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Analysis of a Hybrid Concentrated Solar Power (CSP) & Pumped Thermal Energy Storage (PTES) System and Safety Approaches

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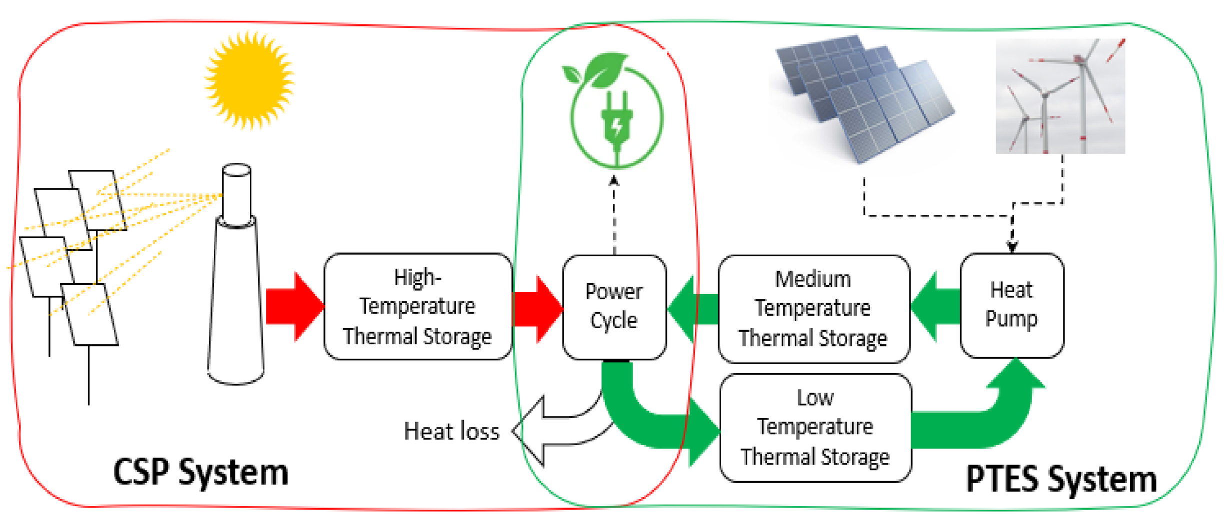
Abstract

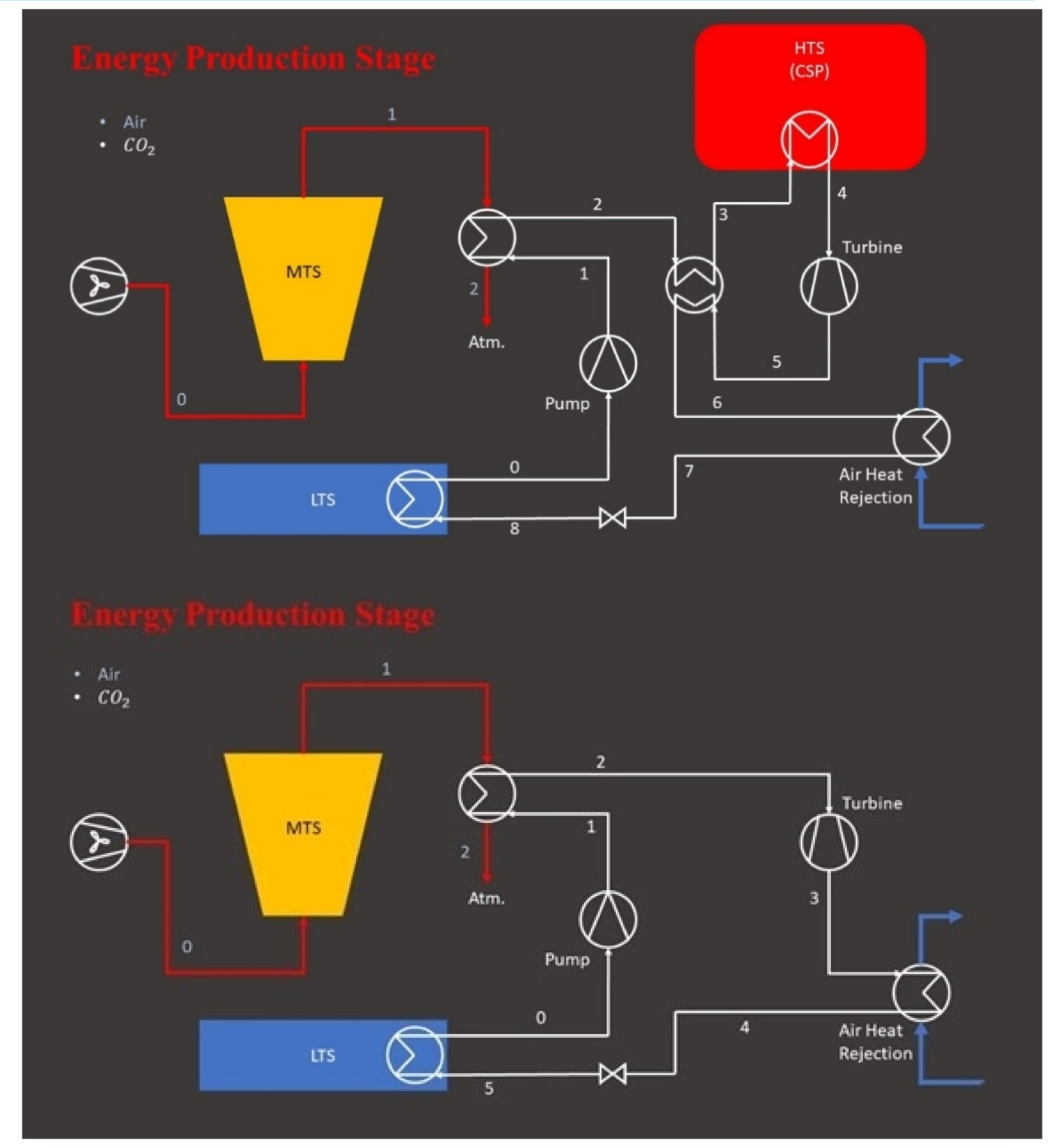
Pumped Thermal Energy Storage (PTES) is a promising approach for complementing or by repurposing waste heat from existing TES systems & natural gas plants. PTES systems have been considered for electricity production systems as standalones, where a heat pump and a heat engine interact via both hot and cold storage to produce electricity using a reciprocating Joule cycle. A hybrid Concentrated Solar Power (CSP) plus PTES system design is being developed at the National Solar Thermal Test Facility (NSTTF) at Sandia National Laboratories. Two different system arrangements were investigated for an optimal pilot-scale demonstration configuration to provide recuperation for a TES system, improving round-trip efficiency >100%. A hybrid Concentrated Solar Power (CSP) and PTES design is presented, composed of 3 TES subsystems at different temperatures, along with an sCO_2 power block. Two different hybrid system design permutations are analyzed where variation consists of the CSP receiver, resulting in different temperatures and variations on the sizing of the TES subsystems. The analysis is for a prototype, lab-scale system to produce 2 kWe over a minimum period of four hrs. The system configurations were executed under steady state conditions, as well as using idealized conditions for components. The factors to consider for the evaluations are sizing of the different thermal energy storage containers and efficiency of energy production loop. Leading to an efficiency difference of more than 10% and size increase/reduction six times on space between the analyzed configurations for the hybrid CSP plus PTES system. This research also presents safety and reliability challenges and risk mitigation approaches for confident operation and reliability.

Project Overview

- Hybrid Concentrated Solar Power (CSP) plus Pumped Thermal Energy Storage (PTES) system design is being analyzed at the National Solar Thermal Test Facility (NSTTF), at Sandia National Laboratories.
- Two different system arrangements are being considered to determine the optimal pilot-scale demonstration configuration.
- System is composed of three thermal storage subsystems:
  - 1. A High Temperature Storage (HTS) with temperatures above 650℃,
  - 2. A Medium Temperature Storage (MTS) with temperatures ranging from 25℃ to 170℃, and
  - 3. A Low Temperature Storage (LTS) system at 0℃.
- Energy stored in the HTS tanks is collected through a CSP particle receiver that allows for thermal storage at temperatures above 650℃.
- Heat energy stored in the MTS tank is obtained using a CO2 heat pump through a heat exchanger,
- LTS will take advantage of the latent heat for liquid-solid phase transition of water.

PTES Design & Configurations



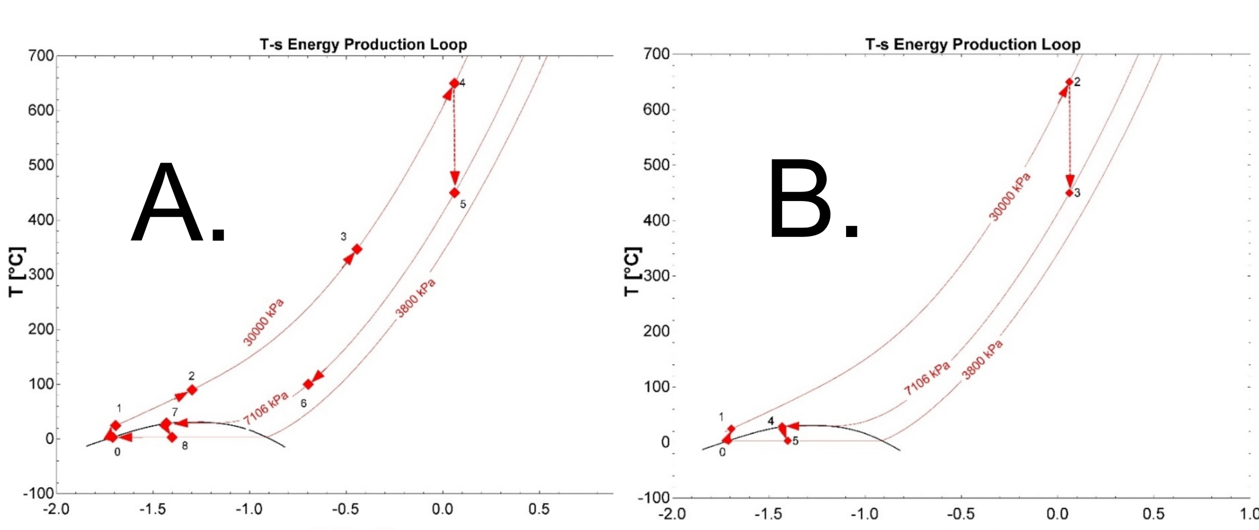


Configuration A

Configuration A uses the HTS tank in direct contact with a supercritical CO_2 (sCO_2) engine system. Also, for this system design, the MTS tank is heated by the CO_2 pump alone, reaching temperatures of approximately 150℃.

Configuration B

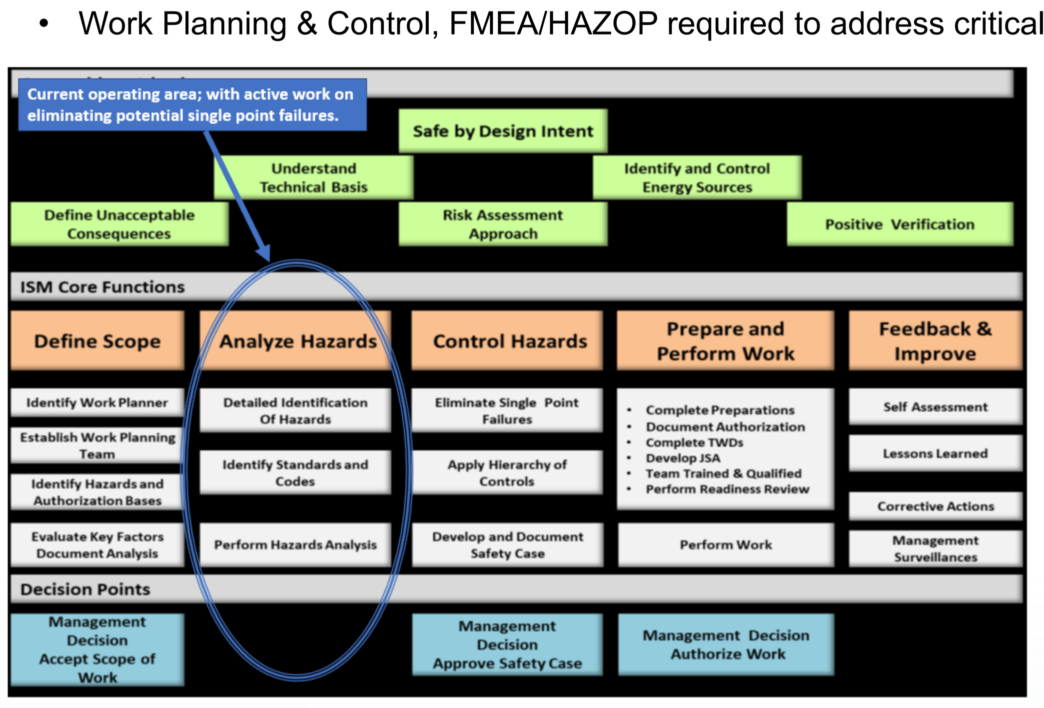
Configuration B uses the CO_2 pump and the CSP system connected to the HTS tank to heat up the MTS tank, increasing its temperatures above 650℃. Also, the MTS can be bypassed to increase discharging time for the energy production phase.



Config. A	Config. B
Efficiency	
32.88%	18.51%
MTS	
Sizing	
$0.229\ m^3$	$1.57\ m^3$
Temperature Range	
25°C-150°C	25°C-650°C

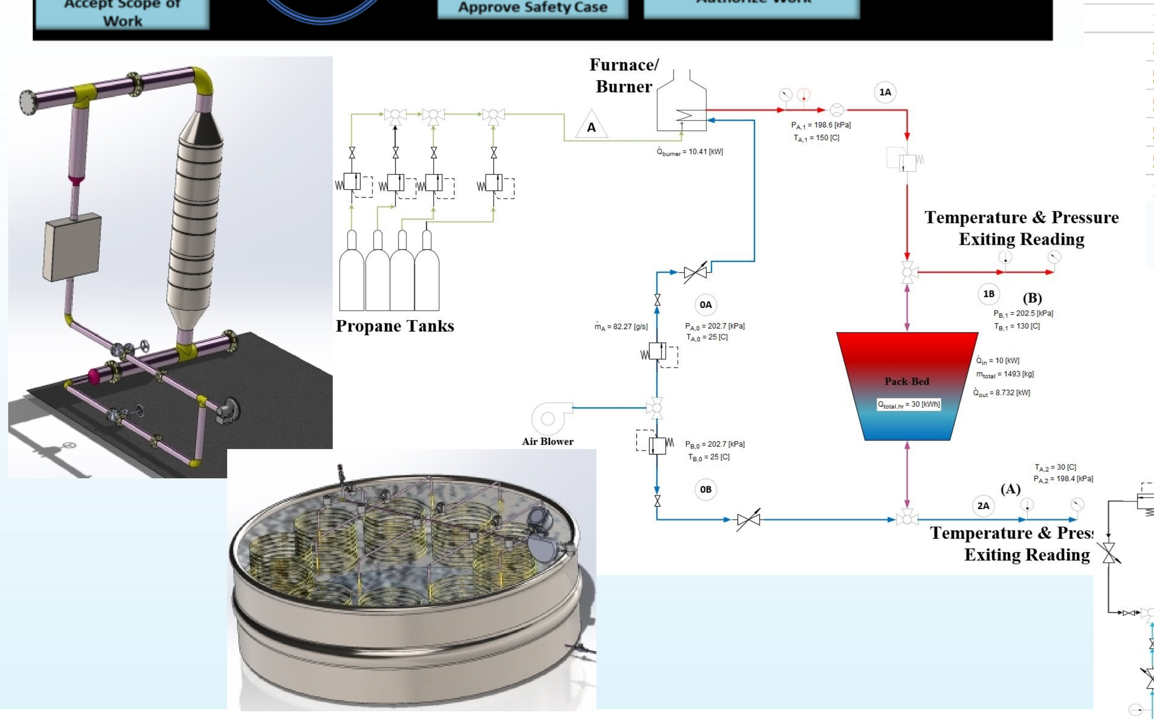
ES&H, WP&&C, Risk Registries & Controls Planning Process

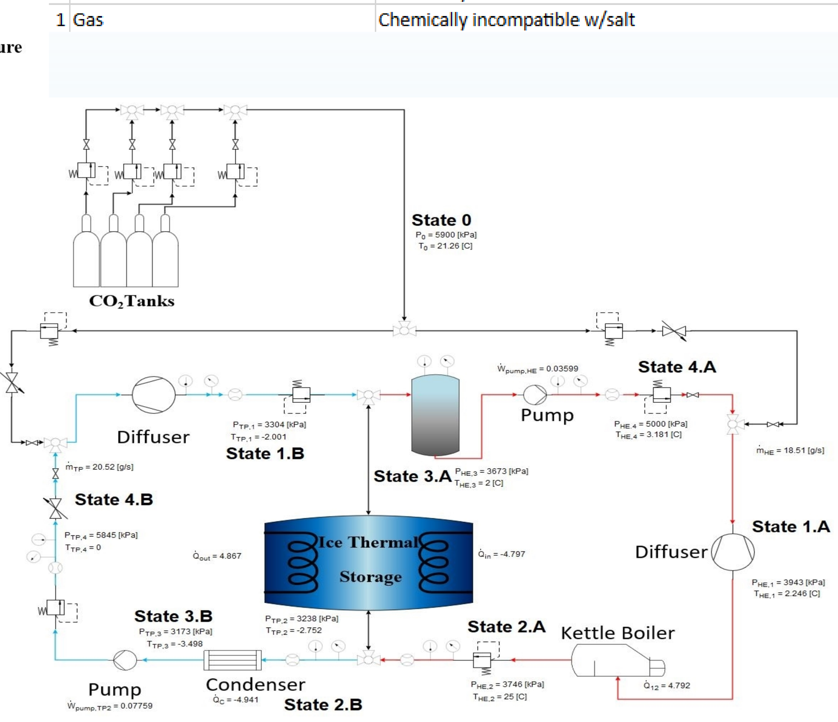
- Work Planning & Control, FMEA/HAZOP required to address critical failure modes in the Gen 3 Liquid-Pathway system



Aspect #	Aspect	Failure Mode	Probability (0.0-1.0)	Impact (0-5)	Risk score
2	Gas conditioning/handling	Insufficient impurity control	0.5	5	2.5
4	Exhaust scrubber	Insufficient contaminant removal	0.4	4	1.6
6	Sensors and controls	Poor Precision	0.4	4	1.6
6	Sensors and controls	Poor Accuracy	0.4	4	1.6
1	Gas	Too Expensive (Materials)	0.3	5	1.5
4	Exhaust scrubber	Too Expensive (Labor)	0.4	3	1.2
6	Sensors and controls	Too Expensive (Materials)	0.6	2	1.2
6	Sensors and controls	Too Expensive (Labor)	0.6	2	1.2
1	Gas	Too Expensive (Labor)	0.2	5	1.0
3	Pump/blower	Availability	0.2	5	1.0
4	Exhaust scrubber	Availability	0.2	5	1.0
6	Sensors and controls	Availability	0.6	2	1.0
2	Gas conditioning/handling	Salt deposition/blockage	0.3	3	0.9
2	Gas conditioning/handling	Too Expensive (Materials)	0.3	3	0.9
2	Gas conditioning/handling	Too Expensive (Labor)	0.3	3	0.9
3	Pump/blower	Too Expensive (Materials)	0.3	3	0.9
4	Exhaust scrubber	Too Expensive (Materials)	0.3	3	0.9
6	Sensors and controls	Chemically incompatible w/gas	0.2	4	0.8
3	Pump/blower	Too Expensive (Labor)	0.2	3	0.6
1	Gas	Chemically incompatible w/tank	0.1	5	0.5
3	Pump/blower	Insufficient flow or head	0.1	4	0.4
5	Valves	Chemically incompatible w/gas	0.1	4	0.4
5	Valves	Too Expensive (Materials)	0.1	3	0.3
5	Valves	Too Expensive (Labor)	0.1	3	0.3
5	Valves	Availability	0.1	3	0.3
1	Gas	Chemically incompatible w/salt	0.1	5	-

- Several permitting requirements are necessary to proceed with pilot-scale construction, pertaining to both the DOE and the U.S. Air Force.
- AF813 forms are a requirement for environment and hazard analysis.
- SNL NEPA controls include Air Quality Permits, Hazwaste stream & Stormwater requirements, and biological survey requirements.
- NFPA code requirements must be met including adherence to NFPA requirements (e.g. NFPA 400), Life Safety Systems Analysis, and Fire Hazard Analysis
- Primary Health Screening (PHS) is the primary beneficiary from staged sodium fires. The risks of sodium fires must be demonstrated for proper NFPA hazard analysis.
- Air Quality Requirements
  - Fugitive Dust Control Permit required prior to operations start.
  - Air Quality Control ES&H application with SNL & KAFB.
- Waste Stream & Stormwater Requirements
  - National Pollution Elimination Discharge System (NPDES) Construction General Permit (CGP) – Stormwater run-off.
  - For National Laboratories - requirements for waste removal from a project site.
  - Waste disposal description reports (WDDR) tool based on Safety Data Sheet (SDS).
  - Waste-related items: Salt sludge, waste construction debris, hazardous waste, emissions quantities, etc.
  - Managed in accordance with SNL Env. Compliance Coord. (ECC) & SNL Waste disposal program.
- Biological Requirements
  - Bio Survey required 3 wks. before project during breeding season
  - Ecological open trenching/Hole excavation mitigation.
  - Notification of any bird mortalities to Ecology Program.





Conclusions

- 2 Hybrid CSP+PTES systems operating at similar input conditions (i.e., efficiency of key components, operating temperature for turbine, and idealized assumptions).
- Configuration A had a 14.37% higher thermal to electrical efficiency.
- ES&H/WP&C process & FMEA assessment performed to evaluate safety
- HTS/MTS/LTS TES thermal and pressure risks assessed with respect to
- NEPA and other facility safety requirements for R&D test beds and for commercial scalability analysis

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