers or larger centrifugal machines) are used as the primary heating machines, they can efficiently serve double-duty as cooling machines for the plant. For instance, in a plant with 2 cooling-only chillers and 2 heat recovery chillers, on a hot day one of the heat recovery chillers can swing to cooling duty and operate in parallel with the cooling chillers; on a design cooling day, both heat recovery chillers can swing to cooling duty. Owners therefore avoid paying for nearly as much redundant tonnage as they do when usage a separate ASHP plant for heating. In effect, a TIER design swaps out multiple ASHPs for a TES storage tank and converts cooling only chiller capacity—which already needed to exist for cooling duty—to heat recovery chiller capacity.

Preliminary pricing from the 1.1M sqft project discussed previously shows the conversion to TIER will yield *mechanical equipment* savings on the order of $900,000. These savings do not account for the electrical, controls, piping, or opportunity cost savings from reclaimed space that will result as well. The TIER redesign replaces 8 ASHPs, each costing $230,000, with one TES tank costing $960,000. Chiller cost per ton is surprisingly lower for the heat recovery machines in this plant than the cooling-only machines, showing that large heat recovery chillers are not necessarily more expensive than their cooling-optimized counterparts.

TIER saves space, improves energy efficiency, and reduces costs relative to a conventional ASHP plant, making it an all-around win for owners and the environment.

More About Taylor Engineers: Founded in 1995, Taylor Engineers is a nationally recognized engineering firm specializing in mechanical systems design and construction, energy conservation, indoor air quality, controls, and system commissioning. Taylor Engineers specializes in cost-effective and innovative solutions that are designed from the start with construction and operation in mind. Complementing our engineering expertise, Taylor Engineers employees have extensive field experience including mechanical contracting; control system installation and operation; HVAC system monitoring, measurement and evaluation; and site auditing. Our cutting-edge design is informed through our involvement in energy and indoor air quality codes and standards, building science research, and the development of state-of-the-art simulation tools.