“In a molten salt Power Tower all of the thermal energy, but more importantly all of its exergy—a term that defines the amount of useful work that can be extracted from heat at a certain temperature—can be stored and recovered”.

Arnold Leitner, founder and former CEO of SkyFuel Inc., discusses the nature of molten salt storage in Power Towers.

Previously in this series we have discussed that parabolic trough plants with oil as the heat transfer fluid (HTF) are not as effective as high-temperature molten salt systems of power towers in storing thermal energy because of the rather low 100°C temperature gap between the hot and cold molten salt storage tanks. With oil removed and molten salt introduced as a HTF both parabolic trough and its Fresnel cousin, the linear Fresnel collector, can overcome this limitation by moving to 550 degree Celsius.

The Enel-owned molten salt demonstration parabolic trough solar field in Priolo Gargallo, Sicily, which provides about 5 megawatt of electric power to an existing power plant reaches 550°C and has 8 hours of full load storage. The molten salt parabolic trough is an Italian-born design developed at the research center ENEA (Italian National Agency for New Technologies, Energy and Sustainable Economic Development) and, in fact, a new tariff is now in place in Italy specifically incentivizing molten salt parabolic trough plants. The tariff caps the deployment of such systems with storage at about 600 megawatt of aggregate capacity by 2017. However, other companies are working or have worked on parabolic trough or linear Fresnel systems with molten salt.

Detractors of molten salt parabolic trough systems will point to two drawbacks of this system over a molten salt power tower. The primary concern is the chance of a molten salt freeze-out in the 50-150 kilometers\(^1\) of receiver lines and header pipes that a large solar field has. The second argument is that it is much harder to get to these high temperatures using a line concentrator—whether parabolic trough or linear Fresnel—especially in not so perfect solar resource areas, because of the low concentration ratio. Another way of phrasing this is that high temperature results in lower efficiency of the parabolic trough collector due to the higher heat losses.

The problem of power towers is, of course, that they stand tall like towers with huge visibility. That may be acceptable in the American Southwest or on Arabic peninsula, but not so much in Italy or, say, India.

\(^1\) For example, for a 50 MW\(_e\) parabolic trough plant with 7 hours of full-load thermal energy storage, which has a solar multiple of about 2 x, there are 100 kilometers of receivers; a 125 MW\(_e\) project without storage, such as one of the Genesis projects in California proposed by NextEra Energy, have about 140 kilometers of receivers.
Let’s return to the concentrating solar power systems that can reach high temperatures with much ease and are thus “made for storage”: power towers. The de facto standard for thermal energy storage is the two-tank molten salt storage system and in towers there are two heat transfer fluids (HTFs) in commercial use—water and molten salt. It is worthwhile to understand and discuss the marriage of both HTF to a molten storage system.

The feasibility of molten salt storage for a molten salt power tower is self-evident. Through an oversizing of the solar field and receiver capacity relative to the maximum thermal energy the steam turbine generator can use, molten salt power towers can easily have 8 hours of full load storage. In fact the 20 megawatt GemaSolar power tower in Spain designed by SENER has 15 hours of full-load storage and the 110 megawatt Crescent Dunes (formerly named Tonopah) power tower in Nevada designed by SolarReserve has 10 hours of storage.

First, it is important to understand that to have eight hours of full load output the solar field and solar receiver have to be at least twice as big as if there was no storage. In effect half the tower and solar field collect and store energy while the other half produces instantaneous power.

In a molten salt power tower all of the thermal energy, but more importantly all of its exergy—a term that defines the amount of useful work that can be extracted from heat at a certain temperature—can be stored and recovered. Setting aside some minor heat losses on the way to and during the time in storage and some pumping work, a molten salt tower can run out of the storage system as efficiently as when it operates directly. This is because there is ultimately no difference whether the hot molten salt first does a detour through the storage tank or is directed directly to the steam generator.

The second lesser known characteristic of molten salt power towers is that they can store heat during times of low solar radiation when the tower would not be able to generate enough high temperature (i.e. higher than 500°C steam to run the turbine directly (that is without drawing energy from storage). Normally as long as there is a shadow—the amateur solar engineer’s “measure” of the amount of direct normal radiation (“DNI”) in the sunlight—which is around 375 Watt per square meter of DNI, we typically think of CSP being able to collect heat. As it turns out a power tower can produce 500+ degree temperature molten salt even at half that value because of its high concentration radio of over 1,000 suns. In that situation the power tower will try to reach 565°C and send heat into the high temperature storage. If at minimum required molten salt flow rates the temperature cannot be held above 565°C the lower temperature molten salt will used to warm up the “cold” storage tank above is nominal 290°C.

Regardless of the approach the key observation is that a molten salt power tower can harness energy for later use even if it could not instantaneously run on the power of the receiver. With storage in place, this means that the a molten salt power tower can collect more energy which results in higher capacity factor—the ratio of average power to peak power—than one would have expected.
Third, without storage at sunrise the rate at which the turbine output can rise is limited because of thermal stresses and it is usually lower than the rise of the sun’s radiation. This means that part of the sun’s energy cannot not be converted to useful energy. This is not a negligible daily loss. This effect is, however, lower with storage capacity systems which at times even allow for a continuous operation of the steam turbine during portions of the year.

Simplicity in operations has its price, though, which is that 565 degrees and the associate steam cycle efficiency of 42-43%—measured as net electrical power/instantaneous receiver power and not diverted to storage—is all that you going to get. Direct steam generation towers don’t have that limitation and BrightSource’s 3rd generation “supercritical”, 620˚C 260-320 Bar power tower can reach 47-48% of efficiency or about 10-15% more—when running directly on steam.

When operating out of storage such a supercritical power tower would need to run subcritically due to the limit of the salt temperature at about the same overall efficiency as the molten salt tower.

But adding molten salt storage to a direct steam molten salt power tower is tricky and ultimately doing so means accepting significant compromises. The reason for this fact is that water at some temperature and pressure condenses and at that point it does not change temperature until all steam has turned to liquid. That causes a problem in heat transfer and it can be seen by studying a temperature-enthalpy diagram of water and molten salt. But seeing the diagram may not necessarily mean understanding the problem for most readers, so we jump to more practical description of the problem and its attempted solution.

In short, if a direct steam, 565˚C power tower used a counter-flow heat exchanger to heat molten salt; it could store all of its energy, but only at a temperature of below 400˚C. All energy is utilized but a lot of exergy is lost, because the highest temperature is now 400˚C not 565˚C. In other words, when running out of storage the steam cycle would be much less efficient. One may as well just add an oil-based parabolic trough solar field next to the direct steam generation power tower and let it charge the storage.

One obvious work-around to the problem of water’s condensation is to only use the heat of the steam above the applicable condensation temperature. In other words this approach takes the cream off the milk, but does not use the skimmed milk. This works great and all exergy is preserved, but only one quarter of the towers energy can be put into storage. So if on average a power tower collects energy for 8 hours then with this design the storage amount is limited to 2 hours of storage. The remainder, 75 percent of power, needs to be used instantaneously.

Two hours of storage may work for many electricity markets, but this is certainly not the vision of the around-the-clock baseload power towers. It also adds a high pressure steam-to-molten salt heat exchanger to the power tower which takes away original, purist
advantages of direct steam power towers—namely that the HTF and the working fluid are the same and thus that there is no need for a heat exchanger.

To go beyond the limit of only being able to store a quarter of the energy BrightSource has proposed a three-tank molten salt storage system, which adds a medium temperature storage tank. This adds another tank and a lot of salt, because the mass-weighted average temperature “delta” of the system is only 100˚C. While that figure and required mass is the same for an oil-to-molten salt storage system, there is some thermodynamic benefit in this 3-tank design as some of the hot salt is “hotter” than for the parabolic trough plant and thus the exergy—i.e. useful work that can extracted—is still higher. In other words, this storage system is more efficient. There is in principle no more limit of how much of the energy can be stored as in the simply counter-flow heat exchanger.

Contrast this to the simplicity of the molten salt power tower with molten salt storage and it begs the question if storage—especially with more than 2 hours of full load storage—are worth it for direct steam generation plants. The storage becomes better for supercritical direct steam generation power towers, simply because the “milk” becomes fatter and the ratio of cream to skimmed milk increases, but it does not come close to a molten salt power tower which with storage can even harvest more energy than without it—as discussed above. In other words its energy capture ratio actually (again neglecting losses to and in storage) increases above 100%. Now, anything more than 100% is always something to love.