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Technoeconomic Analysis of Low Temperature Reservoir Technologies for sCO_2 based Pumped Thermal Energy Storage Systems

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Abstract

Pumped Thermal Energy Storage (PTES) provides economic long-duration electrical energy storage free of geographical limitations. PTES uses a heat pump cycle with two thermal storage reservoirs at different temperatures to store excess electrical power during periods of high supply and low demand and return the electrical power to the grid at periods of low supply and high demand using a thermodynamic power cycle. Using their extensive experience in developing commercial sCO_2 power cycles, Echogen is developing a transcritical CO_2 PTES system that stores thermal energy at moderate temperatures (335°C and 0°C) , with a competitive round-trip efficiency (RTE) and substantially lower cost than competing storage technologies.

A key part of this energy storage process is the low-temperature reservoir (LTR). For the CO_2 heat pump, the thermal energy transfer from the LTR occurs by evaporating liquid CO_2 at nearly constant temperature. By selecting the operating state of the heat pump cycle appropriately, this constant temperature can be maintained slightly below the freezing point of water. Since these two processes are both nearly isothermal, the exergy loss associated with the heat extraction from the LTR can be minimized, which improves the cycle RTE.

Two main LTR technologies are considered for the ice formation and storage: (i) Ice-on-Coil (IOC) and (ii) Ice slurry generators (ISG). In Ice-on-coil (IOC), a cold fluid flows through embedded tubes in a static water bath, causing ice to form on the outer surface of the tubes transiently. This approach has the advantage of relative simplicity, with no moving parts. In ice water slurry generators (ISG), ice is created in the form of small particles that remain in suspension in a liquid phase. This mixture of solid ice particles in the liquid phase is termed ice slurry. For ISG, two main technologies have been considered in the present study –: (a) ice-phobic heat exchangers and (b) super-cooler heat exchangers. Ice-phobic and super-cooler heat exchanger technologies are passive ice slurry technologies where there are no moving parts except for pumping water/slurry through the system.

As these LTR technologies differ in the method of making ice or ice slurries, the physical component requirements and their maintenance requirements also differ considerably. The focus of the present study is to evaluate the above three LTR technologies for (i)performance by integrating them into commercial scale sCO_2 PTES system and (ii)economic analysis considering mainly the capital costs.

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Nomenclature

AES	Active Energy Systems
COP	Coefficient of performance
EPS	Echogen Power Systems
IHEX	Icephobic heat exchanger
IOC	Ice-on-Coil
ISG	Ice slurry generator
LTR	Low temperature reservoir
LTX	Low temperature heat exchanger
PTES	Pumped Thermal Energy Storage
RTE	Round trip efficiency
SCHE	Super-Cooler heat exchanger
SP	State point
SPF	SPF Institute of Solar Technology

1 Introduction

The ever increasing dependence of electrical grid on renewable energy sources (such as solar and wind) and decline in traditional energy sources (such as coal and natural gas) puts the grid reliability in cross-hairs due to intermittent availability of renewable sources. One way of solving this problem is to store the excess renewable energy when its available and use the stored energy later when demand increases. Echogen is developing one such energy storage technology called pumped thermal energy storage (PTES). During thermal energy storage, PTES system draws excess electricity from the grid and uses transcritical CO_2 heat pump cycle to transfer thermal energy from low-temperature reservoir to a higher-temperature reservoir. During electrical energy demand, this stored thermal energy is transferred back to low-temperature reservoir through sCO_2 power cycle, converting the temperature differential back to electrical energy.

Heat Pump Cycle (also called Charging cycle): In sCO_2 PTES system, during heat pump cycle (thermal energy storage cycle), electrical energy is drawn from the grid to run a compressor which in-turn compresses CO_2 to supercritical pressure and high-temperature. See figure 1 to 5 for reference. This high-temperature CO_2 transfers heat to high-temperature and medium-temperature reservoir fluids. The CO_2 exiting medium-temperature reservoir is at moderate temperatures but still at supercritical pressures, which is expanded across a turbine connected to generator. CO_2 exiting turbine is saturated or slightly subcooled liquid (low pressure and below 0°C). This sub-0°C CO_2 is evaporated in low-temperature reservoir while cooling the LTR fluid. This CO_2 from low-temperature reservoir serves as inlet to compressor and the cycle repeats.

Heat Engine Cycle (also called Generating cycle): Operation of sCO_2 power cycle (thermal energy discharge cycle) using high-temperature and low-temperature reservoirs as temperature differential is similar to the heat engine cycles explained in [1, 2, 3]. See figure 1 to 5 for reference. Subcooled CO_2 from lower-temperature reservoir is pumped to supercritical pressures. This high pressure CO_2 picks-up heat from medium- and high-temperature reservoir fluids. The high enthalpy sCO_2 runs the turbine, which in-turn spins the generator. The turbine exhaust CO_2 is condensed back to liquid using low temperature reservoir before returning to pump and the cycle repeats.

The main focus of this paper is low temperature reservoir (LTR), one of the critical component in PTES systems, as its performance effects the low pressure of the system there-by pressure ratio across turbomachinery and overall efficiency of the system. Two main LTR technologies are considered for the ice formation and storage: (i) Ice-on-Coil (IOC) and (ii) Ice slurry generators (ISG). Two major technologies have been considered for ISG in the present study –: (a) ice-phobic heat exchangers (I^2HEX) and (b) super-cooler heat exchangers (SCHE). Ice-phobic and super-cooler heat exchanger technologies are passive ice slurry technologies where there are no major moving parts.

It is to be noted that, of the three LTR technologies, IOC for CO_2 applications is being developed by Echogen, I^2HEX by Active Energy Systems (AES) based in Oak Ridge, Tennessee and SCHE by SPF Institute of Solar Technology (SPF) based in Rapperswil, Switzerland.

In the present study, for fair comparison of above LTR technologies, a 100 MWe 10-hour charge/10-hour generate CO_2-based PTES system is selected. Once the net power and duration of the PTES system is fixed, the cycle optimization studies can be performed to determine the overall effect of a LTR technology on PTES system.

Following sections describe the LTR technolgeis and there integration with CO_2-based PTES system. Later sections describe the cycle optimization methodology and the model results and discussion.

2 Low temperature reservoir technologies

The key difference between IOC and ISG technologies is that, in IOC ice is directly formed on the tube surface - this approach has the advantage of relative simplicity, with no moving parts. In ice water slurry generators (ISG), ice is created in the form of small particles that remain in suspension in a liquid phase. This mixture of solid ice particles in the liquid phase is termed ice slurry.

2.1 Ice-on-coil (IOC)

The IOC is a LTR technology which mainly consists of embedded tube banks in static bath of water. IOC is a well known technology in refrigeration and HVAC industry [4, 5, 6], but application of that technology for CO_2 based PTES systems is an unexplored territory. During ice making or 'charging' process, cold saturated CO_2, at about -5°C to -3°C, enters the tube bank (usually at bottom header) causing the water to freeze on the outer surface of the tube while CO_2 vaporizes. During ice melting or 'generating' process relatively warm CO_2 (about 20°C) enters the tube bank (usually at top header) causing the ice on the outer surface of the tube to melt while the CO_2 is cooled to saturated liquid conditions.

Figure 1 shows the process flow diagram for both charge and generate cycles of a PTES system with ice-on-coil (IOC) as low temperature reservoir (LTR) technology. In IOC, as CO_2 flows through the tube banks embedded in a static bath of water - there is no auxiliary loads associated on the water side.

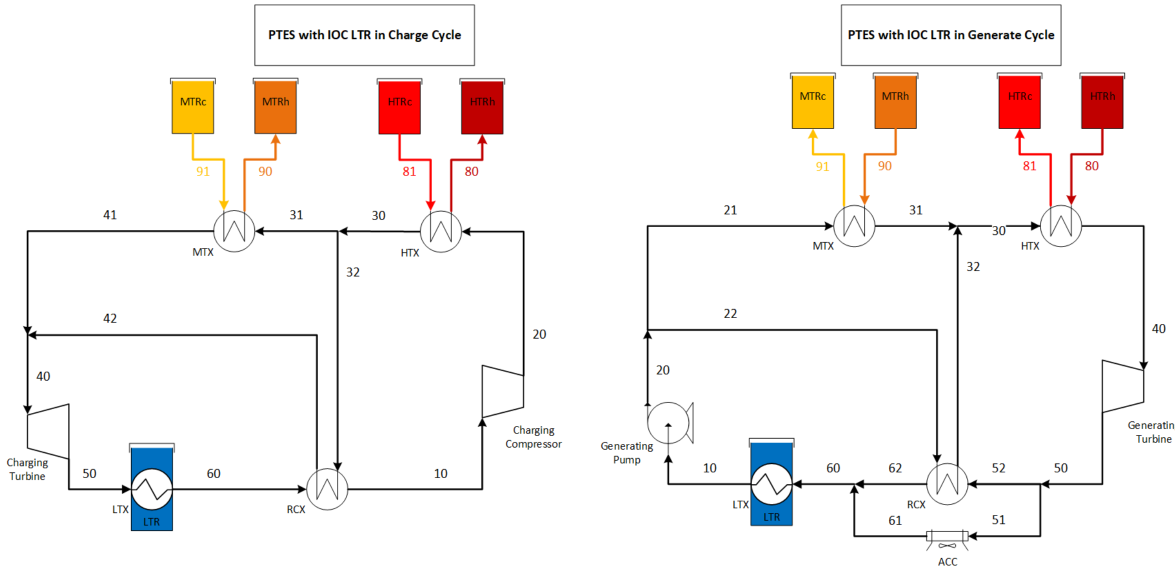

Figure 1: Process flow diagram for PTES system with IOC as LTR technology.

2.2 Ice-phobic heat exchanger (I^2HEX)

I^2HEX technology is a passive ice-slurry technology. Figure 2 provides the process flow diagram for both charge and generate cycles of a PTES system with ice-phobic heat exchanger (I^2HEX) as low temperature reservoir (LTR) technology developed by AES. In charge cycle, I^2HEX is located between state point-50 and state point-60. The major components for I^2HEX system are ice-slurry generation tank, ice-slurry storage tank, POA oil to CO_2 heat exchanger, oil circulation pump and water/slurry pump.

During charge cycle, as cold CO_2 from charge turbine passes through CO_2-POA oil heat exchanger - oil is cooled to sub-0 °C temperatures. This cold POA oil enters the slurry generation tank at the bottom through drop distributor. The ice-slurry generation tank is about 80% water and 20% POA oil by volume. To make ice, the drop distributor produces cold oil drops, which buoyantly rise and cool the surrounding water (direct contact heat exchange), producing ice slurry. Oil collects at the top of the tank, where it is pulled off and pumped back to the CO_2-POA oil heat exchanger. The ice-slurry in the slurry generation tank is actively pumped into slurry storage tank and an equivalent amount of make-up water from storage tank is pumped into slurry generation tank. A representative temperature/heat transfer plot for CO_2-POA oil heat exchanger operation in PTES system is shown in figure 3.

During generate or ice-melt cycle, the ice-slurry present in the storage tank is used as the low temperature heat sink in the heat engine cycle. The same heat exchanger used in CO_2-POA oil service during charge cycle, is used as low temperature heat exchanger (LTX), in figure 2, to melt the ice in storage tank during generate cycle. The ice-slurry from the storage tank is pumped through LTX and warm water from LTX back to storage tank during generate cycle. A representative temperature/heat transfer plot for ice melt operation in generate mode is shown in figure 4.

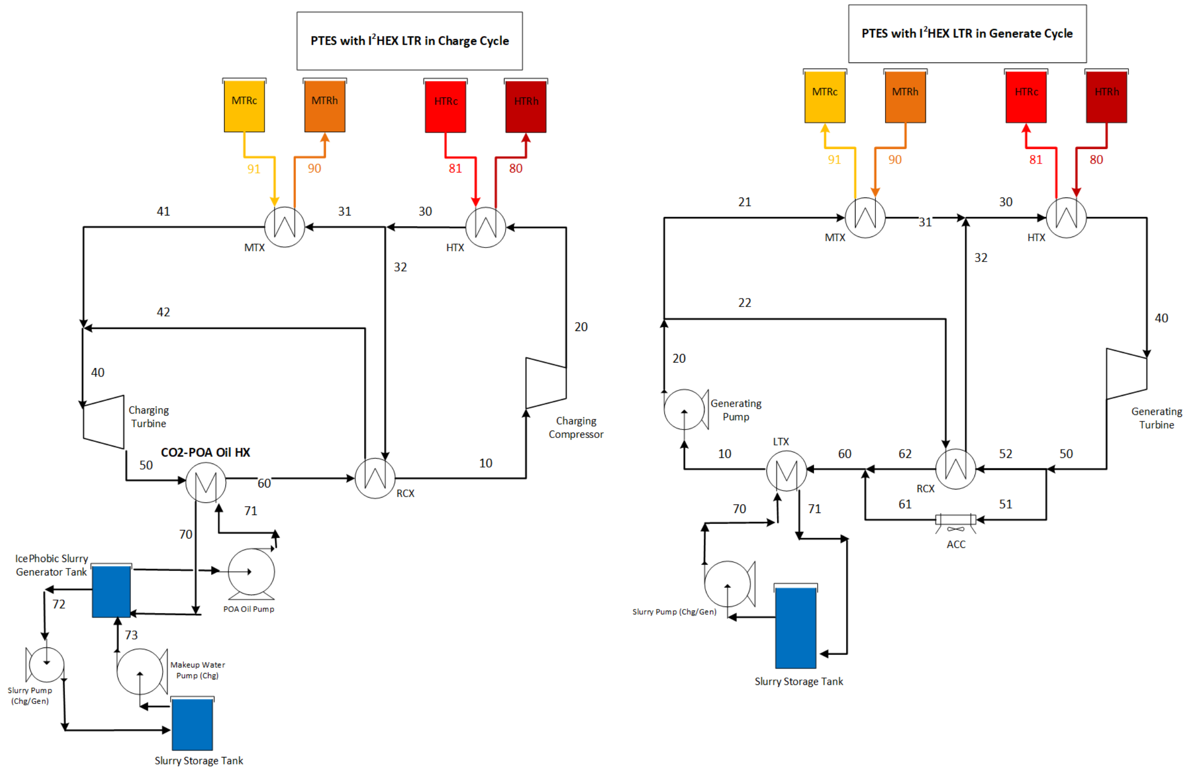

Figure 2: Process flow diagram for PTES system with I^{2}HEX as LTR technology.

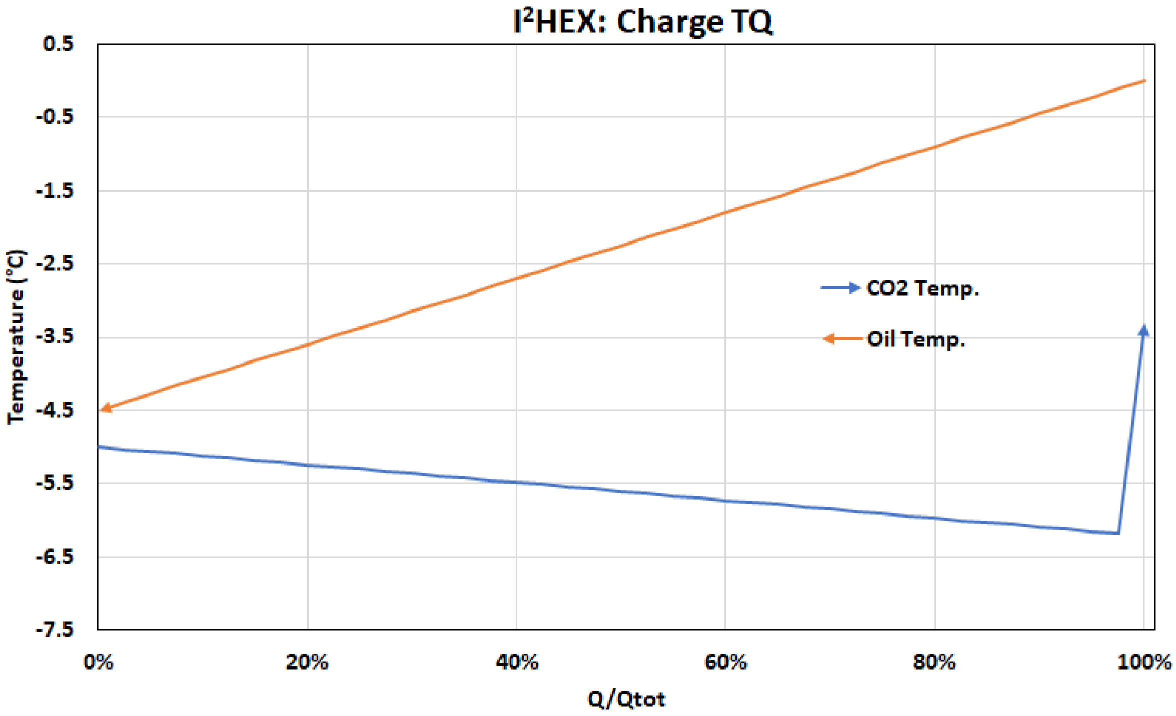

Figure 3: Representative temperature/heat transfer plot for I^2HEX as LTR in PTES system during charge cycle.

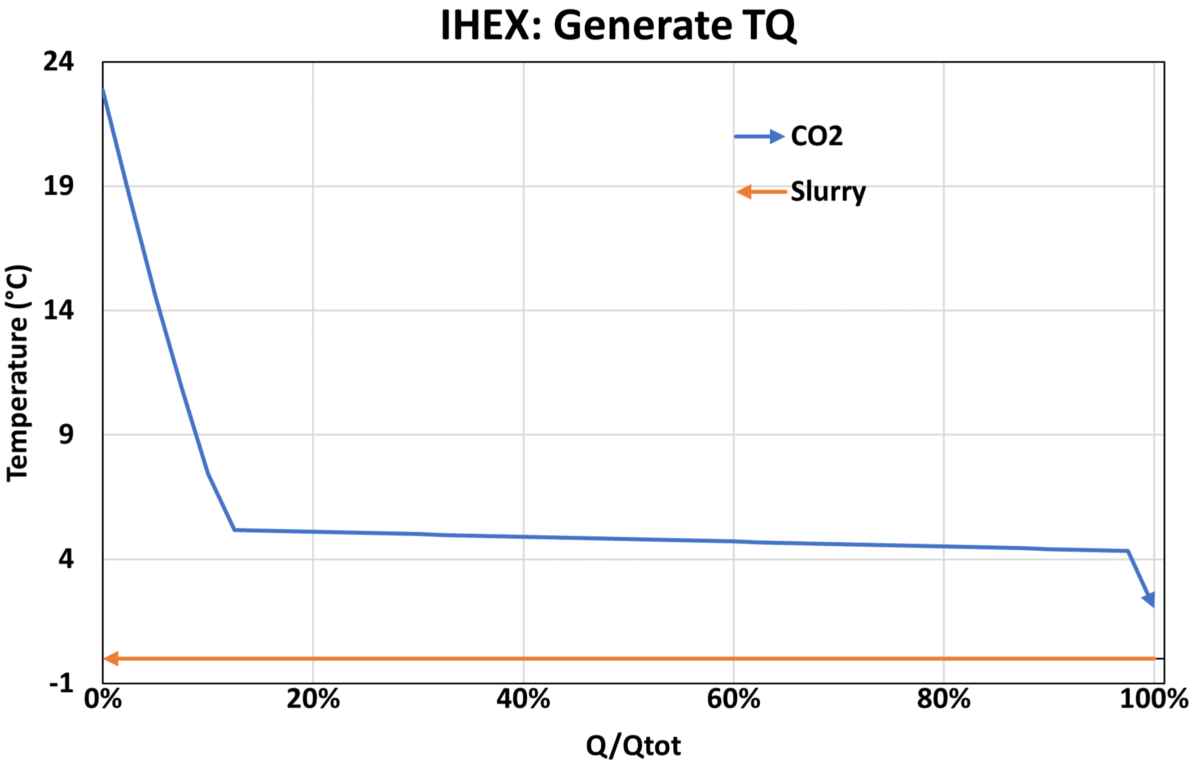

Figure 4: Representative temperature/heat transfer plot for ice melt cycle using LTX in PTES system.

2.3 Super-cooler heat exchanger (SCHE)

Similar to I^2HEX technology, SCHE is also a passive ice-slurry generation technology. Some literature related to SCHE is given in [7, 8, 9]. Figure 5 shows the process flow diagram for both charge and generate cycles of a PTES system with supercooler heat exchanger (SCHE) as low temperature reservoir (LTR) technology developed by SPF. In charge cycle, SCHE is located between state point-50 and state point-60. The major components of SCHE system are SCHE itself, crystallizer, pump, HX to warm water going in to SCHE. SCHE is a highly polished stainless steel brazed plate heat exchanger which can handle supercooled water.

During charging cycle as cold CO_2 from charge turbine passes through SCHE - water is subcooled to sub-0 °C temperatures. A representative temperature/heat transfer plot for SCHE operation in PTES system is shown in figure 6. This subcooled water from SCHE is 'crystallized' in a crystallizer, the ice-slurry water from crystallizer is pumped into a storage tank. It is to be noted from SCHE charge cycle PFD in figure 5 that water from storage tank needed to be warmed to about 0.5 °C before going into SCHE - which is achieved by using process CO_2 from state point-41 and a CO_2-to-water heat exchanger. It can be noted from figure 6 that during charging cycle, SCHE is majorly sensible heat transfer on water side.

During generate or ice-melt cycle, the ice-slurry present in the storage tank is used as the low temperature source in the heat engine cycle. The same SCHE heat exchanger can be used as low temperature heat exchanger (LTX), in figure 5, to melt the ice in storage tank. The ice-slurry from the storage tank is pumped through LTX and warm water from LTX back to storage tank during generate cycle. A representative temperature/heat transfer plot for ice melt operation in generate mode is shown in figure 7.

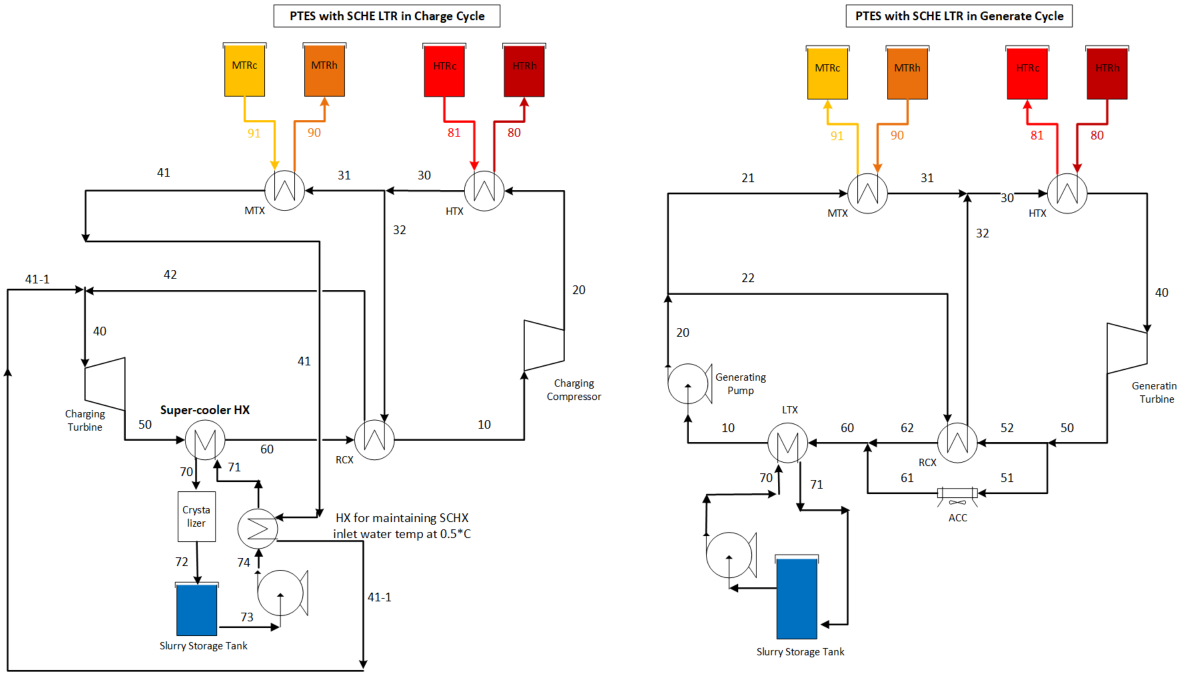

Figure 5: Process flow diagram for PTES system with SCHE as LTR technology.

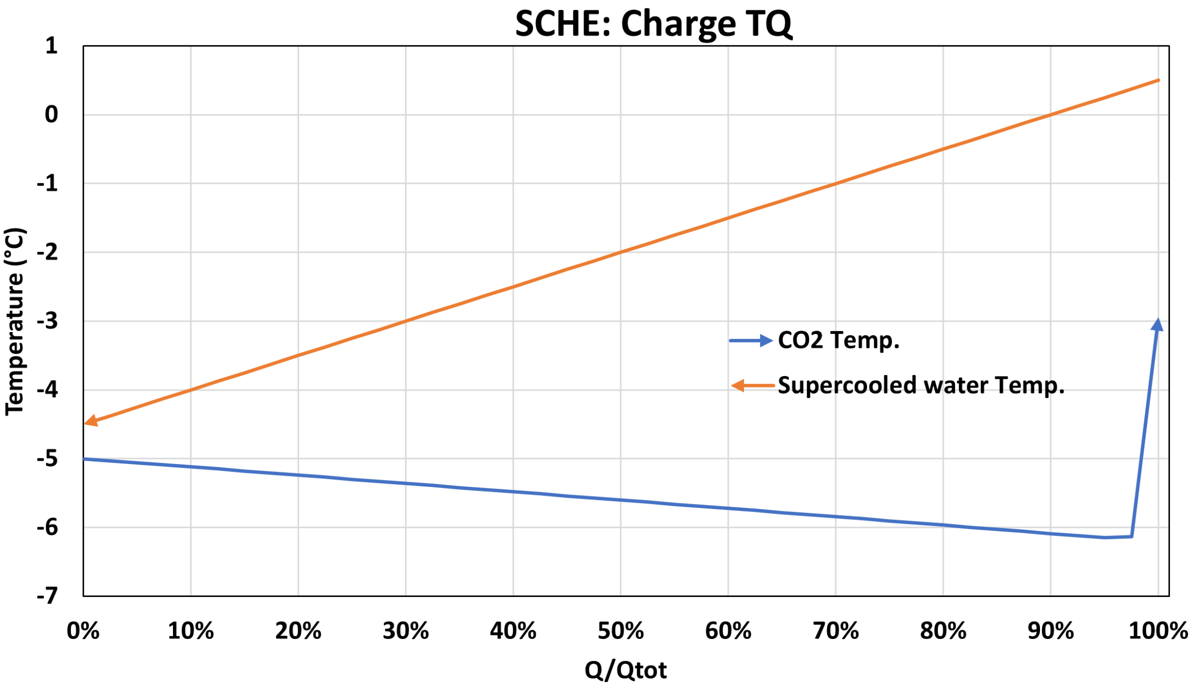

Figure 6: Representative temperature/heat transfer plot for SCHE as LTR during charge cycle in PTES system.

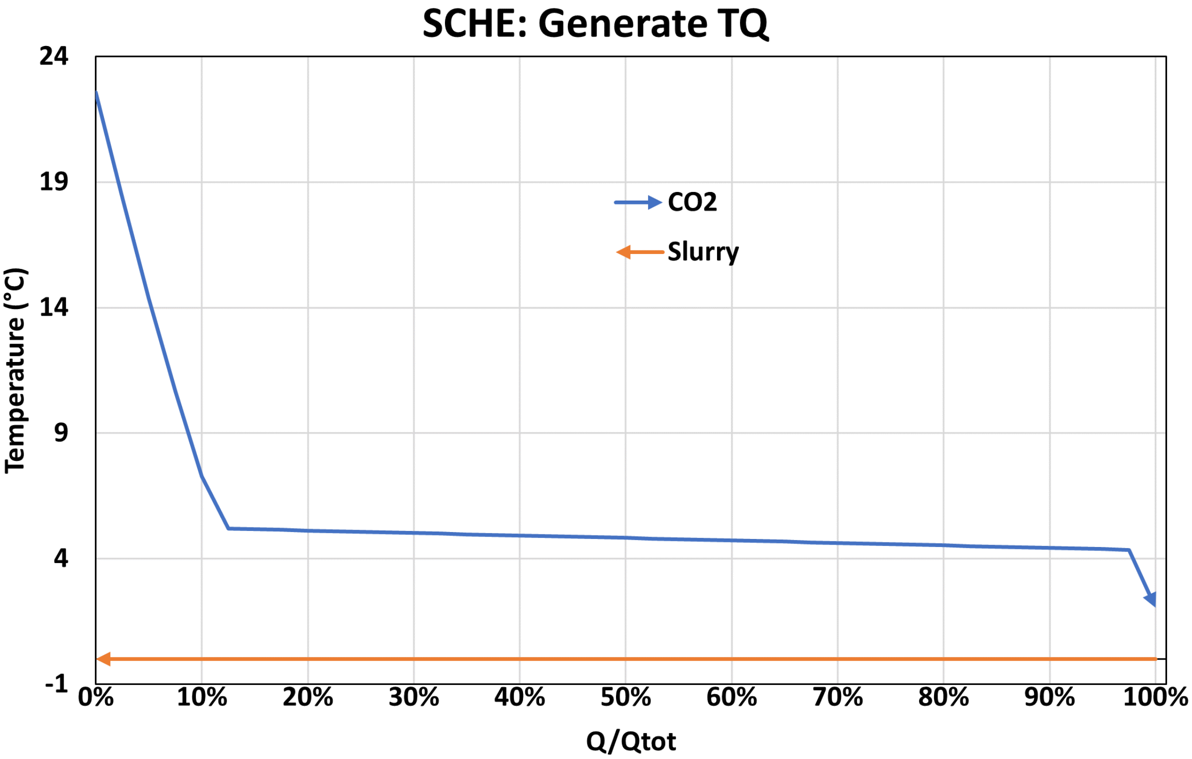

Figure 7: Representative temperature/heat transfer plot for ice melt cycle using SCHE in PTES system.

3 Optimization methodology

Echogen has built PTES system models for combined charge and generate cycle optimization for a given set of variable ranges and constraints. The optimization parameters can either be (i)to maximize net round trip efficiency (RTE) of combined charge and generate cycle or (ii)to minimize overall PTES system cost to hit a target net RTE (should be less than max RTE).

In the present study the optimization tool is used to maximize net RTE of a 100 MWe 10-hour charge/10-hour generate PTES system for all three LTR technologies. The results of this optimization study is used to compare three LTR technologies for various parameters including charge cycle gross/net COP, generate cycle gross/net efficiency, gross/net RTE, slurry flow rates, auxiliary loads etc.

4 Results and discussion

Performance optimization: Echogen's PTES cycle optimization model was used to run combined cycle (charge and generate) optimization and studies were performed for above three LTR technologies with CO_2 temperature at state point-50 (inlet to LTR) was constrained to three different temperatures of $-5\,^{\circ}C$, $-4\,^{\circ}C$ and $-3\,^{\circ}C$. Optimization parameter for all these studies being to maximize PTES system net RTE. Figure 8 to 12 provide results from this optimization study.

One general conclusion that can be drawn from this study is - a net 50% RTE can be achieved by using any of the three LTR technologies (figure 10).

The other conclusion that can be drawn from these plots is that SCHE is under performing compared to IOC and IHEX as LTR. This is mainly stemming from the phenomenon in SCHE that, using a CO_2-to-water heat exchanger (figure 5) in charge cycle which in turn effecting the gross cycle performance (COP, efficiency and RTE). As we are warming water from state point-74 to state point-71, in charge cycle, it posses as additional compression work on the charge compressor, there by reducing the net RTE.

It can also be observed from the COP, efficiency and RTE comparison plots that on a gross basis IHEX is performing better than IOC technology but on net basis IOC is performance is better, this is stemming from the parasitic load needed to pump water/slurry in IHEX system which is not present in IOC system.

Cost Component: Echogen over the years had developed cost curves for various components (heat exchangers, valves, turbo machinery, etc.) based on vendor quotes and DOE cost models. Using this cost models, equipment cost analysis was done for each of the LTR technology discussed above. Figure 13 provides the data from this analysis. On a \$/kWe basis, I^2HEX system is more expensive than the IOC and SCHE system. This is because the extra equipment needed to operate I^2HEX system, for example I^2HEX system need atleast three pumps to operate during charge cycle where as SCHE only needs one, I^2HEX need two storage tanks while SCHE only has one. Also POA oil (also expensive) is less effective heat transfer fluid compared to water.

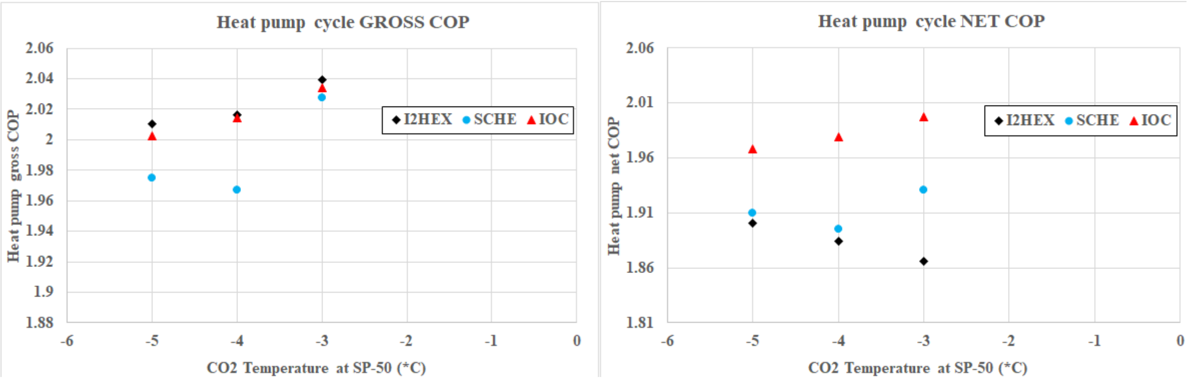

Figure 8: Charge cycle COP for PTES system with IOC, IHEX and SCHE as LTR technologies.

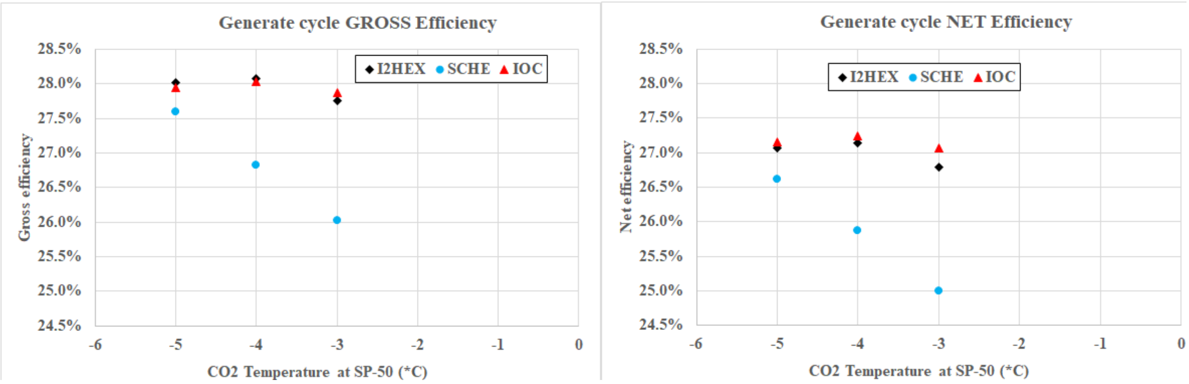

Figure 9: Generate cycle efficiency for PTES system with IOC, IHEX and SCHE as LTR technologies.

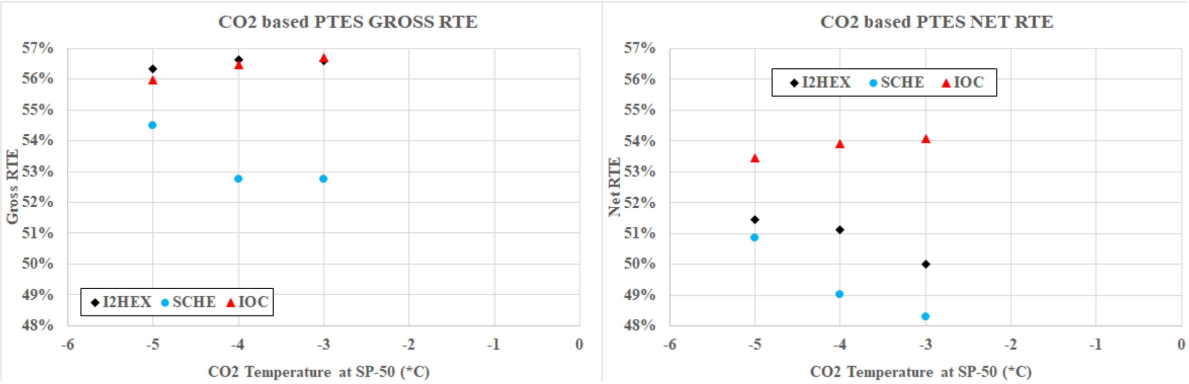

Figure 10: Overall PTES system RTE with IOC, IHEX and SCHE as LTR technologies.

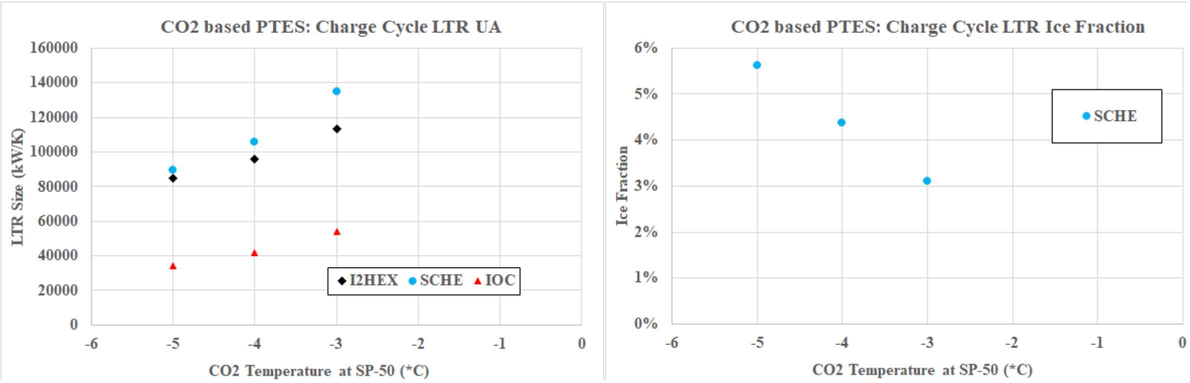

Figure 11: (left) IOC, IHEX and SCHE heat exchanger size requirement and (right) slurry ice fraction produced during charge cycle.

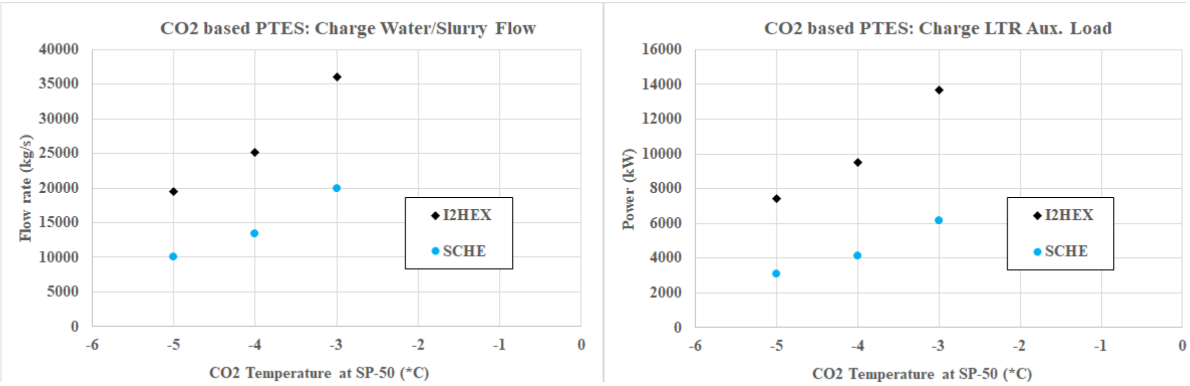

Figure 12: (left) IHEX and SCHE water/slurry flow rates and (right) auxiliary loads to attain this flow requirement during charge cycle.

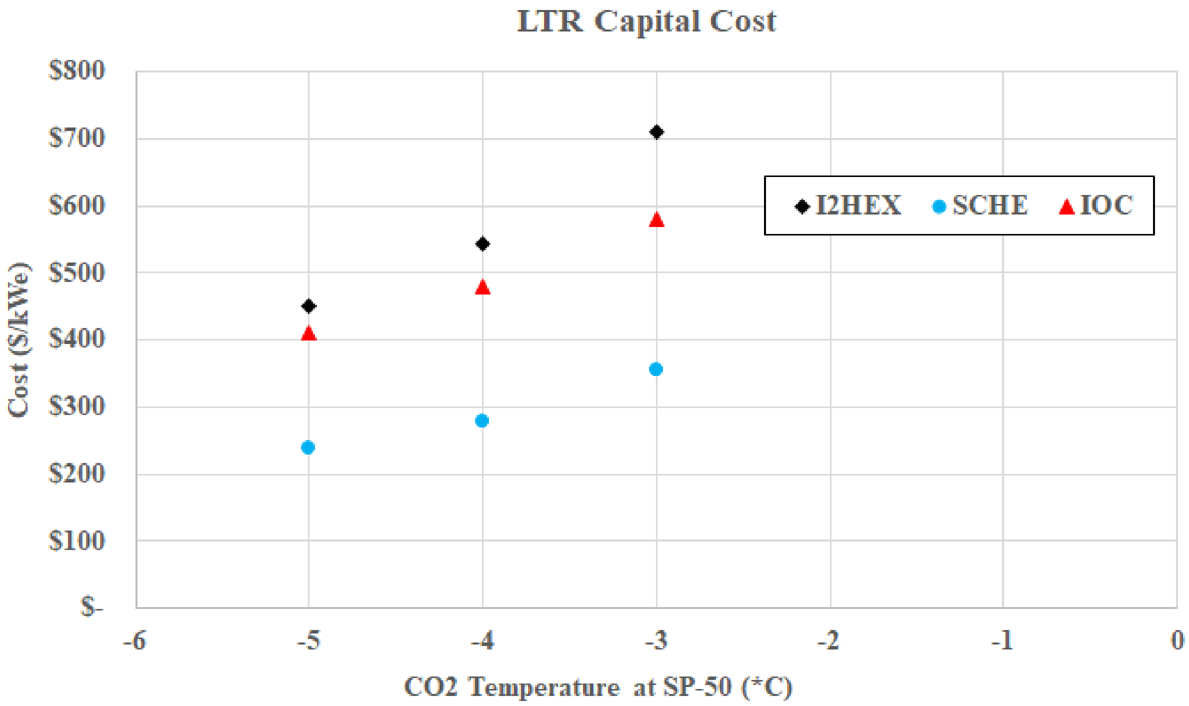

Figure 13: Cost analysis for each of the LTR technology discussed in this paper.

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