Low Temperature Thermal Storage as a Rankine Cycle Cooling Solution

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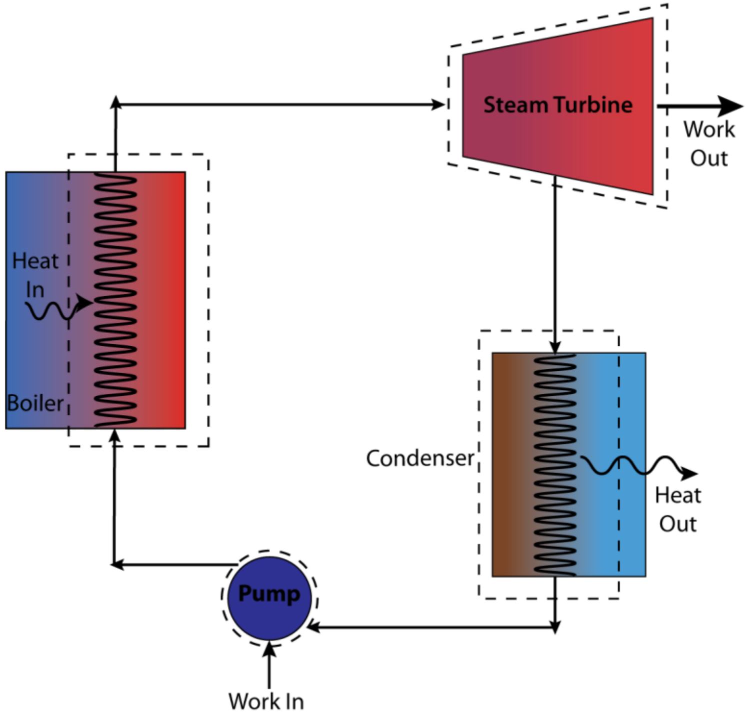
Overview

- Motivation for technology
- Concept
- Operating strategies
- Targeted climatic conditions and geographic locations
- Phase I investigation – preliminary benchmarking against ACC
- Phase II investigation – extended benchmarking against ACC

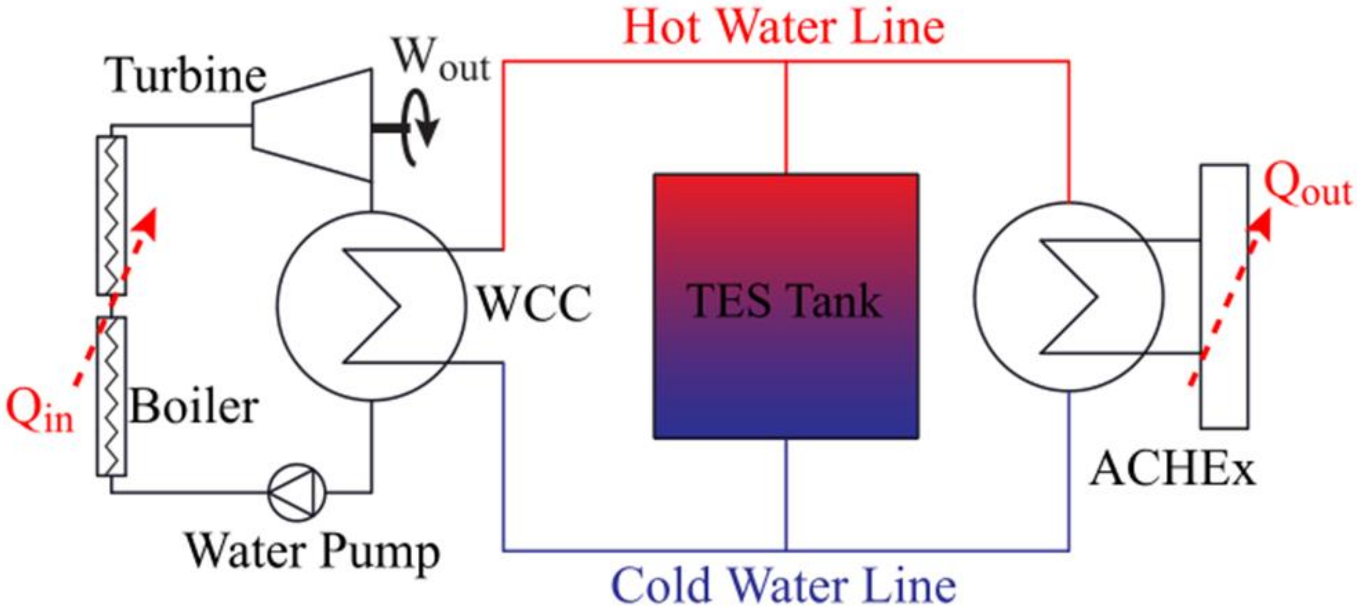
Motivation

- Due to water restrictions and natural shortages, air is becoming increasingly popular as a cooling medium in thermoelectric power plants
- A-frame Air-Cooled Condenser (ACC) is current industry standard for dry-cooling
- Number of ACC issues:
  - Minimum temperature to which turbine outlet steam can be cooled is the ambient air temperature
  - Thermodynamic efficiency penalty in hot climates
  - Air in leakage
  - Scope for improvement in dry-cooling methodologies to enhance performance of air-cooled plants

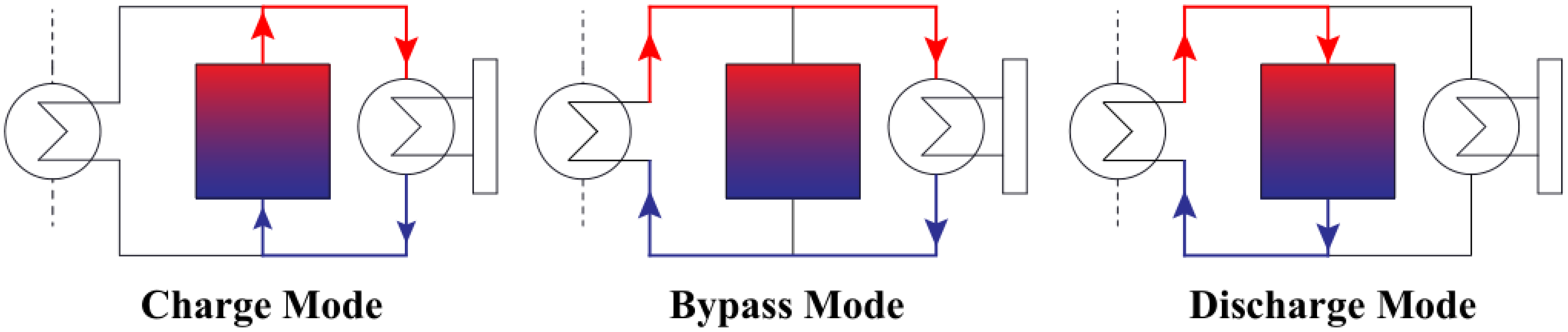


LTTS Concept

- **L**ow **T**emperature **T**hermal **S**torage – **LTTS**
- A cooling solution consisting of a water-cooled condenser (**WCC**), thermal energy storage tank (**TES Tank**), and an air-cooled heat exchanger (**ACHEx**)
- Exploits the natural ambient temperature “swings” to condense steam at sub-ambient temperatures

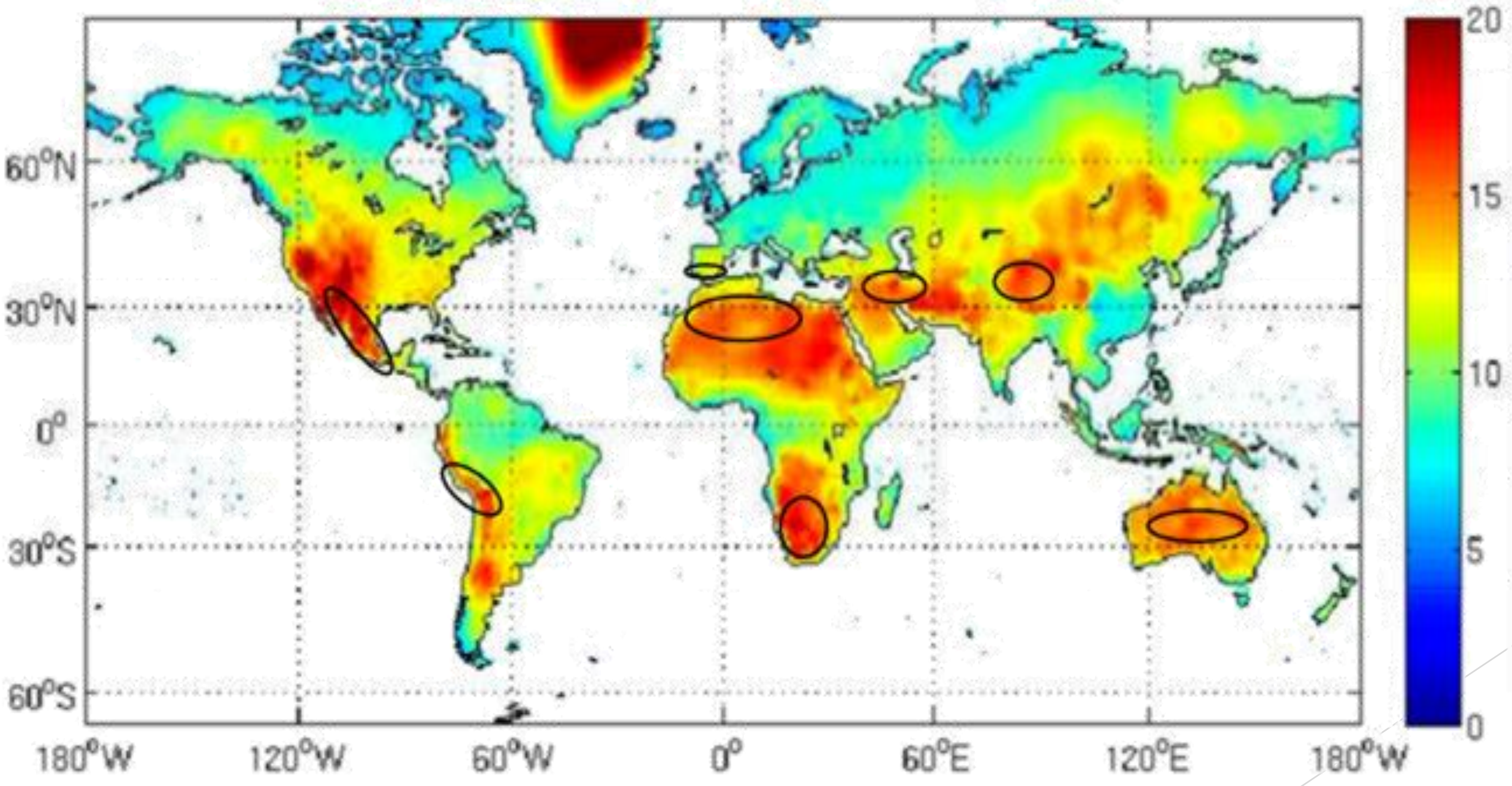


LTTS Operating Strategies

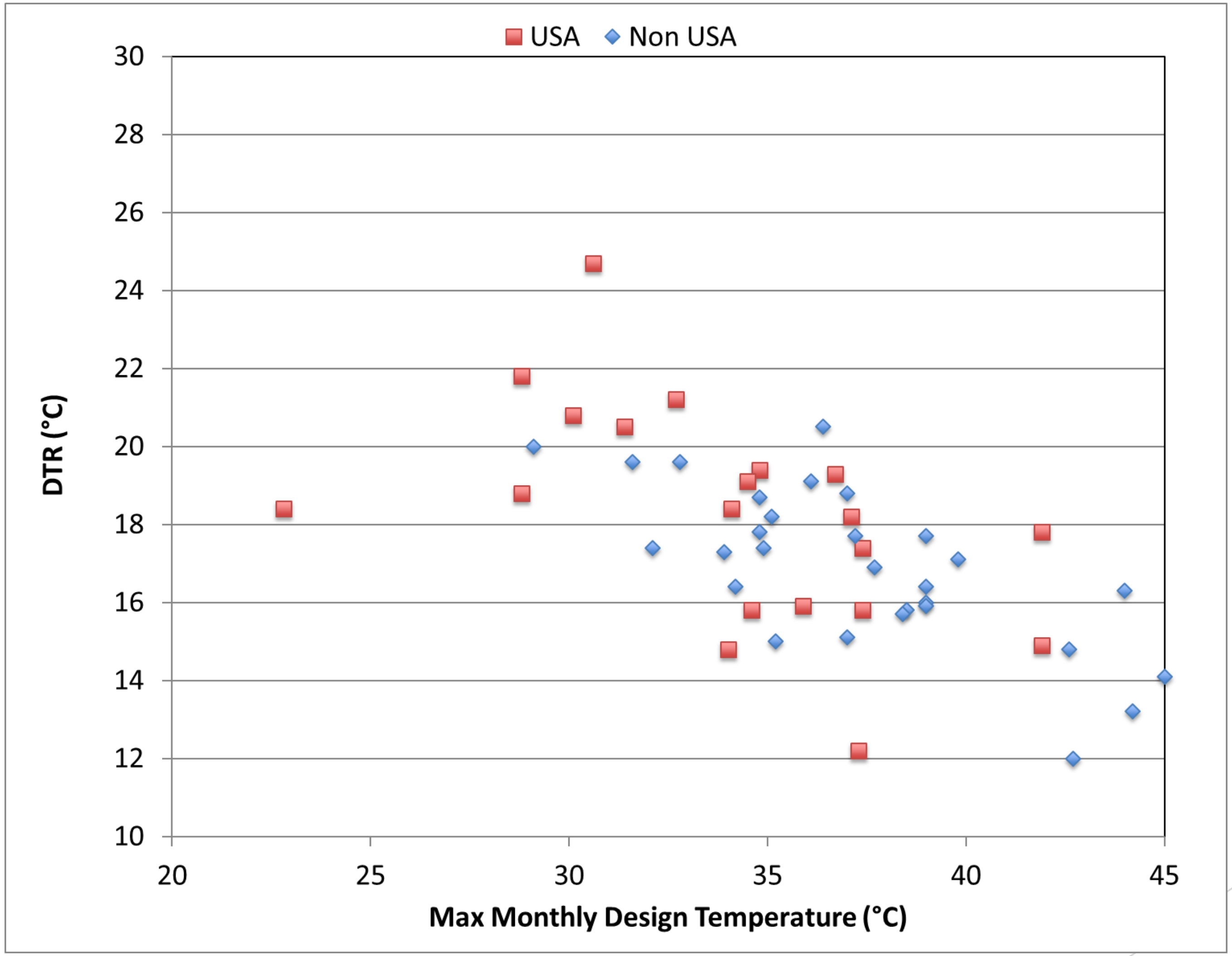


- Charge Mode: water is pumped from the tank to the ACHEx, cooled, and returned to tank for storage. Engaged when ambient temperature is low
- Bypass Mode: water from the WCC is cooled in the ACHEx, before being returned to the WCC. Engaged during periods of moderate temperature
- Discharge Mode: chilled water (which was cooled during the charge mode) is pumped from the tank to the WCC, where it condenses the steam at sub-ambient air temperatures. Engaged when ambient temperature is highest

Places with wide daily temperature swings (DTR)



Representative DTRs

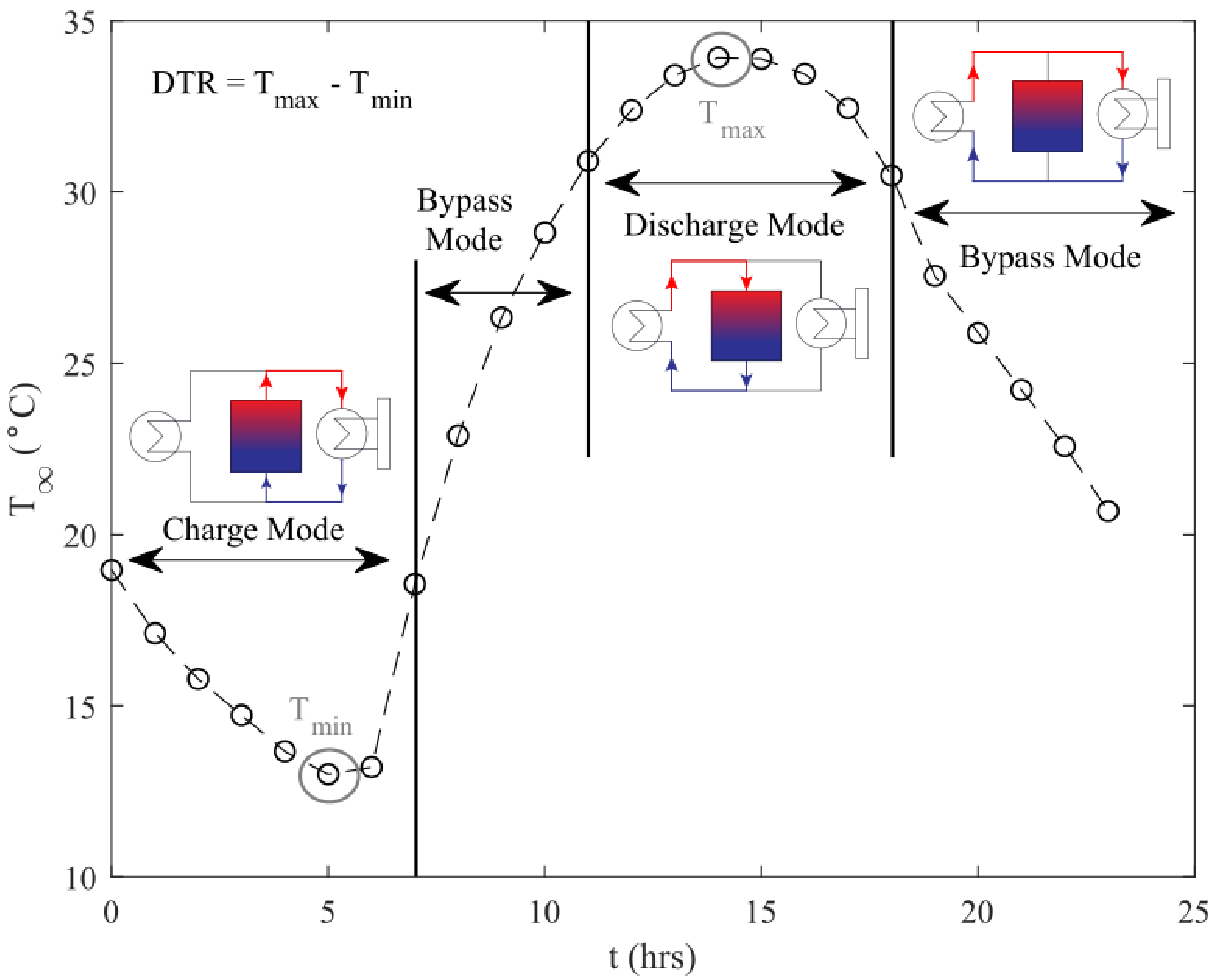


Phase I Investigation

- 8 hours bypass, 8 hours discharge, 8 hour charge (8B/8D/8C)
- Modelling based on a single daily temperature profile in a single location
- Used for
  - Feasibility study
  - Preliminary exploration of design space

LTTS Operating Strategies

- Operational Scenario
  - 24 hr operating cycle is represented by site-specific ambient temperature profile
  - Ambient temperature profile is divided
  - LTTS operating modes are assigned
  - Case study: 8 hrs of charge, 8 hrs of bypass, 8 hrs of discharge

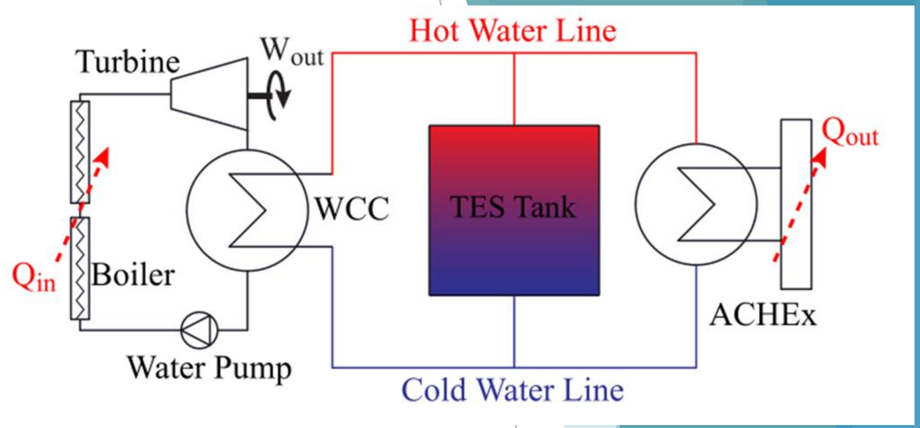


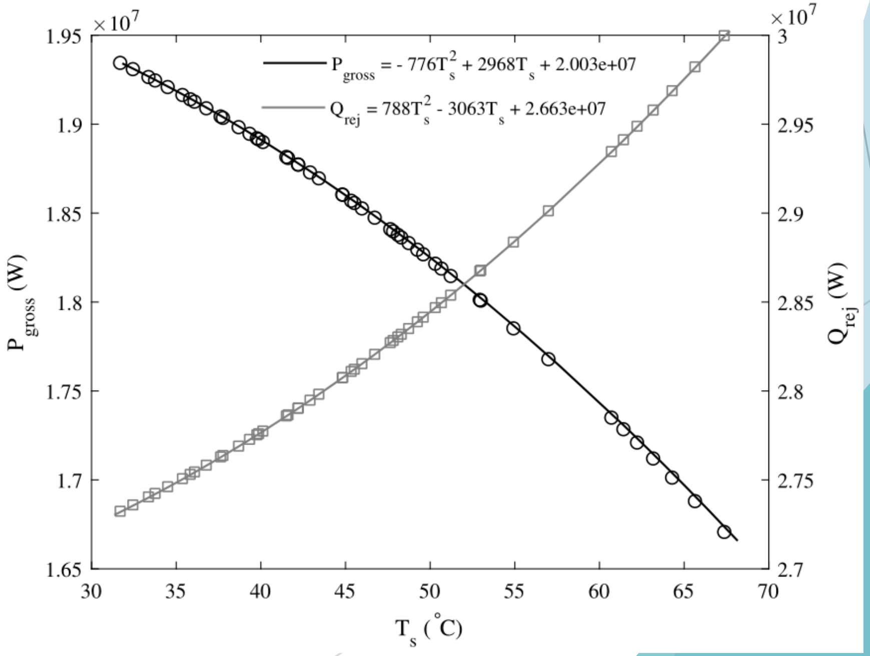
Thermodynamic Modelling

- Thermodynamic model developed to calculate plant performance with LTTS installed
  - Relationship between turbine and cooling solution
  - Each component is modelled on MATLAB
- Steam Turbine
  - 20MW nominal electrical output
  - Steam inlet temperature of 540°C
- Water-Cooled Condenser
  - Modelled as a standard “shell-and-tube” surface condenser

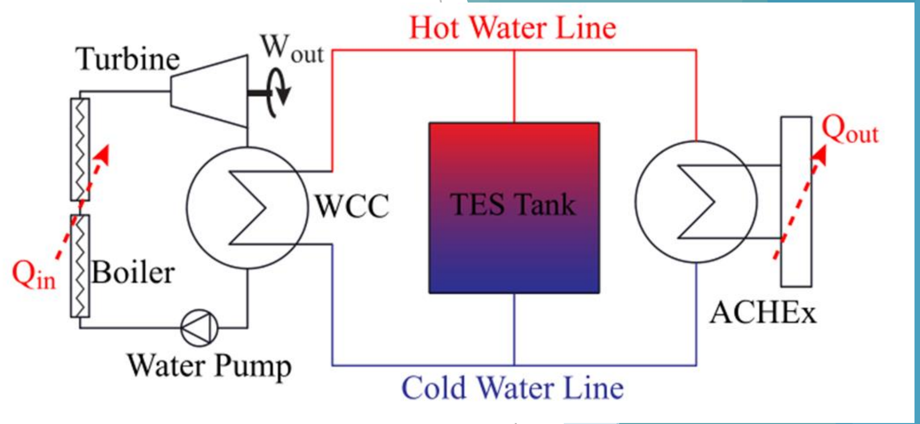
$$\dot{Q} = \dot{m}_w Cp(T_{w,o} - T_{w,i})$$

$$\dot{Q} = 1 - e^{-NTU}[\dot{m}_w Cp(T_s - T_{w,i})]$$





Thermodynamic Modelling



- Air-Cooled Heat Exchanger
  - Cross-flow, multi-row design
  - Bundles of122 annular-finned round tubes, arranged in a staggered 4 row configuration
  - Area was modelled as a variable (24,000 – 119,000 m^2)

$$T_{w,o} = T_{w,i} - \epsilon\left(T_{w,i} - T_{\infty}\right)$$

- Thermal Energy Storage Tank
  - Modelled as a prestressed concrete, thermally insulated, stratified water tank
  - Assumed to be adiabatic, and that no thermal mixing occurs in the tank
  - Sized to ensure that it had sufficient capacity to store the thermal load from the longest discharge period

$$V_{TES} = \frac{\dot{m}_w}{\rho_w} \times t_{DC} = 19{,}000 m^3$$

Benchmarking – ACC Model

- Air-cooled Rankine cycle model run in parallel with LTTS model
- ACC operating period = LTTS bypass period + LTTS discharge period
- Industry standard A-Frame ACC was modelled
  - A = 56,000 m^2 (6 cell unit)
  - Fans were modelled as single speed (on/off)
  - Fans were regulated in an effort to best maintain a constant steam temperature (set-point)

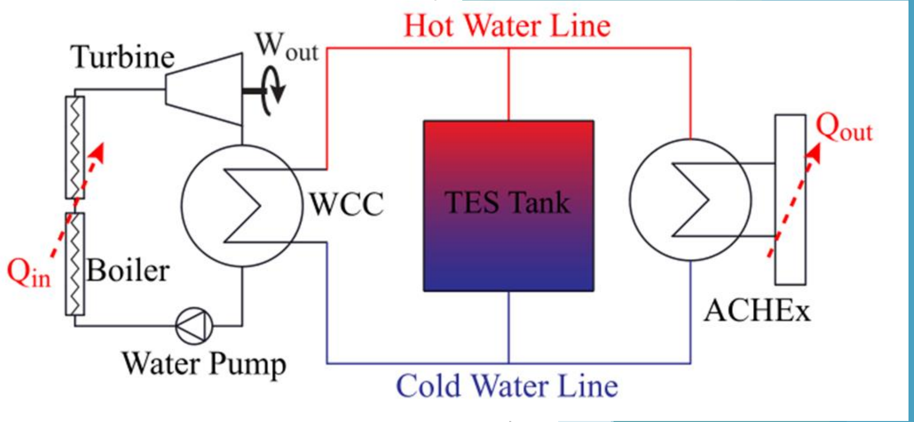
$$\dot{Q} = 1 - e^{-NTU}[\dot{m}_a Cp(T_s - T_\infty)]$$

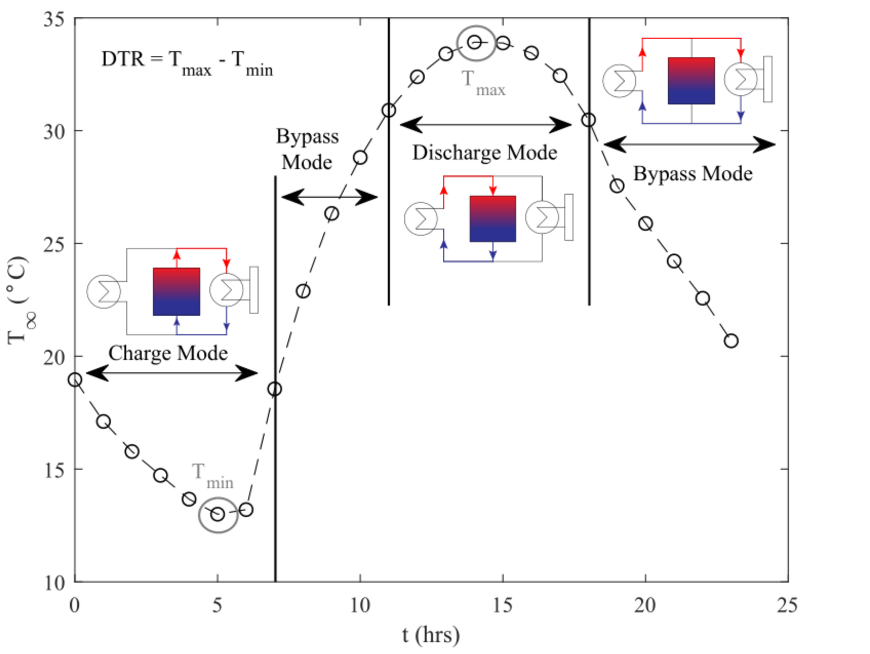
$$T_s = 38°\mathrm{C} \text{ when } T_\infty < 13°\mathrm{C}$$

$$T_s = T_\infty + 25°\mathrm{C} \text{ when } T_\infty > 13°\mathrm{C}$$

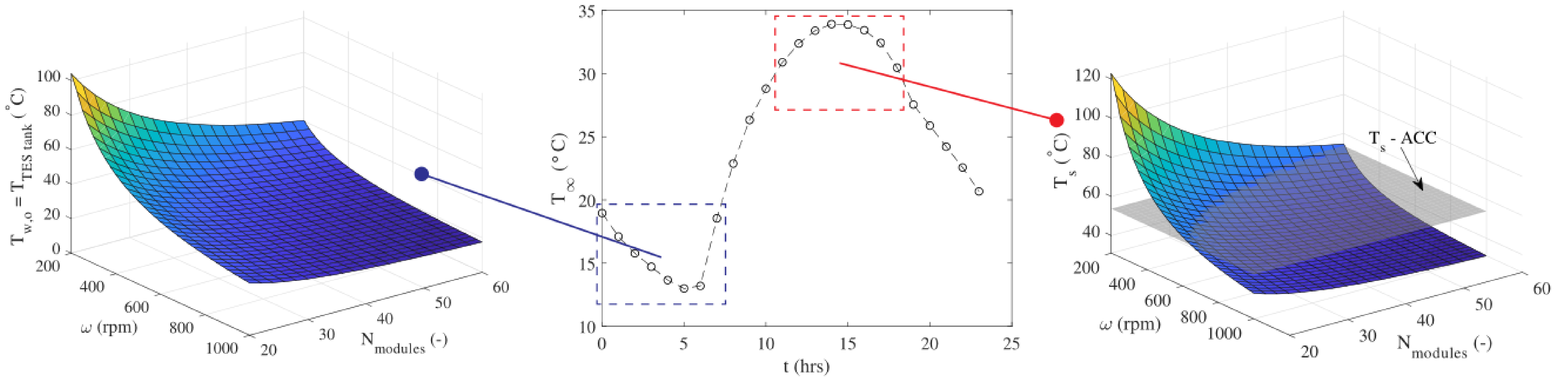
Modelling Procedure

1. Ambient temperature profile is divided
2. TES tank size is set (based on discharge duration)
3. ACHEx heat transfer area (number of modules) is set
4. ACHEx fan speed range is set
5. Bypass: $T_{w,o}$, T_s, P_{gross}, P_{fan}, and P_{net} are all calculated
6. Charge: Average T_w during charge period is calculated.
   - This is equivalent to the tank temperature
7. Discharge: T_s and P_{gross} are calculated from tank temperature obtained in Step 6
8. ACC model is run in parallel

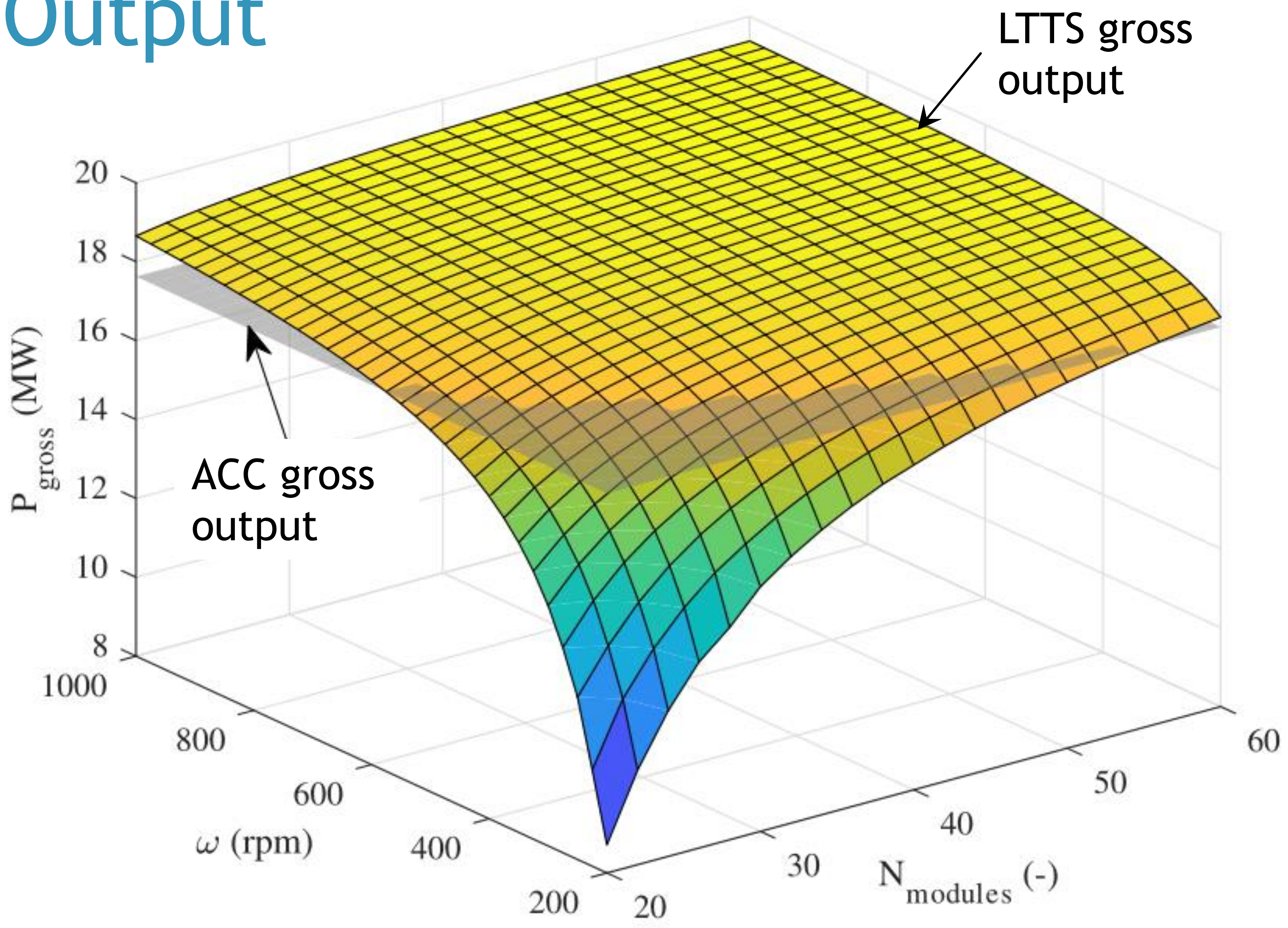




Phase I 8B/8D/8C Results – Temperature Profiles



Phase I 8B/8D/8C Results – Discharge Power Output

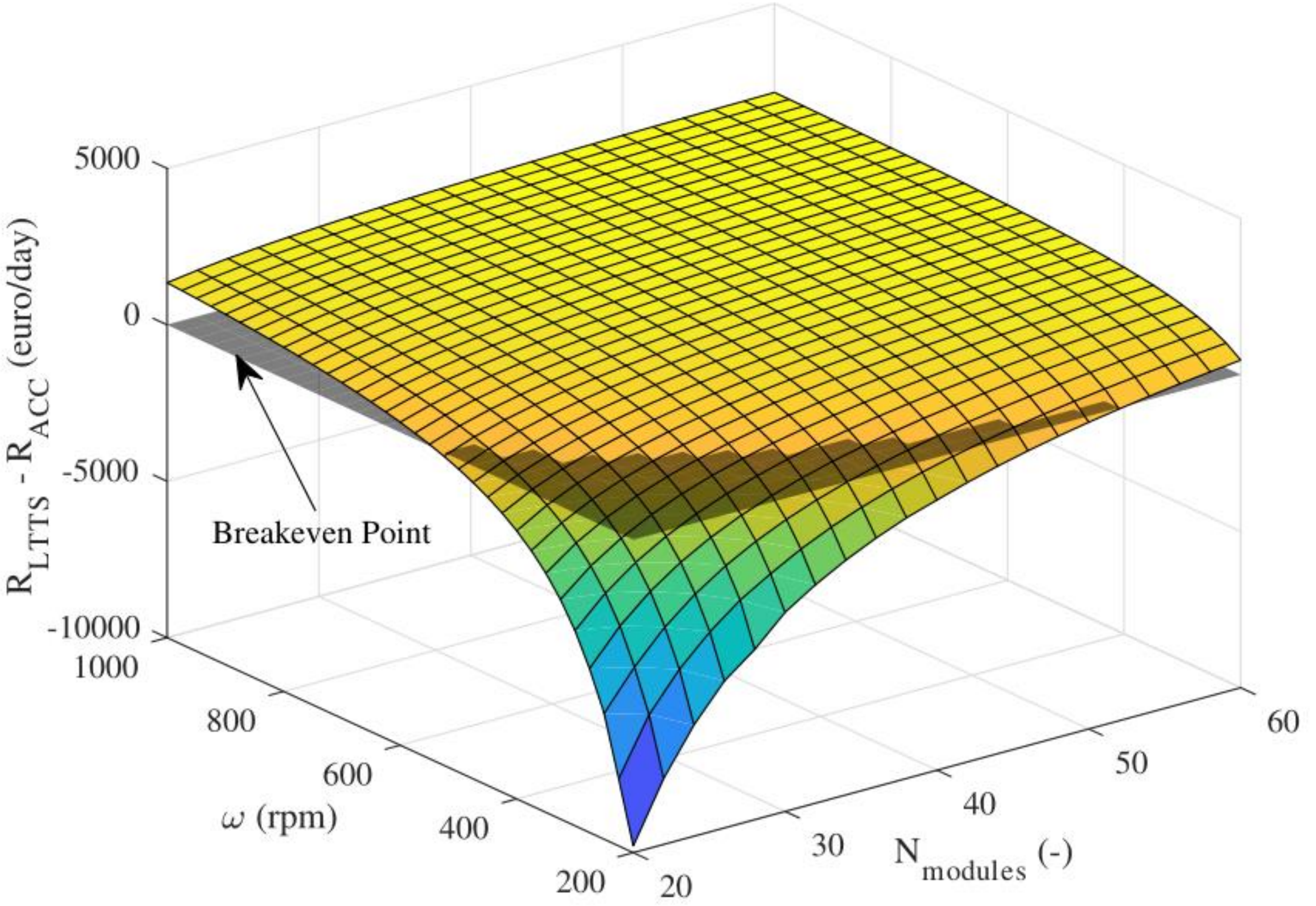


Phase I 8B/8D/8C Results – Revenue

$$R_{LTTS} = \sum_{t=S_{BP}}^{E_{BP}} \left(SP \times P_{net,BP}\right) + \sum_{t=S_{DC}}^{E_{DC}} \left(SP \times P_{gross,DC}\right) - \sum_{t=S_C}^{E_C} \left(PP \times P_{fans}\right)$$

$$R_{ACC} = \sum_{t=S_{ACC}}^{E_{ACC}} \left(SP \times P_{net,ACC}\right)$$

$$SP = €0.14/kWh$$
$$PP = €0.035/kWh$$

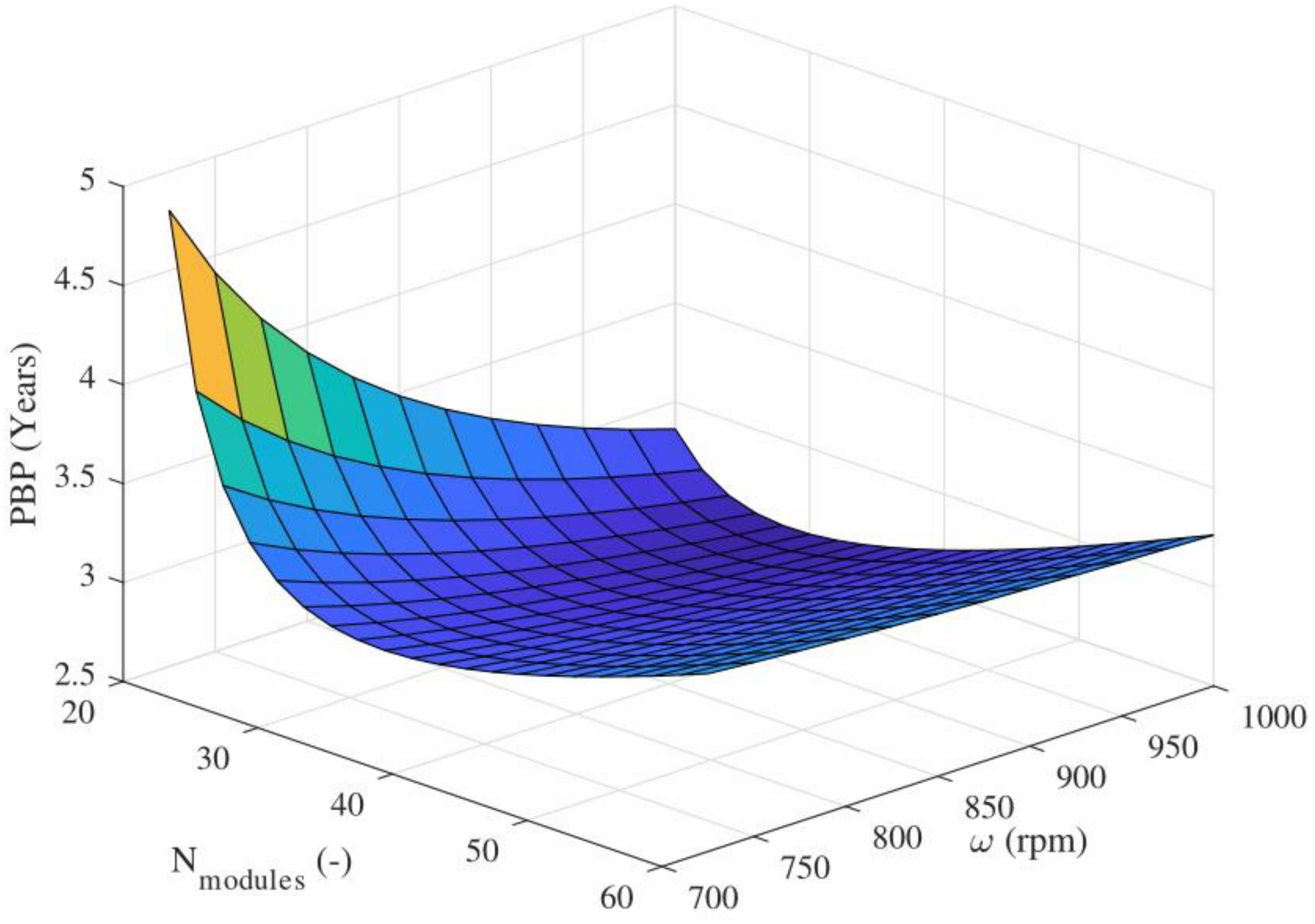


Phase I 8B/8D/8C Results – Payback Period

$$PBP = \frac{CAPEX_{LTTS} - CAPEX_{ACC}}{R_{LTTS} - R_{ACC}}$$

$$CAPEX_{LTTS} = CAPEX_{WCC} + CAPEX_{Tank} + CAPEX_{ACHEx}$$

- $CAPEX_{WCC}$ = €0.2 M
- $CAPEX_{Tank}$ = €120/m^3 = €2.5 M
- $CAPEX_{ACHEx}$ = €29,000/tube bundle = €1.5 M
- **$CAPEX_{LTTS}$ = €4.2 M**
- **$CAPEX_{ACC}$ = €2.4 M**

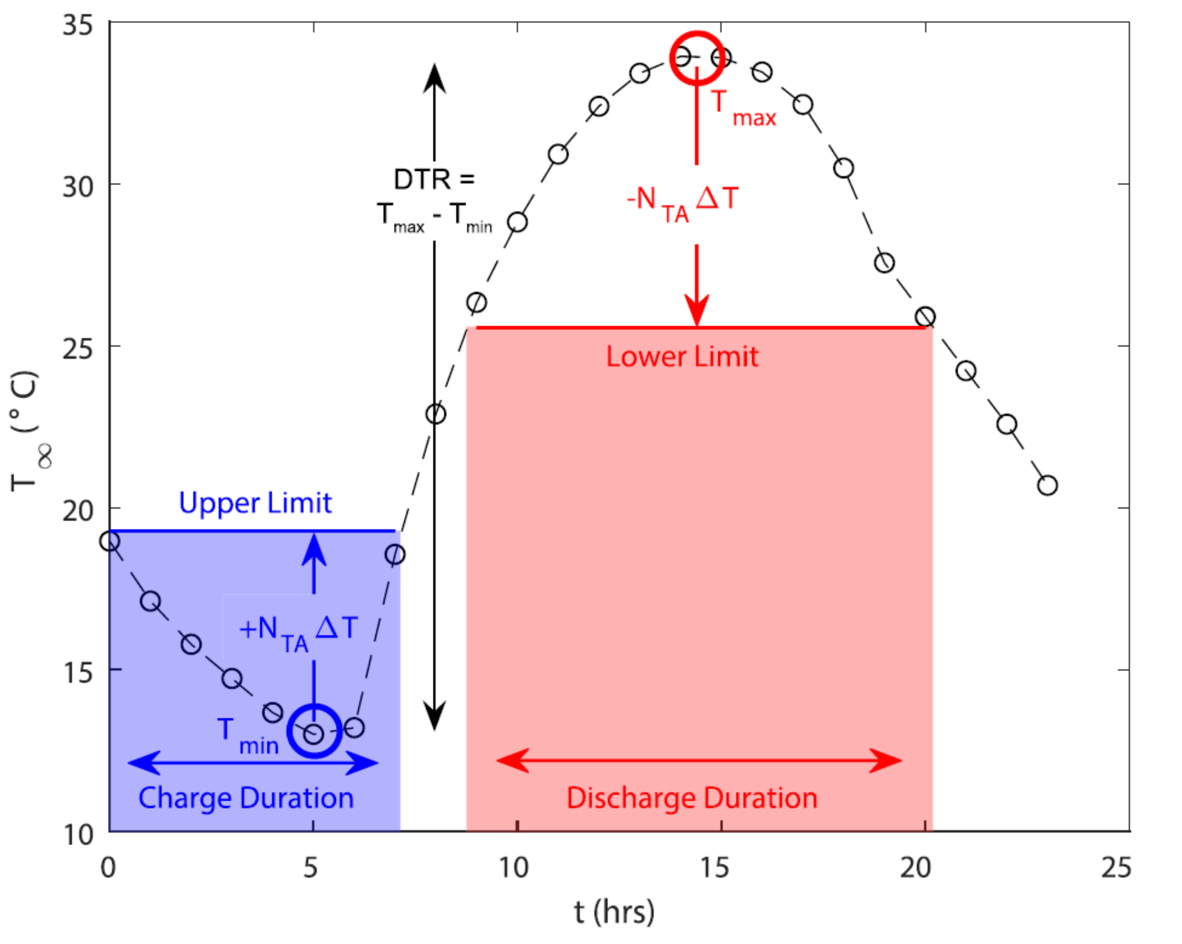


Phase II Investigation

- Multiple Time Apportionments (TA)
- Multiple sites
- Month by month data

Phase II – Time Apportionment

- For each site and each month, five individual TAs were modelled.
- TAs are denoted N_{TA} =1 to N_{TA} = 5.
- For all TAs, the durations of the charge, bypass and discharge periods are defined as follows, where $\Delta T = 0.1(T_{max} - T_{min})$:
  - Charge duration: time during a daily temperature cycle for which $T_{min} \leq T < (T_{min} + N_{TA}\Delta T)$
  - Discharge duration: time during a daily temperature cycle for which $(T_{max} - N_{TA}\Delta T) < T \leq T_{max}$
  - Bypass duration: tie during a daily temperature cycle for which $(T_{min} + N_{TA}\Delta T) \leq T \leq (T_{max} - N_{TA}\Delta T)$



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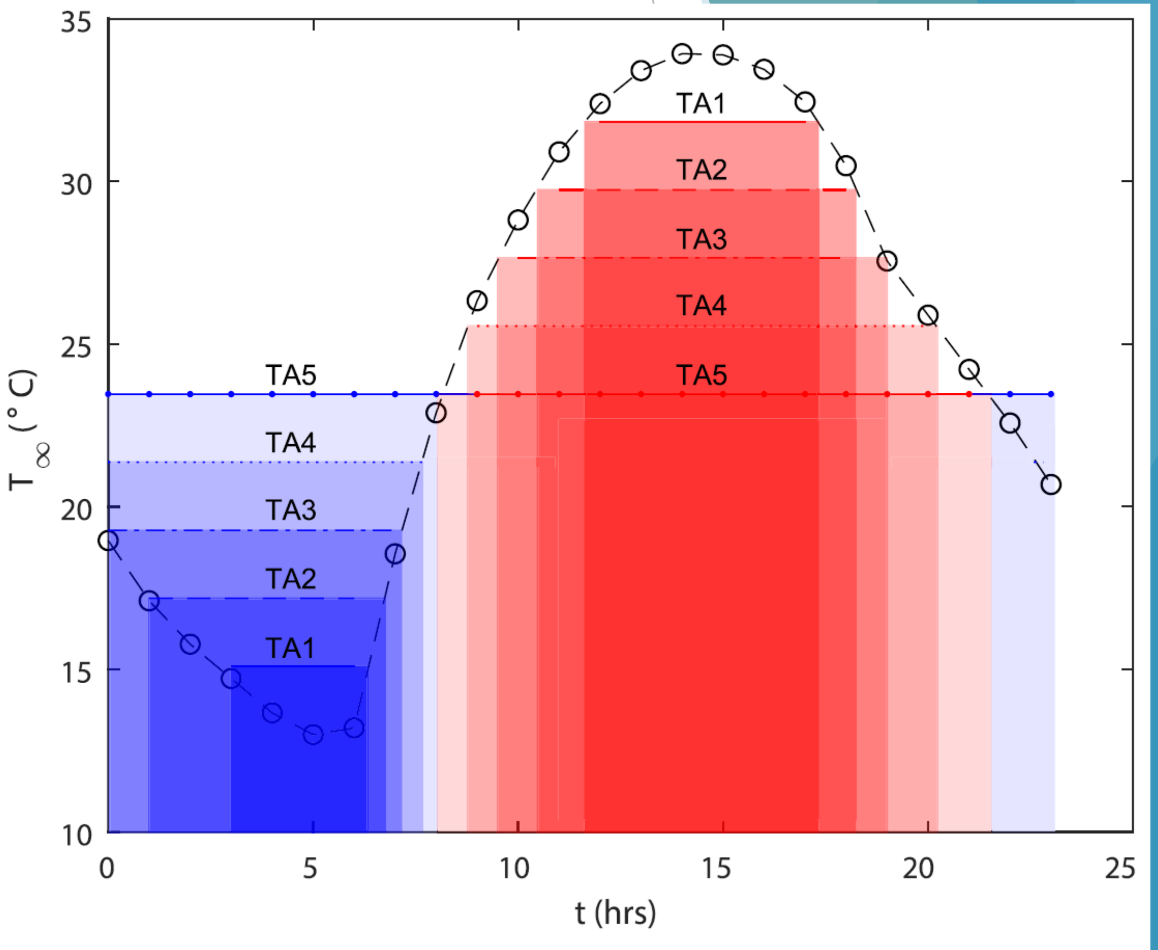
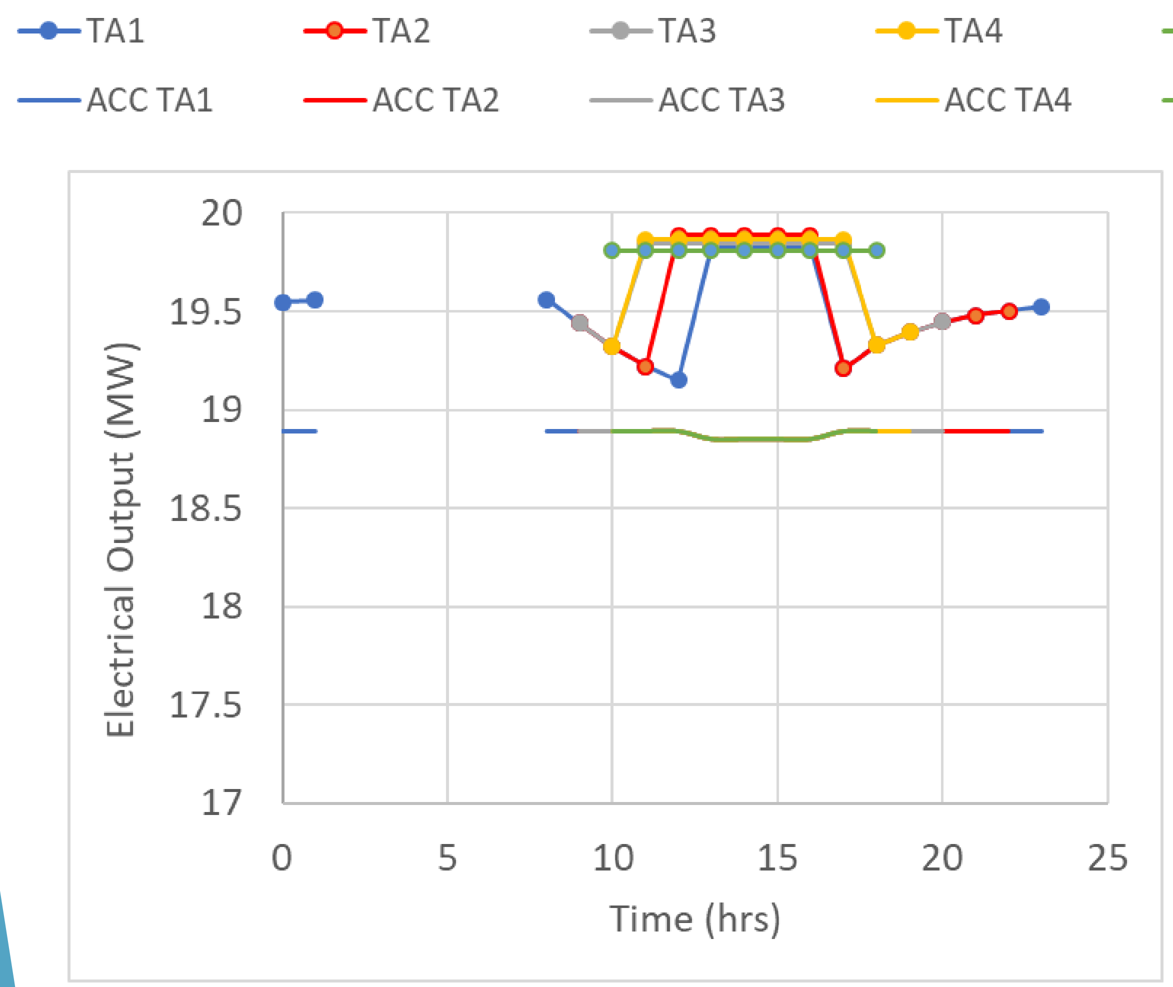
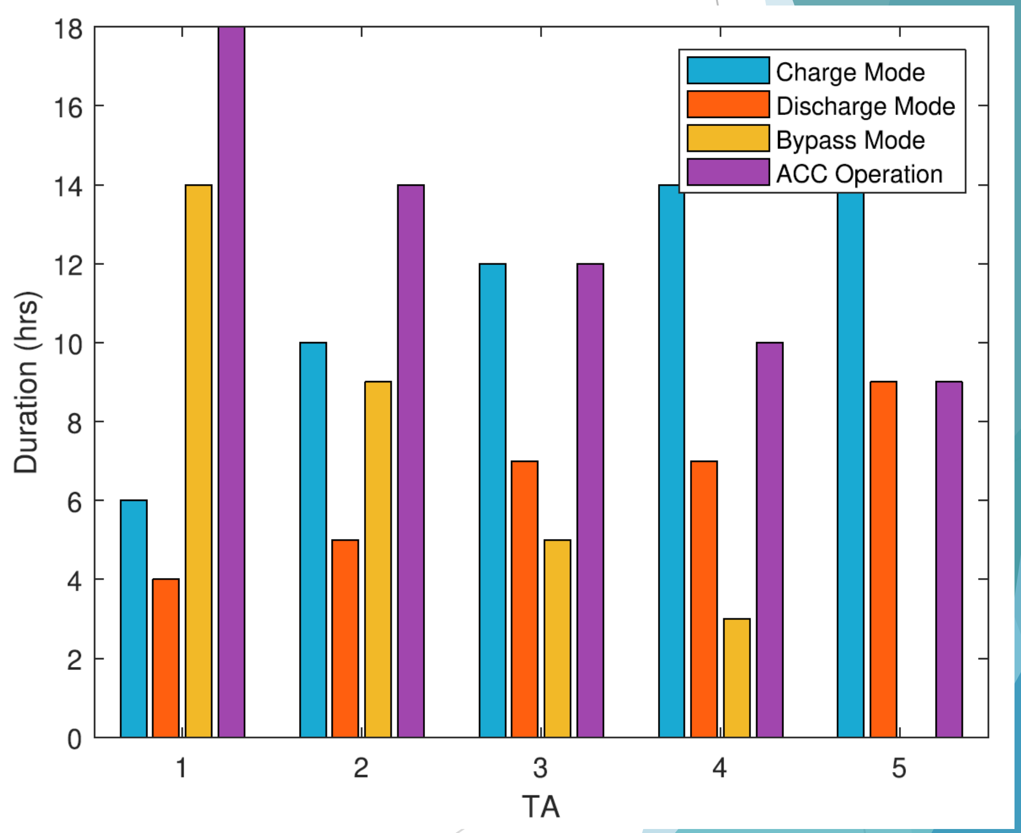


Hourly output: LTTS vs ACC, Bishop January

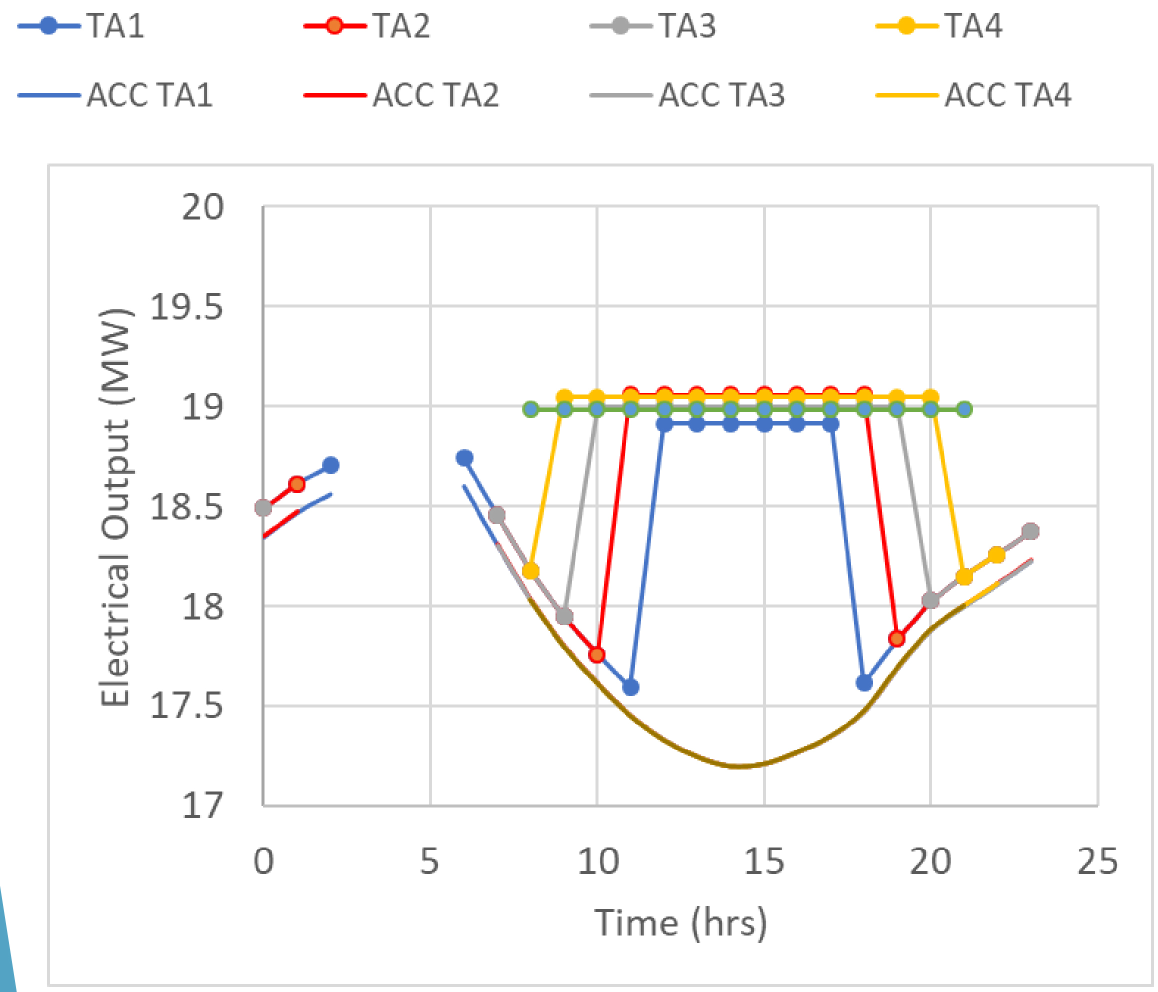


Daily Power Output



Time Apportionments

Hourly output: LTTS vs ACC, Bishop July



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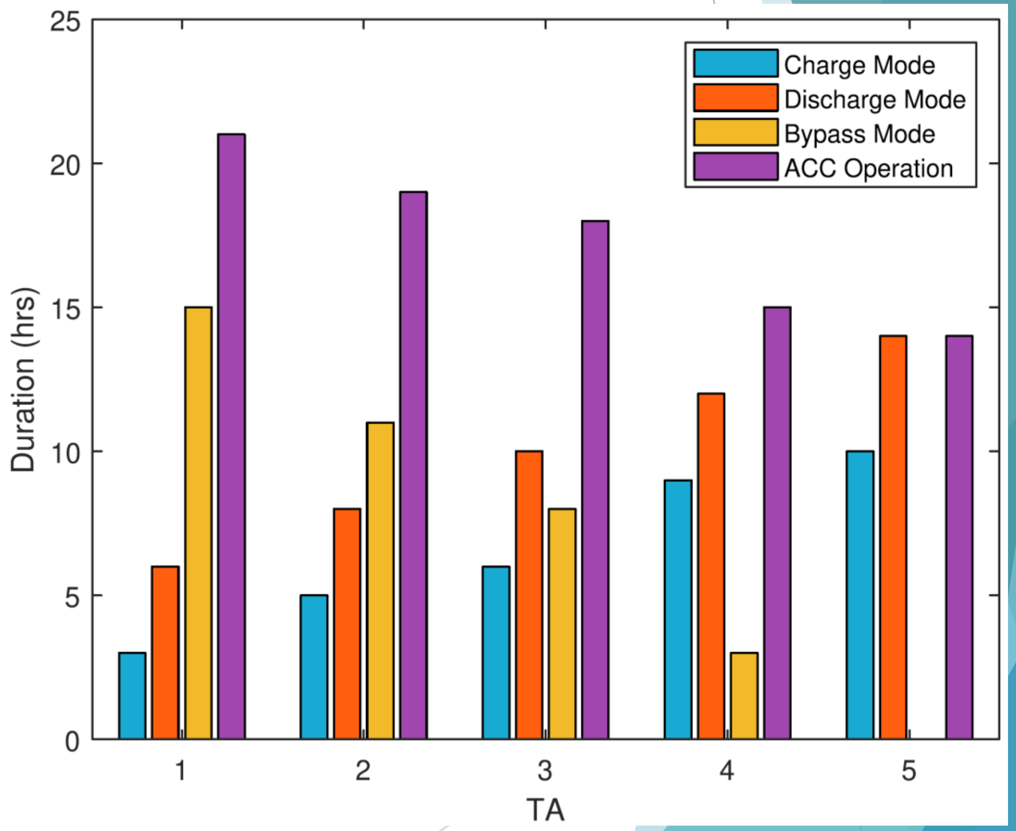
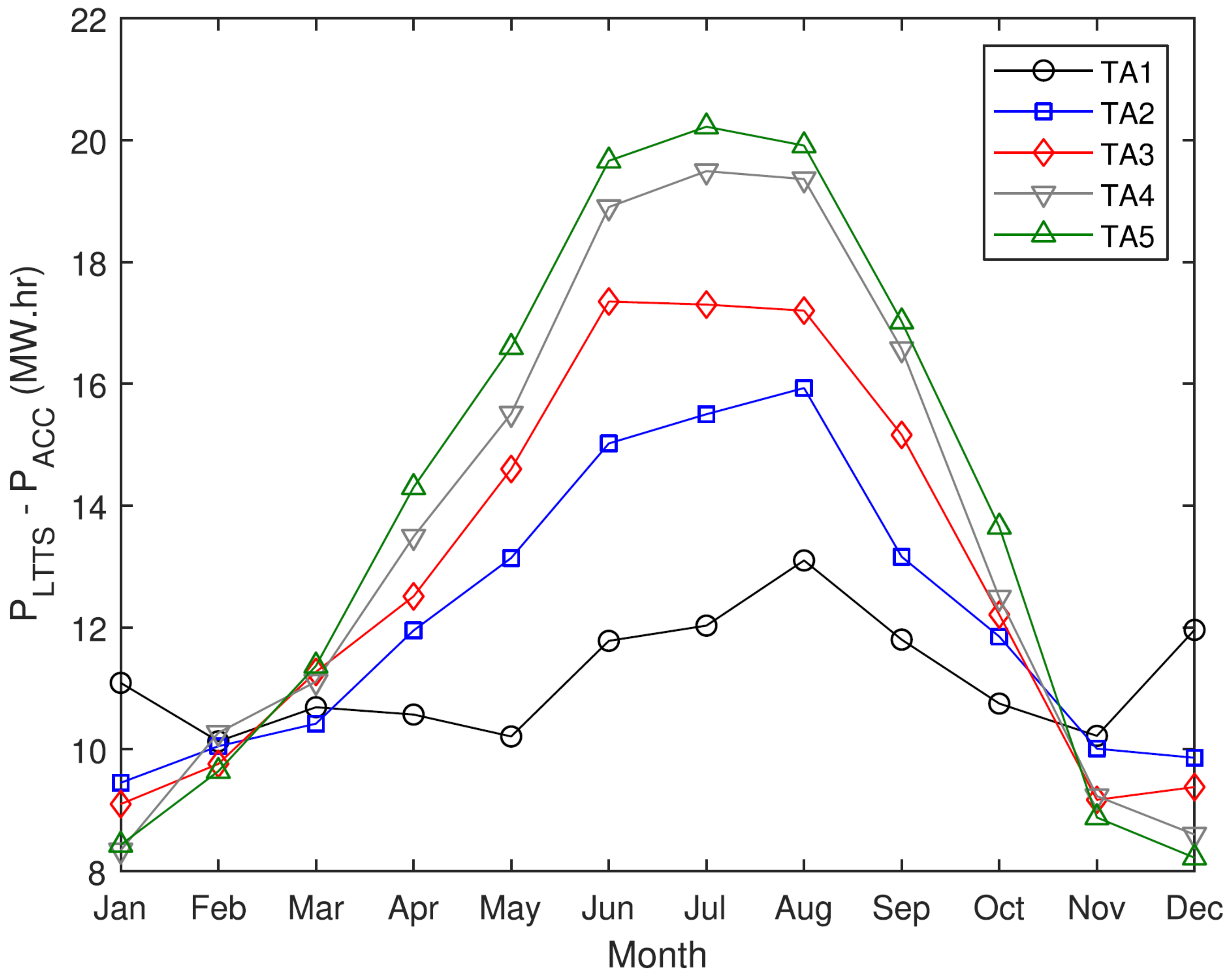


Time Apportionments

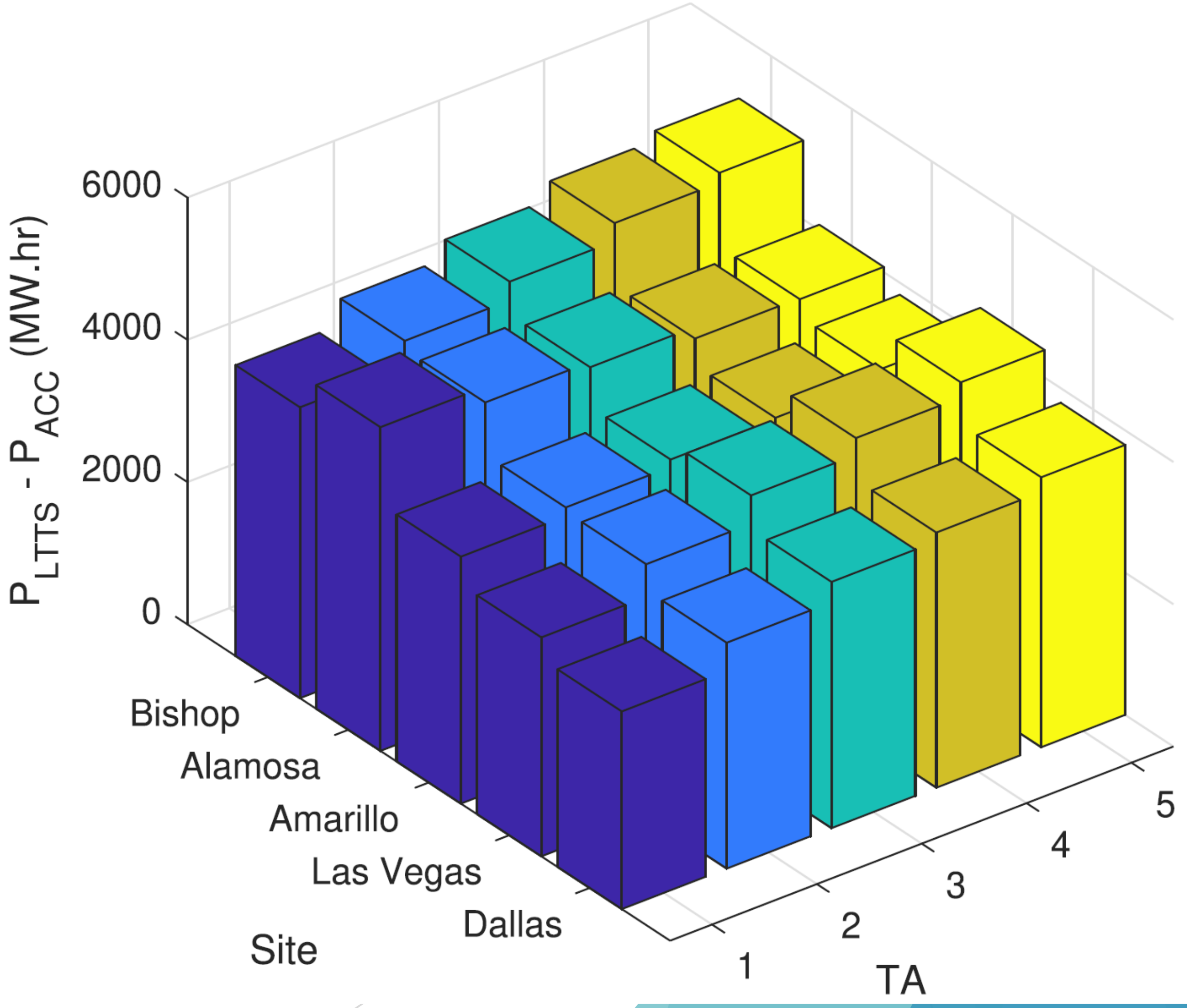
LTTS/ACC monthly power output comparison

- Midsummer peak in output gain
- LTTS power output gain relative to ACC increases as TA progresses from TA1 to TA5
- This trend is due to higher summertime temperatures and longer discharge durations in TA5 than TA1



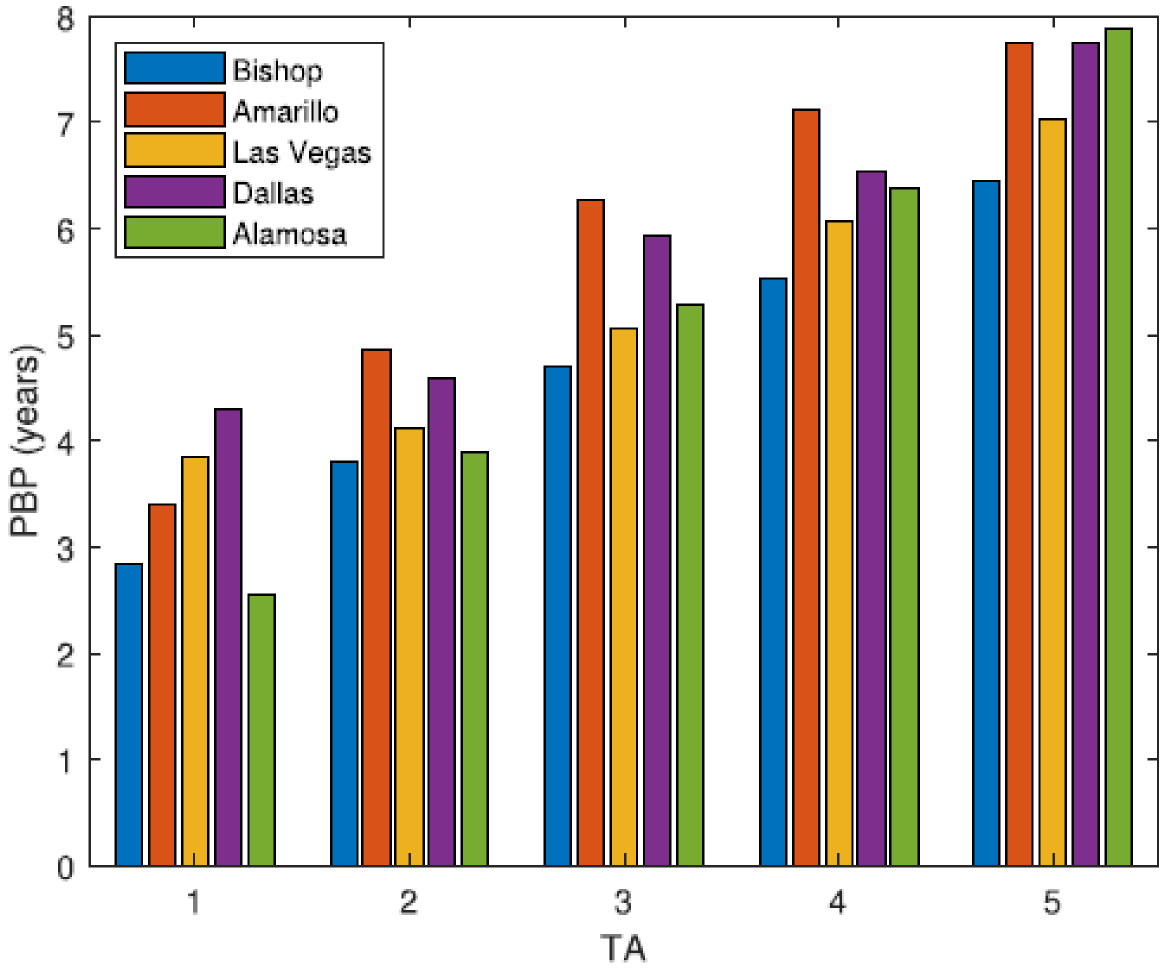
Summary of additional power produced by LTTS per year for each location and TA

- Sites presented in order of decreasing summertime DTR
- Not definitive, but data suggest reducing benefit with reduced DTR
- Little evidence of correlation between peak summer temperature and LTTS performance gain
- Correlation between increased discharge mode operation time and increased LTTS performance gain holds for all but Alamosa

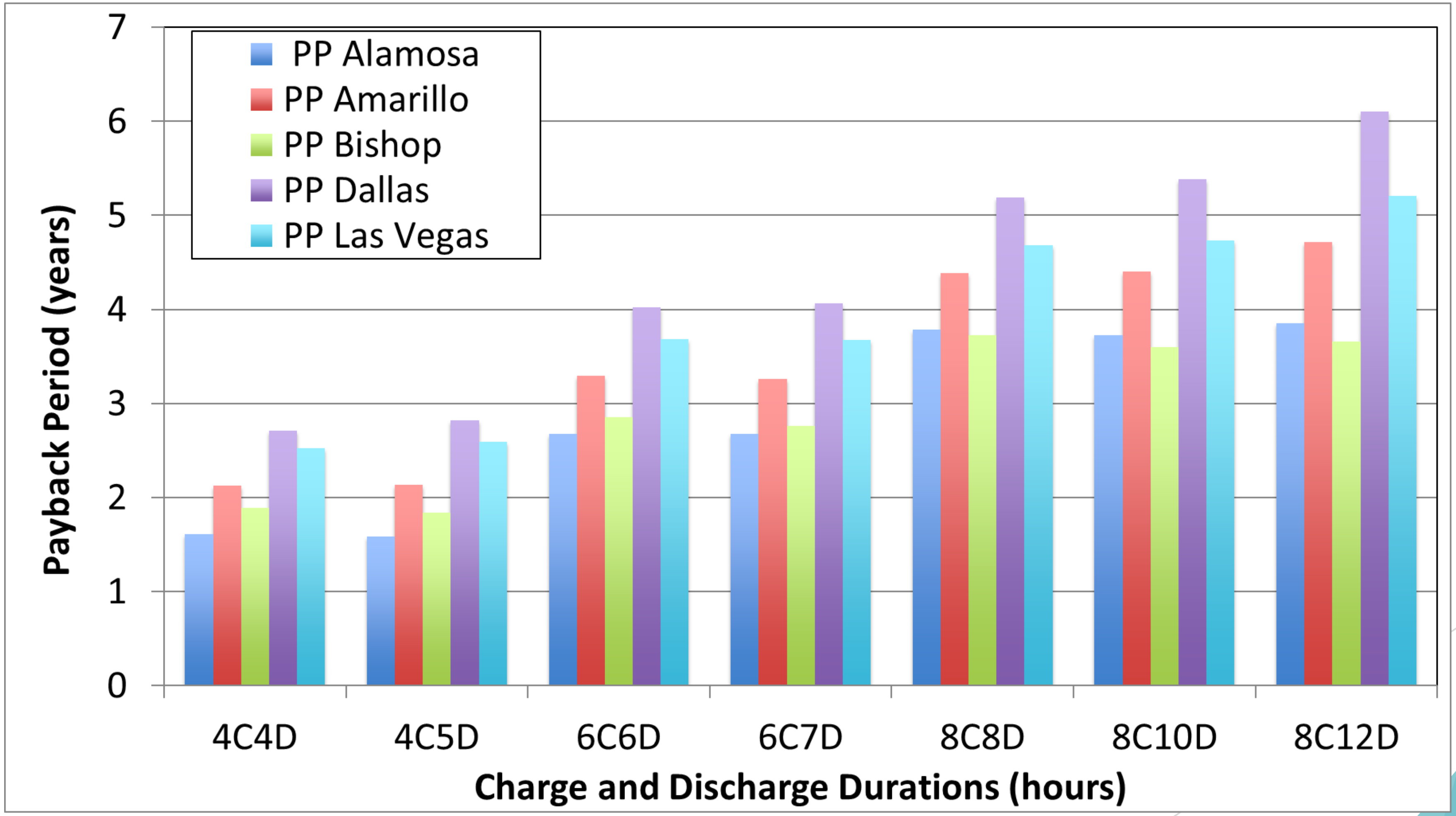


Summary of payback periods

- Increased PBP from TA1 to TA5 due to increased capital cost associated with storage tank
  - ~6hrs TA1 Vs 12-14hrs TA5
- Temperature based definition of TAs prevents full utilisation of storage capacity throughout much of the year
- Preliminary work on improvement of TA strategy showing promise in further reduction of PBP



TAs with fixed charge/discharge durations

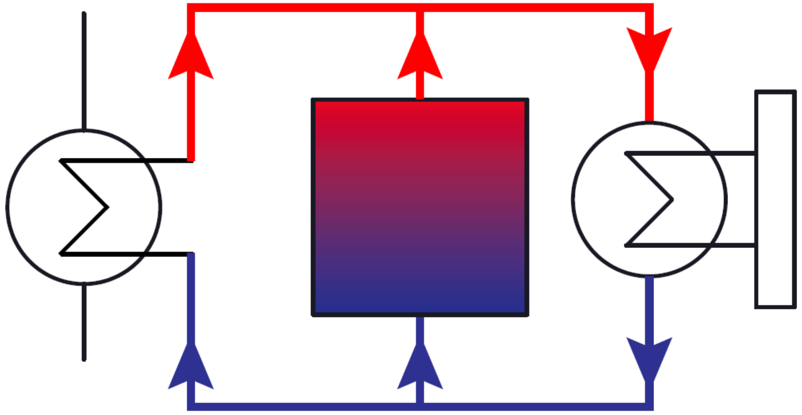


Conclusions

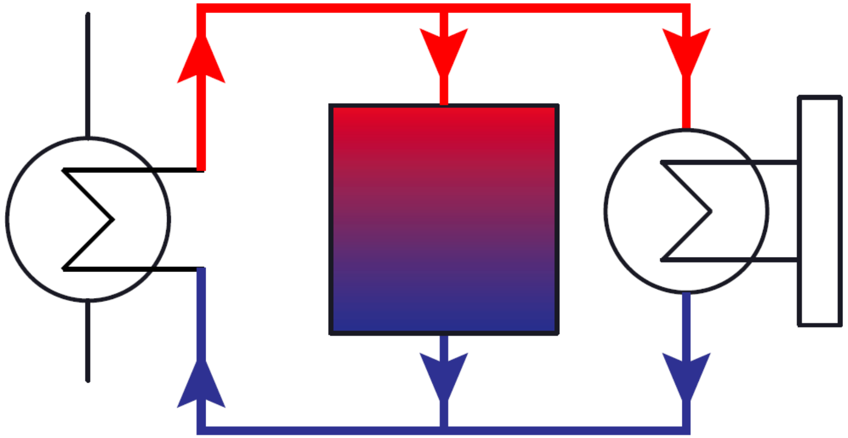
- The study has demonstrated the thermodynamic and economic merit of LTTS, and has proven that it is feasible for utility-scale thermal power plants when using chilled water as the storage medium.
- The effectiveness of LTTS has been shown to be related to the diurnal temperature range.
- Feasibility in economic terms appears most favourable for systems with short discharge phase durations (not exceeding 7–8 h). Payback periods of less than 2 years achievable.
- Potential outlined in this study provides sufficient motivation for extending the investigations of LTTS.

Future work

- Modelling
  - Modelling scenarios with parallel charge and parallel discharge
  - Improved time apportionment strategies
  - Different heat source temperatures
  - More refined ACC modelling – variable speed fans
  - Tank stratification studies
  - Refinement of low pressure constraints for ACC and LTTS
- Refinement of CAPEX data
- Benchmarking against other cooling configurations
- Analysis of electricity buy and sell prices in various markets
- Storage density enhancement
- Demonstration



Parallel Charge



Parallel Discharge

IP Status

- Patent protection secured in a number of jurisdictions
- Proceeding to grant in others

Questions?