ENERGY STORAGE:
A Clear Need for the Power Grid –
But How Best to Achieve It?

A White Paper
Prepared by the
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The Turbine Inlet Cooling Association (TICA) is a non-profit organization that promotes the development and exchange of knowledge related to gas turbine inlet cooling (TIC) for enhancing power generation worldwide.

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EXECUTIVE SUMMARY

- The recent and continuing growth of intermittent renewable power generation (often out-of-phase with peak power demand) is increasing the value of, and need for, Energy Storage.
- Energy Storage is available in various technologies, each with advantages and limitations for addressing certain power grid challenges.
- Batteries (whether traditional or advanced) provide value for frequency control and short-term storage. However, batteries have serious drawbacks including limitations for multi-hour storage applications, high unit capital costs, short life expectancy, environmental disposal concerns, and other issues.
- Thermal Energy Storage (TES) is a particularly attractive and mature technology for multi-hour storage applications, with attributes which include long life expectancy, high energy efficiency, and low unit capital costs.
- In particular, large Chilled Water (CHW) TES provides extremely low unit capital costs:
    - $/ton-hr which are lower than other Energy Storage options, and
    - $/ton which are lower than those of equivalent chiller plants.
- Turbine Inlet Cooling (TIC) provides valuable benefits:
    - Higher CT power outputs during hot weather times of peak power demand and value, and
    - $/kW below those of the most economical simple cycle or combined cycle CT power plants.
- Combining large CHW TES with TIC provides even greater benefits:
    - even higher power outputs during times of peak demand and peak power value,
    - $/kWh which are lower than other Energy Storage options, and
    - $/kW which are even lower than other peaking power generation options, including non-TES chiller-based TIC. Adding TES to TIC often reduces net capital cost, resulting in achieving the benefits of Energy Storage at a negative capital investment.
- Numerous Case Studies of TES-TIC illustrate longevity, award-winning technology, large-scale applications, customer satisfaction (through repeat installations), and extremely low unit capital cost.

<u>Conclusions</u>

1. Though batteries undoubtedly have a useful role to play as storage for the electric power grid (and for microgrids), they should not automatically be the default choice of energy storage for all applications.
2. Particularly for large, multi-hour storage applications, Chilled Water (CHW) Thermal Energy Storage (TES) should be considered, as its unit capital cost, round-trip energy efficiency, and life expectancy are clearly far superior to those of batteries.
3. CHW TES should be applied for demand-side applications of air-conditioning or process cooling, most especially when implemented at times of necessary investments in cooling capacity.
4. Turbine Inlet Cooling (TIC), complemented by CHW TES, should be applied in supply-side (power generation) applications, for both new and existing, Simple Cycle and Combined Cycle, Combustion Turbine power plants. CHW TES-TIC will maximize hot weather, high-value, peak power output, and do so at very low unit capital cost (in $/kW), while also providing Energy Storage at very low (even at an effectively negative) net unit capital cost (in $/kWh).

INTRODUCTION – THE NEED FOR, AND VALUE OF, STORAGE

Most systems, whether in nature or man-made, incorporate some form of storage as useful or necessary. Examples include:

- organs in the body humans and animals, such as the stomach, spleen, bladder, and brain,
- domestic water storage and wastewater storage tanks in a municipal water district,
- the fuel tank in your car,
- the battery in your laptop computer and cell phone,
- the water tank in your home's hot water heater, and even
- the ice cubes in your cold drinks.

The electric power grid (as well as microgrids) would also benefit greatly from having storage. However, it has long been seen as a challenge to provide grid storage in a widespread and economical way. And the value of grid storage continues to grow for the following reasons:

1. The implementation of air-conditioning has driven the growth in peak power demand, while widening the gap between peak and base-load demand.
2. Time-of-day differentials have risen in the power plant fleet's marginal heat rates, emissions, and electricity cost and value.
3. Short-term temporary back-up power is needed for unexpected interruptions in grid power.
4. And now, there is the rapidly expanding deployment of renewable power resources (wind and solar) which are highly intermittent and even out-of-phase with the demand for power.

Thus storage has become a recognized essential need for the grid, and more so as yet additional renewable resources are mandated and implemented. With little or no storage in the grid now, the problems have already become quite apparent, for example:

- In Texas, due to nighttime periods when the combination of excessive wind power production added to the remaining base-load nuclear and coal power generation assets (which cannot economically be throttled) far exceeds total grid demand for power, short-term pricing of electric energy plummets as low as negative $0.10/kWh on many nights, while the pricing explodes to several dollars per kWh during high demand daytime periods.
- In Nebraska, also related to excessive nighttime production of wind power, electricity pricing has been as low as negative $0.20/kWh.
- In California, negative energy pricing has also become common due to high levels of intermittent solar power and the resultant "duck curve" of the electric grid.

Data from the Electric Reliability Council of Texas (ERCOT), which manages the Texas electric power grid, has illustrated that at the time of day when the electric grid is experiencing its peak demand for power, wind power assets are very typically producing a scant 20% of their nameplate ratings. Other parts of the country typically exhibit similarly low wind production at critical peak demand times. Effectively, the already high, reported unit capital costs of subsidized wind power generation (often $2,000 to 3,000/kW) are effectively five times those values (or an astronomically high $10,000 to $15,000/kW) if rated at their average effective output at times of peak power demand on the electric grid.

In the summer of 2017, ERCOT experienced a record instantaneous peak demand of approximately 70,000 MW. At that time, the ERCOT grid had connected wind power plants with a total nameplate capacity of roughly 23,000 MW. However, at the time of peak demand, the actual output of all the connected wind power plants was less than 600 MW, or only about 2.5% of their rated capacity. Essentially, in spite of all this mandated and expensive, tax-payer-subsidized renewable power plant capacity, it failed to yield any significant reduction in the need for conventional power generation assets.

Thus, a massive application of Energy Storage is necessary in order to take full advantage of existing, intermittent renewable power assets, and to justify the continued growing implementation of yet more such renewable power. But how is that Energy Storage element best added to the grid?

STORAGE TECHNOLOGY OPTIONS

Many technologies can be used for Energy Storage, some mature and proven, others in various stages of conception or development. Each technology has its own advantages and limitations for various storage applications.

Pumped Hydroelectric Storage

Traditionally, the most significant storage technology employed in the electric grid has been Pumped Hydroelectric (PH) storage. PH is a very large-scale technology, with a many decades long history of application, well-suited to multi-hour storage, and with an extended life expectancy. However, it has only limited siting possibilities, an extremely challenging and lengthy permitting/construction schedule, relatively low round-trip energy efficiency, and moderately high unit capital cost.

Electrochemical Battery Storage

Mature battery types include Lead-Acid and Sodium-Sulfur. Advanced batteries include Lithium-Ion (Li-Ion) and many other types. Batteries are compact (high energy density), relatively easy to site, quick to install, and quite flexible in terms of rapid charge and discharge capabilities. However, they have only moderate round-trip energy efficiency, very limited life expectancy, potential costly hazardous material disposal issues, and high unit capital cost (even though costs have been dropping). Also, some particular battery technologies require rather exotic materials (from not the most stable sources) and pose safety concerns (fires and/or explosions).

Mechanical Flywheel Storage

Mechanical flywheel storage is under development, yet to be fully commercialized. It offers flexibility in siting, rapid responsiveness (quick charge/discharge), quick permitting/construction schedules, relatively high round-trip energy efficiency, and a fairly long projected life expectancy. However, Flywheel Storage has some structural safety issues (leading to scaling limitations) and extremely high unit capital costs (likely to limit the technology to shorter duration applications, rather than multi-hour ones).

Compressed Air Energy Storage

Compressed Air Energy Storage (CAES) has been in the development for many decades. There have been two utility-scale pilots in operation for over 20 years, one in Germany and one in Alabama in the USA. CAES has attractive reported "target" unit capital costs and an extended life expectancy. However, as is the case with PH, CAES has only limited siting possibilities, a challenging and lengthy permitting/construction schedule, and relatively low round-trip energy efficiency.

Table 1 – Comparison of Energy Storage Options

Typical Characteristics	Pumped Hydro	Traditional Batteries	Advanced Batteries	Mech'l Flywheels	Compr'd Air ES	CHW TES
Maturity Status	**excellent**	**excellent**	dev'mental	dev'mental	dev'mental	**excellent**
Safety Issues	medium	**low**	yes	yes	medium	**low**
Flexibility of Siting	very low	**very high**	**very high**	**high**	very low	**high**
Ease of Permitting	difficult	simple	simple	medium	difficult	simple
Overall Schedule (yrs)	10+	**1 to 2**	**1 to 2**	**1 to 2**	3 to 5+	**1 to 2**
Dispatchability	good	**excellent**	**excellent**	**excellent**	good	temp lmtd
Round-trip Efficiency (%)	70 to 85	80 to 90	80 to 90	90	70 to 80	**near-100**
Expected Lifetime (yrs)	**40+**	7 to 15	7 to 10	20	**40+**	**40+**
Hazardous Disposal Issues	**low**	medium	high	**low**	**low**	**low**
Secure Material Sources	yes	yes	shaky	yes	yes	yes
Unit Capital Cost ($/kWh)	moderate	very high	high	extreme	moderate	**low**

Table 1 provides a simplified accounting of the typical inherent characteristics of all those storage technologies, as well as the characteristics of large Chilled Water (CHW) Thermal Energy Storage (TES). As shown, CHW TES rates very well versus the alternative storage technologies, for a variety of reasons specific to each technology comparison. The only serious limitations to CHW TES are that it:

1. has relatively low energy density (in ton-hrs/gallon or kWh/ft3),
2. is less economical in small capacities,
3. is not easily capable of being fully charged or discharge in minutes, and
4. can only be discharged when there is a nearby cooling load.

However, these limitations are not significant when considering utility-scale, multi-hour storage applications. Nevertheless, the electric utility marketplace has been turning quickly and increasingly to battery storage, primarily to Li-Ion batteries. Though this is not without its reasons, it also has some serious drawbacks, worthy of caution.

BATTERY STORAGE – ADVANTAGES AND LIMITATIONS

Batteries provide several characteristics which make them attractive as grid Energy Storage. Accordingly, they are often the chosen technology, without consideration of other options.

Advantages

- Energy Density – Batteries are high in energy density, and thus compact.
- Siting Flexibility – Almost any location is a candidate site for batteries.
- Installation Schedule – Permitting, procurement, and installation schedules are relatively rapid.
- Responsiveness to Load – Batteries can be capable of being discharged and recharged quite rapidly.
- Multi-function Capability – Batteries can serve one or more functions, including: frequency control, load following, peak shaving, and load shifting.

But after taking a closer look at other characteristics, batteries pose various challenges and serious drawbacks, even for Li-Ion batteries which are the most prevalent type being applied commercially at the present time.

Limitations

- Energy Efficiency – Round-trip energy efficiencies are typically listed in the range of 80% (to 90%), depending on the type of battery and the depth of charge/discharge per cycle. Tesla reported that its highly publicized Li-Ion installation in the South Australia grid had an output of 2.42 GWh from an input of 3.06 GWh for the entire month of December 2017, an efficiency of only 79%.
- Material Sourcing – They require exotic, costly materials, e.g. Lithium-Graphite anodes and Nickel-Manganese-Cobalt Oxide (NMC) cathodes in Tesla's Li-Ion daily-cycle application batteries). And these materials are primarily sourced from potentially unreliable locales, e.g.70% of Graphite from China, and 70% of Cobalt from the Congo, China, and Russia.
- Safety and Environmental Issues – Li-Ion batteries have a cautionary history of explosions and fires in operation, adding regulations, restrictions, and costs to potential application sites. In addition, the mining and refining steps, associated with the sourcing of some of the exotic materials from their diverse locales, pose serious concerns of environmental damage.
- Material Disposal – The compound mix of hazardous, heavy metal components makes frequent end-of-life recycling/disposal a very complex and costly endeavor (or else a long-term hazardous waste issue, if installations are simply abandoned in-place).
- Life Expectancy – Various battery types are listed as having a lifetime of 7 to 15 years (or only 7 to 10 years for some, including Li-Ion); and the number of charge/discharge cycles has an impact on life, such that a battery that cycles on a daily basis (as one typically would for electric load management) will have a shortened life; e.g. Tesla has noted a life of 1,000 to 1,500 cycles for its Li-Ion batteries, which would equate to only 4 to 6 years if cycled for just 250 days/year. Also, batteries have a reduction in effective capacity during their lifetime, exacerbated if the cycling is at or near full charge/full discharge levels.
- Initial Cost – Even though battery costs have been falling, they are still high, and represent only part of the cost of a completed storage installation. Tesla's NMC Li-Ion daily-cycle batteries have been specified to be $3,000 for a rated 7 kWh, or $429/kWh merely for the batteries themselves. A recent project proposal in Texas was priced at $2.3 million for 3.0 MWh of storage, or $767/kWh for a full Li-Ion battery installation. Typical project costs are in the range $500 to $800/kWh. And these already high initial costs are compounded by the very short life and the end-of-life disposal costs.

With these daunting issues counterbalancing the benefits of batteries, it behooves utilities and other users of Energy Storage to consider alternatives where batteries may not be the best choice. One of those alternatives, specifically for large multi-hour storage applications is Thermal Energy Storage.

THERMAL ENERGY STORAGE (TES)

Thermal Energy Storage (TES) can store heat or cooling. The thermal energy can be stored in a material medium as a change in temperature (sensible heat storage) or as a change in phase (latent heat storage).

- Hot TES applications commonly use sensible heat storage in hot water, hot oil, hot rocks, or molten salt.
- Cool TES applications commonly use either:
    - latent heat storage in ice (or in an alternative Phase Change Material or PCM), or
    - sensible heat storage in water (or in an alternative Low Temperature Fluid or LTF).

"Chilled water and hot water stratified thermal storage is the world's most viable storage technology."

- *George Berbari*, founder and CEO of DC PRO Engineering, Sharjah, UAE (*District Cooling and Trigeneration Summit*, 2016, Riyadh, Kingdom of Saudi Arabia)

For purposes of this discussion, we focus on sensible heat storage as thermally-stratified Chilled Water TES, as it benefits from an inherent and dramatic economy-of-scale, making it the most applicable TES technology for large-scale storage of cooling (and thus for utility-scale storage of the electricity consumed in cooling). This can be stored cooling either:

1. on the demand-side of the electric utility grid (for air-conditioning or process cooling) or
2. within the supply-side of the grid (for Turbine Inlet Cooling of Combustion Turbine power plants).

<u>Chilled Water (CHW) TES</u>

Thermally-stratified CHW TES employs a large insulated storage tank, filled with water at all times. The lower portion of the tank holds a zone of cool, relatively dense ("supply") water, while the upper portion of the tank holds a zone of warmer, less dense ("return") water, with a narrow band between those two zones containing the temperature gradient or thermocline. The two distinct temperature zones are kept from mixing through the use of flow diffusers at the top and bottom of the tank which slow the incoming and outgoing flow of water in the tank, to a degree that the density differences between the two water zones is adequate to maintain their separation. During off-peak periods of low cooling loads or low electric grid power demand (usually at nighttime), warm water is removed from the upper zone of the tank, cooled in a chiller plant, and returned to the lower zone of the tank, causing the thermocline to rise as the TES tank is charged. During on-peak periods of high cooling loads or high electric grid power demand (usually in daytime), cool water is removed from the lower zone of the tank, sent to the cooling loads, and returned to the upper zone of the tank, causing the thermocline to fall as the TES tank is discharged.

Even in relatively small applications, CHW TES provides a competitively low, installed unit capital cost. And as TES capacity increase, the unit costs drop dramatically, as shown in the examples in Table 2, each of which is a recent installation (from 2013 through 2018).

The most significant factor in the TES unit capital cost is the scale of the installation. But many other factors impact the unit cost as well, including tank configuration, site & soil conditions, project labor requirements/rates, the energy consumption (kW/ton) of the chiller plant equipment, and, quite importantly, the chilled water supply and return temperature difference (with a larger difference resulting in a smaller less costly tank).

Cool TES is not only an effective means to reduce operating energy costs (by shifting electric use from on-peak to off-peak times and by reducing on-peak electric demand), but also can save substantial capital costs (when TES is implemented in lieu of otherwise necessary investments in conventional, non-TES cooling equipment). This is because a non-TES chiller plant must have an installed capacity equal to the *instantaneous peak* cooling load on a peak design day (plus any spare capacity deemed necessary), whereas a chiller plant with TES only requires an installed capacity equal to the *24-hour average* cooling load on that peak design day (plus spare capacity).

Table 2 – Installed Unit Capital Costs of CHW TES

End-use Type - Location	Storage Capacity: thermal (ton-hrs)	Storage Capacity: electric equiv. (MWh)	Installed TES Unit Cost: TES tank ($/kWh)	Installed TES Unit Cost: total TES project ($/kWh)
Mission Critical Facility - Missouri	3,600	2.16	404	
University campus - Pennsylvania	6,500	3.9	274	482
College campus - California	8,000	5.6	214	
Military base - South Carolina	11,800	8.3	217	
University campus - Massachusetts	13,392	9.4	272	
University medical campus - Texas	16,000	11.2	259	
University campus - Indiana	16,000	11.2	179	
University campus - California	20,000	12.0	222	
University campus - Texas	24,000	14.4	188	
University campus - Texas	39,000	23.4	150	
Automotive manuf. headquarters - Michigan	39,600	23.8	135	
Military base - Texas	40,000	24.0	115	
Government research facility - Maryland	47,500	33.3	147	
University campus - Nebraska	52,000	39.0	133	300
Turbine Inlet Cooling - Texas	144,000	86.4	53	
Turbine Inlet Cooling - Virginia	267,800	160.7	24	
Turbine Inlet Cooling - Virginia	268,641	161.2	27	

The economy-of-scale of CHW TES results in very low unit costs ($/ton of TES discharge) which can be well below the unit costs of conventional non-TES chiller plant capacity. As a result, in cases of: 1) new construction, 2) retrofit expansions, or 3) retirements/replacements of aging chiller equipment, the capital credit for avoided chiller plant capacity is more than the investment in CHW TES, resulting in a net capital cost saving. In those cases, CHW TES provides necessary cooling capacity, but does so for a capital cost that is better than free, while also delivering the value of Energy Storage to the electric grid. Table 3 provides just a few representative examples of these dual (operating and capital) savings which have accrued from CHW TES use. The examples illustrate a variety of types of end-use, locations, and climates, in both new construction and retrofit expansion situations. Each TES project shows tens or hundreds of MWh of equivalent stored electric energy as well as initial net capital cost savings in the millions of dollars, with the values rising with the capacity of the TES installation.

TES VERSUS BATTERIES

Some direct comparisons between battery storage and TES are illustrative, even eye-opening, when considering not only initial capital costs, but also other performance characteristics.

“Although battery technologies are continuing to evolve and improve, their costs are high. . . . ASHRAE’s recently completed research project, RP-1607, found that thermal energy storage is currently the most cost-effective means to enable greater renewable energy generation deployment.”

- *Douglas Reindl*, Ph.D, P.E., Professor of Mechanical Engineering and Chair of the Department of Engineering Professional Development at the University of Wisconsin-Madison (*ASHRAE Journal*, February 2018, p. 20)

In December 2017, the State of Massachusetts’ Energy Storage Initiative (ESI) announced an award of $20 million in state grants to 26 Energy Storage projects which were also supported by $32 million in private “matching funds.” The individual projects had varied storage capacities and average unit capital costs as follows:

- Mechanical Flywheel Storage $948/kWh
- Battery Storage (primarily Li-Ion batteries) $656/kWh

- Thermal Energy Storage (TES) $240/kWh

Table 3 – Examples of Stratified CHW TES Savings

		Storage Capacity		TES vs. Non-TES Chiller Plant	
End-use Type - Location	TES project timing & type	thermal (ton-hrs)	elec. equiv. (MWh)	approx. annual operating saving	approx. initial capital saving
University campus - WA	1993 retrofit	17,750	13	$ 260,000/yr	$ 1,500,000
District Cooling - Portugal	1997 new	39,800	28	$1,160,000/yr	$ 2,500,000
University campus - Alberta	2005 retrofit	60,000	40	$ 600,000/yr	$ 4,000,000
Automotive R&D - MI	1990 new	68,000	50	>$1,000,000/yr	$ 3,600,000
International airport - TX	2002 retrofit	90,000	60	$2,000,000/yr	$ 6,000,000
District Cooling - FL	2003 new	160,000	120	>$ 500,000/yr	>$ 5,000,000
Turbine Cooling - Saudi A.	2005 retrofit	192,800	290	>$2,000,000/yr	>$10,000,000

In late 2017, Harvard University initiated a Chilled Water (CHW) TES project to be on-line in 2018/19 as part of the District Energy system serving its new Allston Campus in Boston. The TES capacity is 13,392 ton-hrs (9 MWh of equivalent electrical storage). Compared to an equivalent Li-Ion battery installation, the TES project provides the following benefits:

	CHW TES	**Li-Ion Batteries**
Installed Unit Capital Cost	< $300/kWh	approximately double
Avoided Future Chiller Plant Cost	$ millions	zero
Extends Use of Winter "Free Cooling"	yes	no
Summer Round-trip Energy Efficiency	100 to 103%	80 to 90%
Storage Life Expectancy	40 to 50 yrs minimum	7 to 10 yrs
Grants or Tax Credits to Justify Economics	none	needed

The University of Nebraska-Lincoln installed a Chilled Water (CHW) TES system, on-line in 2018, serving its City Campus cooling network. By shifting much of the campus' electric chiller operation from day to night, the TES installation provides the equivalent of 39 MWh of electrical storage, while also providing peak daytime cooling capacity (over 4,000 tons required to meet near-term load growth, plus an additional 4,000 tons for future growth). A comparison of the actual TES installation with an equivalent (hypothetical) battery storage installation follows:

TURBINE INLET COOLING (TIC)

Gas Turbines (GTs), or more broadly Combustion Turbines (CTs), being constant-volume machines, inherently have a reduced mass-flow, and thus a reduced power output, at times of hot weather when air densities are reduced. Depending on the specific CT model and on the ambient air temperature, these output reductions can be as much as 10 to 25% below the standard (ISO) rated output, occurring precisely at those times when power is at greatest demand and has its highest value. Also at those high temperature times, heat rate or specific fuel consumption of the CT (Btu/kWh) can be negatively impacted by several to ten percent. Cooling the ambient air to a lower temperature (commonly referred to as "T2") as it enters the CT can recover all that lost power and efficiency, or produce even more if the air is cooled to a T2 below the ISO temperature of 15 °C (59 °F).

There are various technologies in common usage providing Turbine Inlet Cooling (TIC), including:

- evaporative cooling, which can entail
  - wetted media,
  - inlet fogging, or
  - fog overspray or wet compression;
- chiller-based cooling, which can use
  - electric motor-driven chillers,

    - steam turbine-driven chillers, or
    - heat-driven absorption chillers; and
- chiller-based cooling using TES, which can be
    - ice TES,
    - chilled water TES, or
    - low temperature fluid TES.

(Hypothetical)	(Actual, 2017-2018)	
	Lithium-Ion Advanced Batteries	**Chilled Water (CHW) Thermal Energy Storage (TES)**
Storage Element		
Peak Cooling Discharge Rate	not applicable	8,333 tons
Peak Electric Discharge Rate	6.25 MW	6.25 MW equivalent
Duration at Peak Discharge Rate	6.24 hrs	6.24 hrs
Net Storage (Thermal)	not applicable	52,000 ton-hrs
Net Storage (Electrical)	39.0 MWh	39.0 MWh equivalent
Storage Unit Capital Cost	$350/kWh	$100/ton-hr
Storage Capital Cost	$13.65 million	$5.20 million (38% of batteries)
Full System Capital Cost	$27.3 million	$11.7 million (43% of batteries)
Full System Unit Capital Cost	**$700/kWh**	**$300/kWh (43% of batteries)**
Additional Chiller Plant		
Necessary New Capacity	4,016 tons	zero (TES already provides 8,333 tons)
Unit Capital Cost	$2,900/ton	not applicable
Installed Capital Cost	$11.6 million	zero
Total Capital Cost (Storage + Chillers)	**$38.9 million**	**$11.7 million (30% of batteries)**
Storage Life Expectancy	**7 to 10 yrs**	**40+ yrs**
40-Year Life Cycle Capital Cost	**$132.4 million**	**$11.7 million (9% of batteries)**
Round-trip Energy Efficiency	**80 to 90%**	**near-100%**

Hybrid solutions are also possible. Each TIC technology offers advantages and limitations, specific to any given application. The website of the Turbine Inlet Cooling Association (TICA), www.TurbineInletCooling.org, provides a thorough discussion and details of TIC options, benefits, examples, and much additional information, beyond the scope of this paper.

Evaporative TIC

These technologies are generally the least capital intensive ones. However, inlet evaporation limits cooling to temperatures slightly above the ambient wet bulb temperature, thus limiting power enhancement, especially during weather conditions that are hot and humid, which often are the conditions during which grid power demand is at its peak and has the highest value.

Chiller-based TIC

These technologies can achieve maximized cooling of the inlet air, down to a T2 below ISO values, for maximized enhancement of CT performance. However, they are fairly capital intensive, though unit power costs ($/kW) for the TIC are below those of non-cooled Simple Cycle or Combined Cycle CT power plants. Also, the chiller plant operation consumes a significant parasitic power consumption of electricity (and/or steam), thus reducing the net power enhancement of the power plant output.

Chiller-based TIC with TES

This solution also provides the ability to maximize the cooling of the CT inlet air to a T2 below ISO values, for maximized CT performance enhancement. Furthermore, it also provides a component of Energy Storage which, although adding some complexity and space requirements, reduces the parasitic power loss during peak demand periods, while also offering a reduction in the net capital cost of the overall TIC installation. It is this version of

TIC, which we shall now explore further, as it often offers dramatically attractive solutions not only for low unit capital costs of power generation (in $/kW), but also minimized unit capital costs for multi-hour utility-scale Energy Storage (in $/kWh).

TES COUPLED WITH TIC

TES of various types (ice, chilled water, and low temperature fluid TES) have all been employed in TIC installations, all achieving positive results. We will focus on chilled water (CHW) TES, as it has become the most common TES choice for TIC systems in the past 20 years. This is because CHW TES provides the following advantages:

- the most economy-of-scale, making it a particularly good choice for large utility-scale applications,
- simplicity of design and operation,
- the highest energy efficiency of the TES options, and
- storage supply temperatures down to 39 to 40 °F, adequately low to achieve the desired minimum T2 temperature (of 45 to 55 °F) for almost all TIC applications.

TES can be configured in numerous ways, as best suited for particular applications.

- Daily versus Weekly TES cycles:
    - Daily configurations are designed for TES to be fully charged and discharged on a 24-hour basis, typically charging each night during low power demand periods and discharging each day during high demand periods. This is the almost universal approach for CHW TES.
    - Weekly configurations are designed for TES to be fully charged during an extended weekend period of low power demand, then partially discharged each weekday, and partially recharged each weekday night. Such configurations allow for a smaller capacity chiller plant, but require a much larger TES capacity, than are required for a comparable daily configuration. This arrangement saves capital cost only where the TES technology has a particularly high unit capital cost for the chiller plant (as is the case for Ice Harvester type TES); it is not typically appropriate for CHW TES.
- Partial versus Full TES load shifting
    - Partial Shift TES configurations provide the necessary cooling for TIC through a combination of both discharging TES and operating chillers during a high power demand period. During subsequent off-peak (low demand) periods, the chiller plant operates to recharge TES, with no TIC occurring. One common partial shift system is a 24-hr Load Leveling TES which meets design day loads with a minimum capacity (and minimum cost) chiller plant operating fully loaded around the clock, coupled with a relatively moderate capacity TES; this results in a minimum total capital cost, but still has some significant parasitic power consumption subtracting from the net power enhancement during peak periods. Partial Shift TES is typically the economic design choice for applications where the period of high power value is 10 hrs/day or more.
    - Full Shift TES configurations provide 100% of the cooling from TES during the peak power demand periods. The chiller plant capacity (in tons) must be adequate to meet the desired 24-hr TIC load (in ton-hours), while only operating during a specified number of non-peak hours per day. Thus the chiller plant capacity is greater (and more expensive) than for a partial shift design, while the TES is also larger and more costly; but the parasitic loads (other than some pumps) are completely shifted away from times of peak power demand and peak power value. Full Shift TES is typically the economic design choice for applications where the period of high power value is 6 hrs/day or less.
    - Note that on non-design days, when TIC loads are substantially less than on design days, a TES-TIC system designed for partial shift operation, can actually operate in a full shift mode.

But enough theoretical discussion. Let’s now explore some of the many real-world installations of TES-TIC, their benefits, and what we can learn from them.

CASE STUDIES OF TES-TIC

Actual case studies of TES-TIC illustrate its increasing and varied applications. They include TES-TIC applied for:

- new CT installations as well as retrofits to existing CTs,
- Simple Cycle CT plants, as well as CT Combined Cycle (CTCC) plants,
- various CT suppliers, including GE, MHI, Siemens, Solar, Turbomeca, and Westinghouse,
- small and large CT plants, from 3 MW to 3,000 MW, and
- varied locales and climates around the world.

Some of the examples of utility-scale installations using Chilled Water (CHW) TES-TIC are summarized with pertinent project and performance data in the Table 4.

Table 4 – Examples of Utility-Scale Chilled Water (CHW) TES-TIC

Owner - Location	First Oper	TIC Type	Power Plant CT No. x Type	ISO Power (MW)	Air Temp Amb. (°F)	Air Temp T2 (°F)	TES-TIC Extra Power (MW)	TES-TIC Extra Power (%)	TES Load Shift Power (MW)	TES Load Shift Energy (MWh)
Brazos Elec Coop - TX	2009	r & n	4 x GE 7FA	1,120	95	50	101	11	15	77
Brazos Elec Coop - TX	2010	retro	1 x SW 501F	250	95	50	36	15	4	21
Calpine - TX	1999	retro	3 x W 501 D5	412	95	50	49	21	8	75
Colo Energy Mgt - NM	2009	new	2 x MHI 501FD2	188			19	10	7	39
Dominion - PA	2009	new	4 x GE 7FA	1,038	95	50	115	13	7	75
Dominion - VA	2010	new	2 x GE 7FA	560	95	50	60	14	5	52
Dominion - VA	2014	new	3x1 MHI CTCC	1,329	92	50	107	9	15	158
Dominion - VA	2016	new	3x1 MHI CTCC	1,329	98	46	123	10	19	196
Dominion - VA	2018	new	3x1 MHI CTCC	1,354			132	12	20	198
Duke Energy - FL	2017	retro	4 x (2x1) CTCC	1,912	95	50	220	13	40	240
Sempra - CA	2009	retro	2 x GE 7FA	566			50	12	5	27
SEC - Saudi Arabia	2005	retro	10 x GE 7EA SC	750	122	54.5	180	30	48	290
SEC - Saudi Arabia	2008	retro	40 x GE 7EA SC	3,000	122	50	720	31	213	1,065
Totals for 13 Projects	**1999-2018**		**81 CTs**	**13,808**			**1,912**	**9-31**	**406**	**2,513**
Average per Project	**retro&new**		**6 CTs**	**1,062**			**147**	**15**	**31**	**193**

Note that for these representative examples, hot weather power output enhancement for TES-TIC ranges from 9 to 31%, averaging 16%. And the average daily load shift from storage, per project, is 31 MW and 193 MWh.

TES-TIC Passes the Test of Time

There is an already long and growing use of TES-TIC.

- An early example, still in operation, dates back over a quarter century to 1991 in Lincoln, Nebraska, when the local municipal electric utility, LES, retrofitted TES-TIC to an existing 65.2 MW Simple Cycle peaking plant (with 1 GE Frame 7B CT) to cool design-day ambient air from 101.5 °F to an inlet T2 of 40 °F, producing a net power output increase of 14.3 MW (a 27% net increase) for 4 hours/day.

TES-TIC Earns Awards from the Power Generation Industry

For both 2015 and 2016, *Power Engineering* magazine bestowed its prestigious Project of the Year Award on a plant that incorporated TES-TIC:

- The 2015 award winner was Dominion's Warren County, Virginia, a new 1,329 MW 3x1 CTCC plant (with 3 MHI 501GAC CTs) using 23,700 tons of chiller plant capacity plus 237,000 ton-hrs of chilled water TES to cool design-day ambient air from 92 °F to an inlet T2 of 50 °F, producing a net power output increase of 107 MW (an 8% net increase) for 12 to 14 hours/day.

- The 2016 award winner was Dominion's Brunswick County, Virginia, a new 1,358 MW 3x1 CTCC plant (with 3 MHI 501GAC CTs) using 29,300 tons of chiller plant capacity plus 293,000 ton-hrs of chilled water TES to cool design-day ambient air even further, from 98 °F to an inlet T2 of 47 °F, producing a net power output increase of 123 MW (a 9% net increase) for up to 14 hours/day.

TES-TIC Operates at Very Large Scale

Individual TES-TIC projects can and do account for hundreds of MW of hot weather power enhancement:

- Perhaps the largest TES-TIC to-date in North America is at Duke Energy's Hines Energy Complex near Bartow, Florida, where TES-TIC was retrofit in 2017 to an existing 1,912 MW CTCC plant (with 8 Westinghouse, Siemens and GE F-class CTs) using a retrofitted 28,200 tons of chiller plant capacity plus 315,000 ton-hrs of chilled water TES to cool design-day ambient air from 95 °F to an inlet T2 of 50 °F, producing a net power output increase of 220 MW (a 13% net increase) for 6 to 12 hours/day.
- Saudi Electricity Company (SEC)'s Power Plant 8 (PP8) in Riyadh, Saudi Arabia was an existing 750 MW Simple Cycle plant (with 10 x 75 MW GE 7EA CTs). In 2005 the plant was retrofitted with 11,100 tons of chiller plant capacity plus 192,800 ton-hrs of chilled water TES to cool design-day ambient air from 122 °F to an inlet T2 of 54.5 °F, producing a net power output increase of 180 MW (a 30% net increase) for 6 hours/day.
- SEC followed their PP8 installation with perhaps the largest TES-TIC in the world, at Power Plant 9 (PP9) in Riyadh, Saudi Arabia, an existing 3,000 MW Simple Cycle plant (with 40 x 75 MW GE MS7001EA CTs) retrofitted in 2008 with 4 chiller plants plus 710,000 ton-hrs of chilled water TES to cool design-day ambient air from 122 °F to an inlet T2 of 50 °F, producing a net power output increase of 812 MW (a 31% net increase) for 5 hours/day.

Plant Owners Repeat the Installation of TES-TIC at Multiple Sites

The repeated use of any technology is a powerful testament to successful results and customer satisfaction. Examples of such repeated use of TES-TIC include:

- SEC in Saudi Arabia with 3 projects installed between 1998 and 2008, involving 56 CTs (TES-TIC for both new and existing simple cycle CTs), with TIC producing 1,020 MW of power enhancement (30 to 35% net increases), of which TES accounts for nearly 300 MW for 5 to 6 hours/day, i.e. about 1,500 MWh of storage.
- Dominion in Pennsylvania and Virginia with 5 projects installed between 2009 and 2018, involving 15 CTs (TES-TIC installed with new combined cycle CTs), with TIC producing 537 MW of power enhancement (9 to 14% net increases), of which TES accounts for about 66 MW for 10 to 14 hours/day, i.e. about 679 MWh of storage.

Astonishingly Low Installed Unit Capital Costs for TES-TIC

Installed unit capital costs for large CTCC power plants typically range from $800 to $1,000/kW, based on their rated at ISO power outputs; but when corrected for actual hot weather operating conditions (when power is most in demand and most highly valued), the de-rated outputs yield true unit costs of $900 to $1,200/kW. By contrast, large applications of chiller-based TIC systems (but not using TES) have typical installed unit capital costs of only $300 to $700/kW, with the actual value dependent upon many factors including: the actual CT model's performance variation versus inlet temperature, the ambient dry & wet bulb temperature, the cooled T2 (inlet air temperature), and whether the TIC installation is executed along with a new CT installation versus as a retrofit to an existing CT. Finally, large chiller-based TIC systems that do incorporate TES have typical installed unit capital costs of merely $200 to $500/kW, with the variation dependent upon the factors listed above, as well as on the configuration of the TES system (for "full shift" or "partial shift" of the chiller operation during peak hours) and on the hours/day of TES use.

Because a TES-TIC system typically utilizes a reduced chiller plant capacity, the combined costs for the TES tank and the smaller chiller plant are typically less than for a non-TES chiller plant, only. The result is a reduction in net capital cost, which means that the incorporation of TES occurs at a negative cost, i.e. a net cost savings, while simultaneously providing an increase in peak power enhancement (by minimizing the parasitic power consumption of the chiller plant during periods of peak power value) and realizing the benefits and value of Energy Storage.

- SEC's TES-TIC system for PP8 in Riyadh, Saudi Arabia achieved a net power output increase of 180 MW (a 30% net increase) for 6 hours/day. The TES portion of the system provides 48 MW (of the 180 MW) and allowed a nearly 2/3rds reduction in the chiller plant capacity, with a net capital cost saving of well over $10 million versus a non-TES option. That non-TES option would have produced a 132 MW enhancement at approximately $425/kW in then-current dollars (or about $585/kW in 2018 dollars) versus the actual TES-TIC installation which delivers a 180 MW enhancement at $250/kW in then-current dollars (or $345/kW in 2018 dollars).

SUMMARY AND CONCLUSIONS

<u>Summary</u>

- The recent and continuing growth of intermittent renewable power generation (often out-of-phase with peak power demand) is increasing the value of, and need for, Energy Storage.
- Energy Storage is available in various technologies, each with advantages and limitations for addressing certain power grid challenges.
- Batteries (whether traditional or advanced) provide value for frequency control and short-term storage, but have serious drawbacks and limitations for multi-hour storage applications, including:
    - high unit capital costs ($/kWh),
    - short life expectancy,
    - low round-trip energy efficiency,
    - safety issues,
    - environmental and potential hazardous waste issues, and
    - uncertainties regarding sourcing the necessary exotic raw materials.
- Thermal Energy Storage (TES) is a particularly attractive technology for multi-hour storage applications, with attributes which include:
    - a fully-mature commercial technology,
    - long life expectancy,
    - high round-trip energy efficiency,
    - no significant safety, environmental, or material sourcing issues, and
    - low unit capital costs.
- Large Chilled Water (CHW) TES provides extremely low unit capital costs:
    - $/ton-hr which are lower than all other Energy Storage options, and
    - $/ton which are lower than those of equivalent chiller plants. (Thus, adding TES at times of needed chilled water capacity investment, often reduces net capital cost, resulting in achieving the benefits of Energy Storage at a negative capital investment.)
- Turbine Inlet Cooling (TIC) provides valuable benefits:
    - Higher CT power outputs during hot weather times of peak demand and peak power value, and
    - $/kW which are lower than for the most economical simple cycle or combined cycle CT power plants.
- Combining large CHW TES with TIC provides even greater benefits:
    - even higher power outputs during times of peak demand and peak power value,
    - $/kWh which are lower than all other Energy Storage options, and
    - $/kW which are even lower than other peaking power generation options, including non-TES chiller-based TIC. (Thus, adding TES in lieu of a larger chilled water capacity investment for TIC, often reduces net capital cost, resulting in achieving the benefits of Energy Storage at a negative capital investment.)
- Numerous Case Studies of TES-TIC illustrate:
    - long-term successful applications, dating back to 1991,
    - multiple award-winning applications, from power industry authorities,
    - large-scale applications, with hundreds of MWh to over 1,000 MWh each,
    - satisfaction by owners having repeat installations, numbering as many as five, and
    - extremely low installed unit costs, with one example being $250/kW for the full TES-TIC system and storage being a net saving of over $10 million vs. a non-TES TIC option.

Conclusions

1. Though batteries undoubtedly have a useful role to play as storage for the electric power grid (and for microgrids), they should not automatically be the default choice of storage for all applications.
2. Particularly for large, multi-hour storage applications, Chilled Water (CHW) Thermal Energy Storage (TES) should be considered, as its unit capital cost, round-trip energy efficiency, and life expectancy are clearly far superior to those of batteries.
3. CHW TES should be applied for demand-side applications of air-conditioning or process cooling, most especially when implemented at times of necessary investments in cooling capacity (i.e. during new construction, retrofit expansions, or retirement/replacement of cooling equipment).
4. Turbine Inlet Cooling (TIC), complemented by CHW TES, should be applied in supply-side (power generation) applications, for both new and existing, Simple Cycle and Combined Cycle, Combustion Turbine power plants. CHW TES-TIC will maximize hot weather, high-value, peak power output, and do so at very low unit capital cost (in $/kW), while also providing Energy Storage at very low (even at an effectively negative) net unit capital cost (in $/kWh).

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