CST Power blocks for improving annual efficiency

ASTRI Symposium on The Future of Concentrating Solar Thermal Technology

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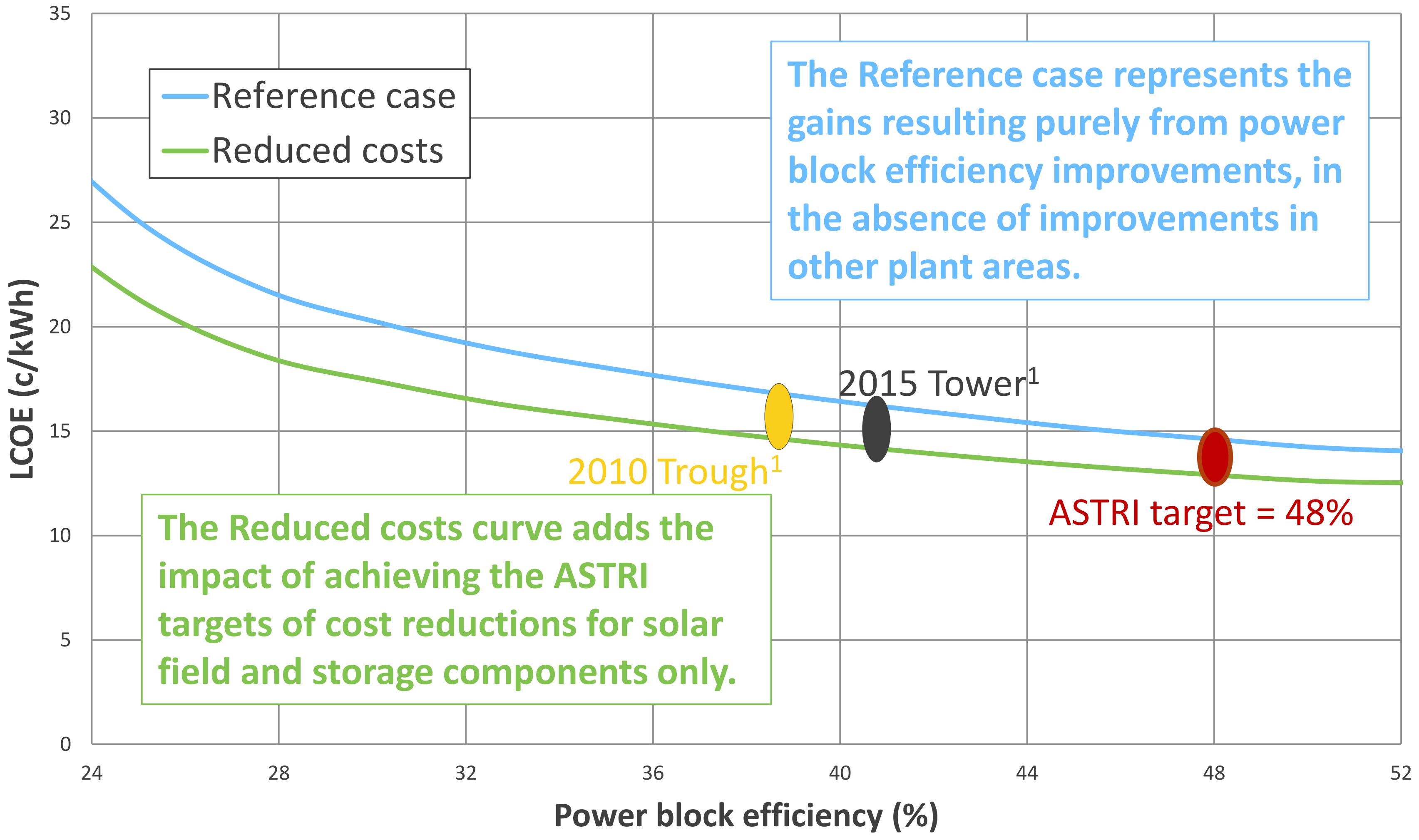
Node Overview

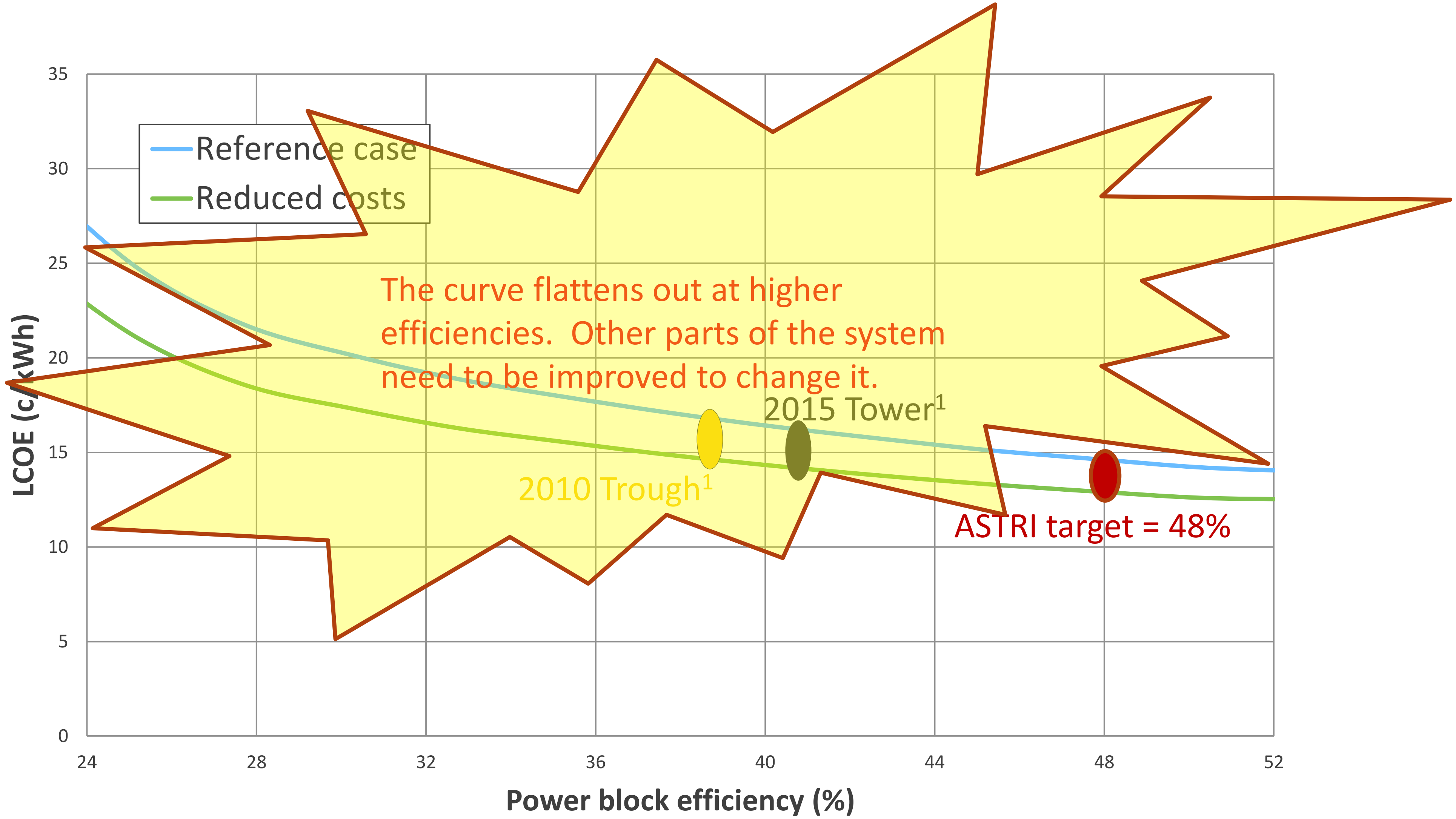
- The aim
  - Help the ASTRI objective of reducing the levelised cost by increasing the power conversion efficiency
- The focus
  - Novel high-temperature cycles *Supercritical CO_2 and others*
  - Advanced dry and hybrid cooling towers
- Interaction
  - Significant interaction with the thermal storage development (Node 2)
  - Significant interaction with the receiver development (Node 1)

Efficiency Dividend



[1] Sunset Vision Study (p.115). Also actual efficiencies on recently built CST plants.

Efficiency Dividend



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Node Projects

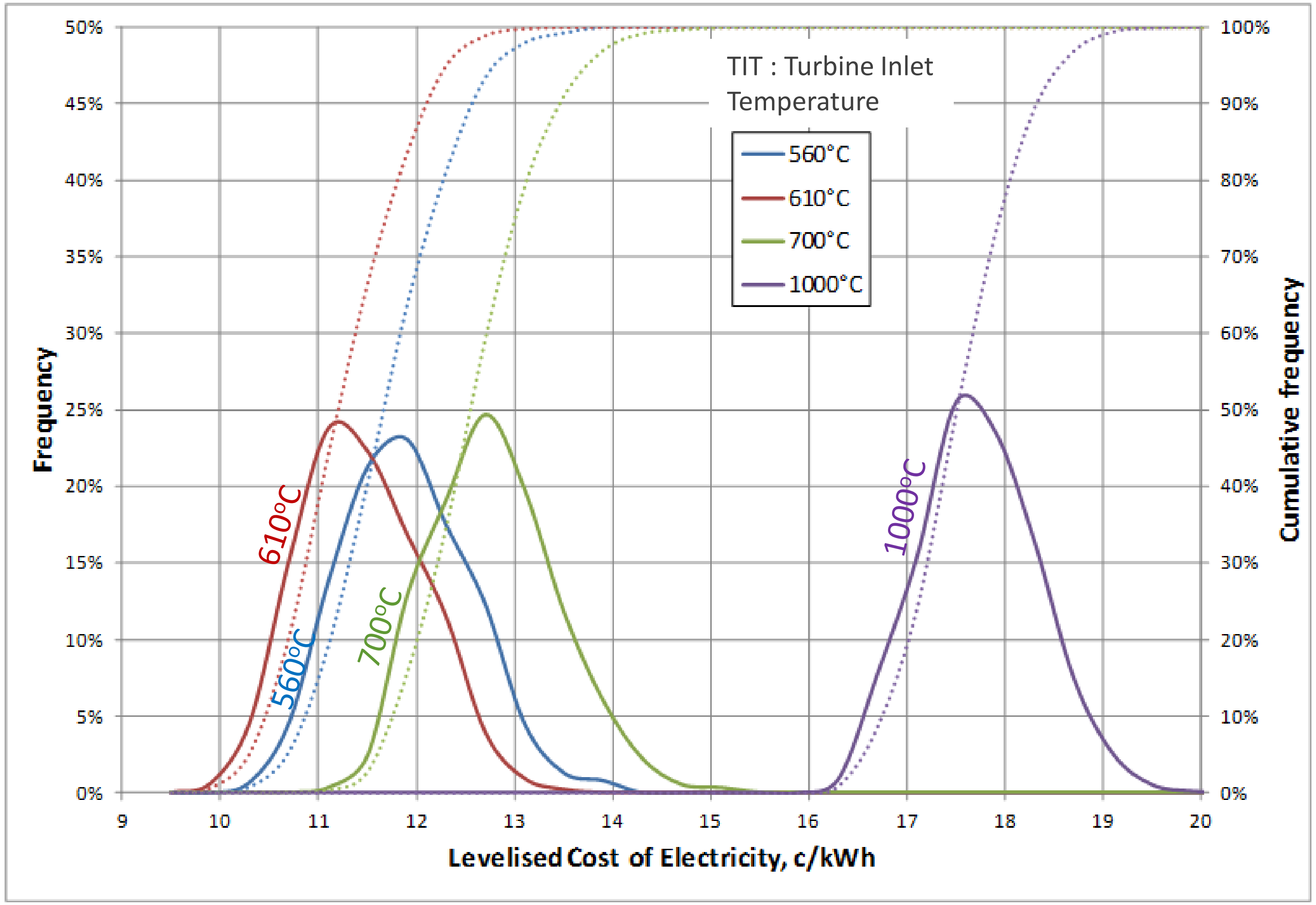
- Project P31A – Design a sCO_2 power block optimised for the radial sCO_2 turbine developed in the project:
  - Techno-economic optimisation of power cycles for future sCO_2 plants
  - Supercritical CO_2 power cycle and turbine technology
    - Design tools for turbomachinery using sCO_2
    - Foil bearing design
    - Dry gas seals
    - Specialist codes for sCO_2 and other fluids with nonlinear properties
  - Hybrid cooling technologies for efficient power generation in arid areas.
- P32 – Considers a broad range of alternative power blocks including Rankine, Brayton and Combined cycles with:
  - Different working fluids (He, air, ORC, supercritical steam)
  - Different engines (steam and gas turbines)

Why Supercritical CO_2?

Supercritical CO_2 cycles are attractive for three reasons:

- More efficient than steam cycle above 560°C
  - ✓ and keeps getting better at higher temperatures
  - ✓ The ASTRI target is a turbine inlet temperature of 610 °C

Why 610ºC?



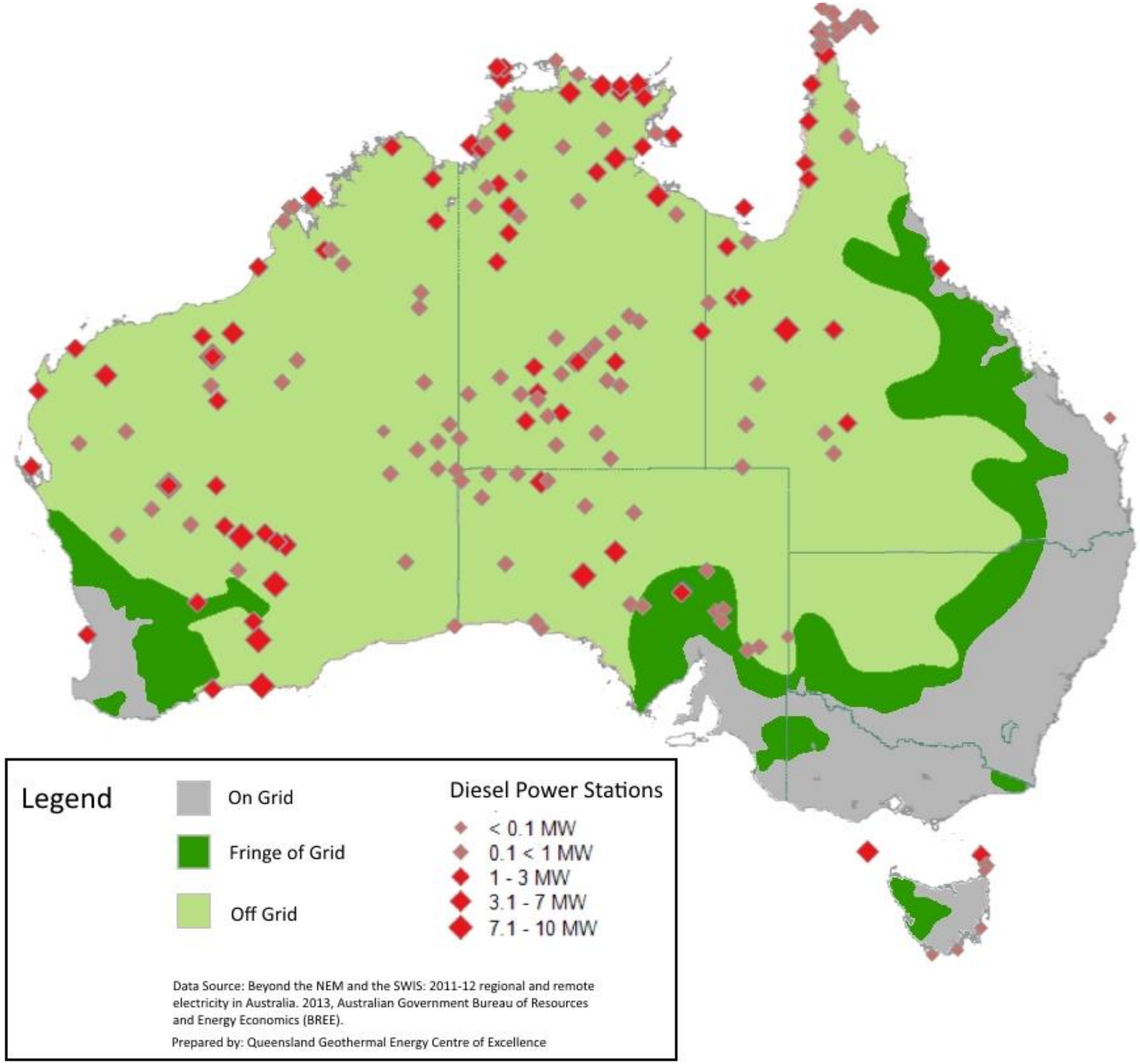
TIT : Turbine Inlet Temperature
560°C
610°C
700°C
1000°C
Frequency
Cumulative frequency
Levelised Cost of Electricity, c/kWh
50%
45%
40%
35%
30%
25%
20%
15%
10%
5%
0%
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
9
10
11
12
13
14
15
16
17
18
19
20
610ºC
560ºC
700ºC
1000ºC

Why Supercritical CO_2?

Supercritical CO_2 cycles are attractive for three reasons:

- More efficient than steam cycle above 560°C
  - ✓ and keeps getting better at higher temperatures
- Simpler and more compact; therefore cheaper
  - ✓ Later, I will show you how small a 1-MWe turbine rotor is
- Can be downsized without a cost penalty
  - ✓ This is important especially for Australia. We will see why.

P31A – The relevance for Australia



The present CST technology has nothing offer to replace these power stations.

A sCO_2-based CST will start by targeting the low-hanging fruit first and will progress to utility-size installations.

Small plant also means higher optical efficiency

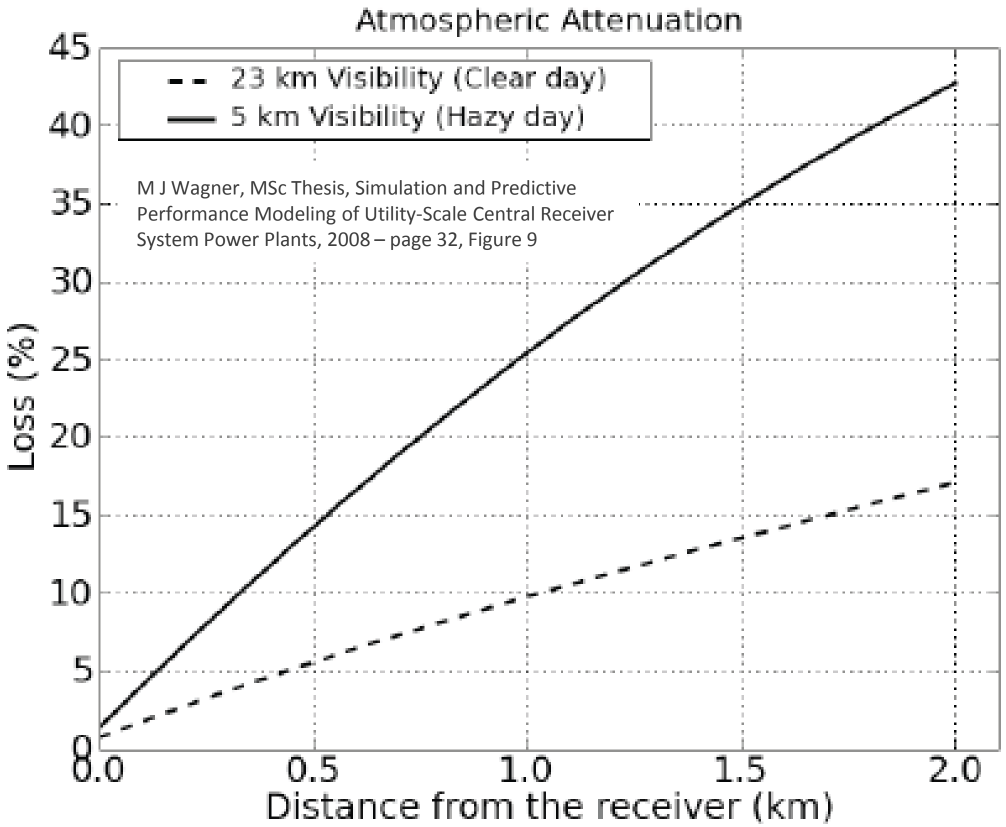
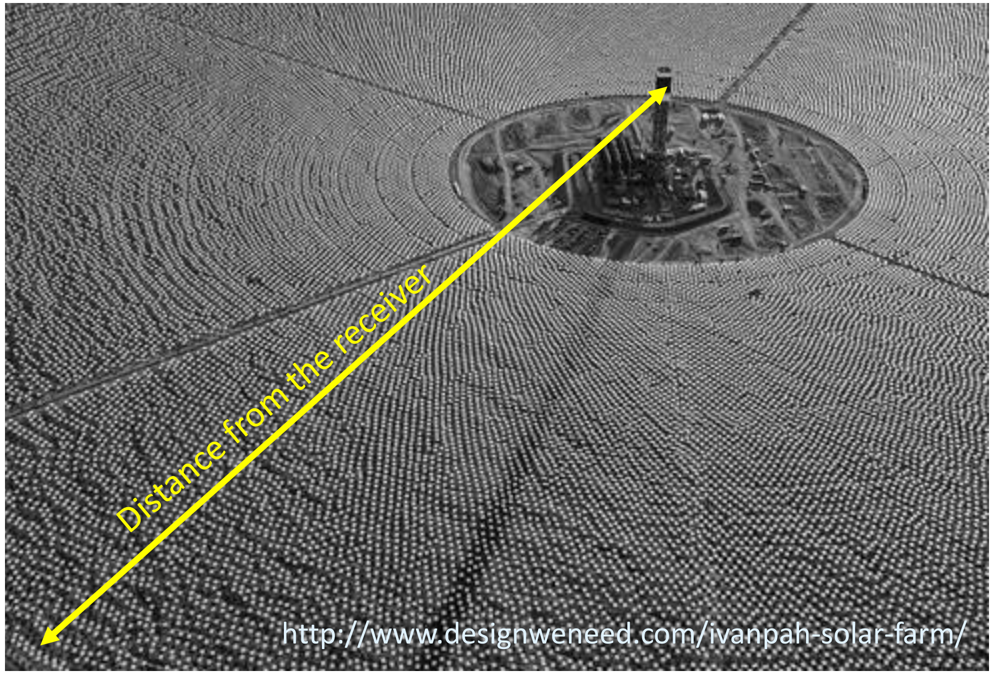
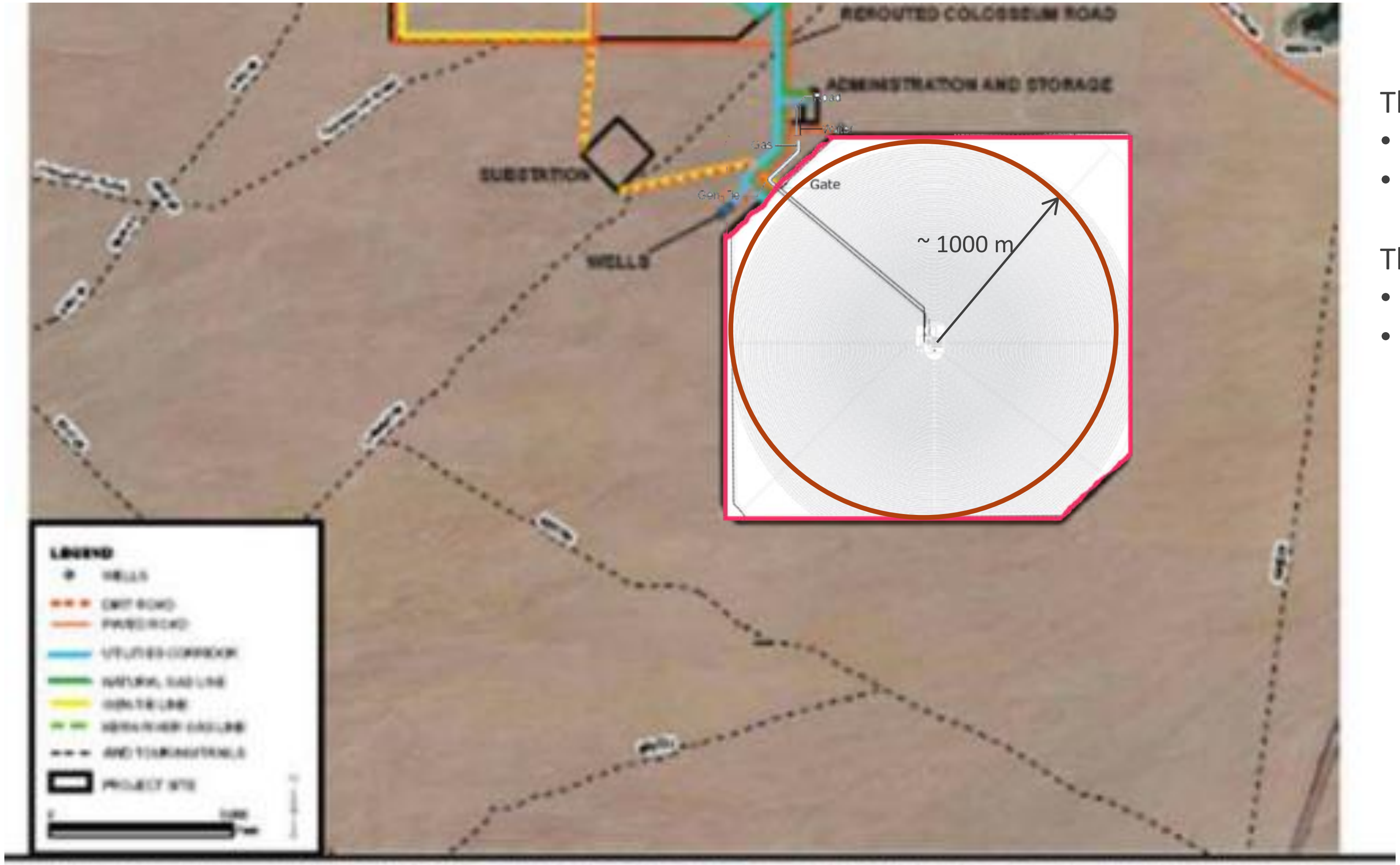


Figure 9: The atmospheric attenuation for Daggett, CA, at visibilities of 23km and 5km (Hottel, 1976).

Supercritical CO_2 makes it possible to build small power plants with small fields. This may mean efficiency gains of around 5% and more because of shorter light transmission paths.



Ivanpah



U.S. BUREAU OF LAND MANAGEMENT and CALIFORNIA ENERGY COMMISSION - SITING, TRANSMISSION AND ENVIRONMENTAL PROTECTION DIVISION, OCTOBER 2009
SOURCE: Data Response 21 - Fig.1 - Trails

The closest distance = 150 m

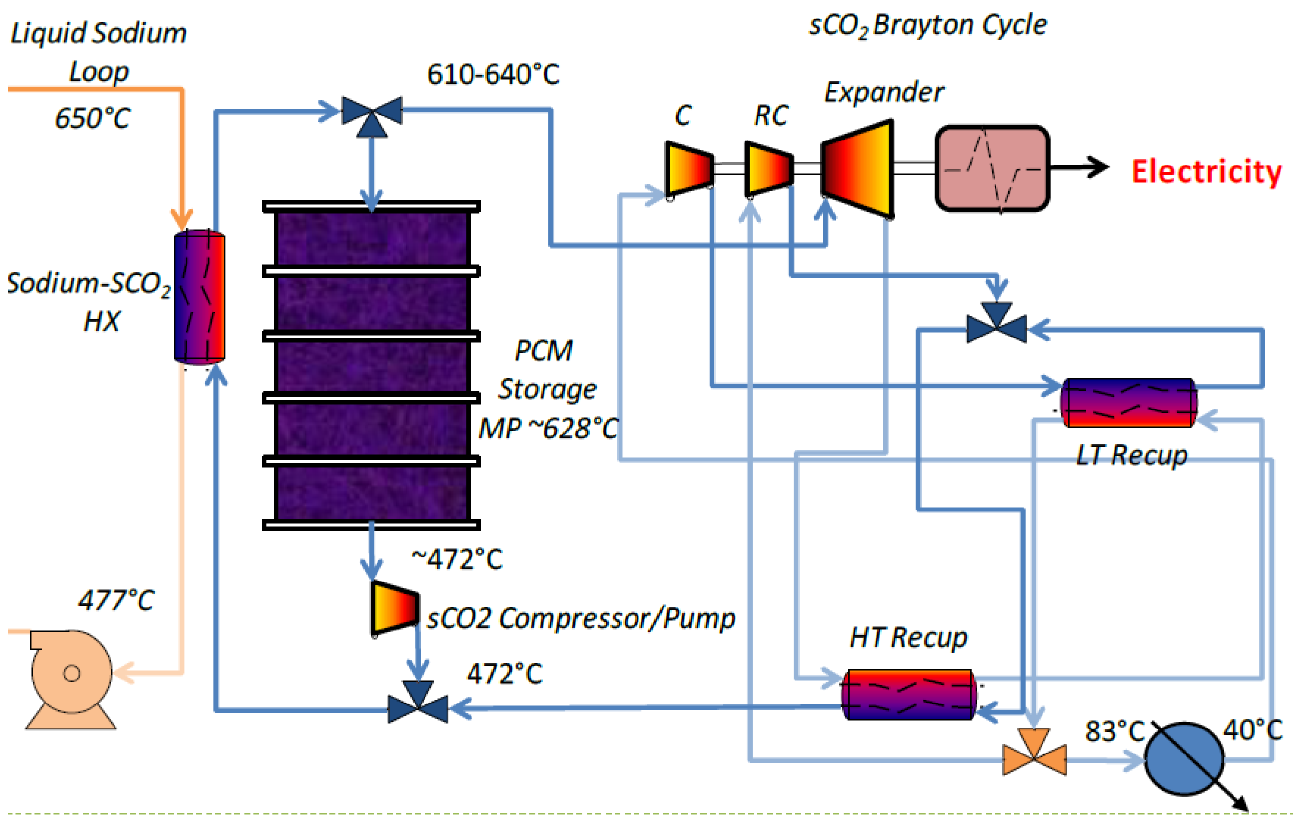
- 2% power loss on clear days
- 5% power on hazy days

The longest distance = 1000 m

- 10% power loss on clear days
- 25% power loss on hazy days

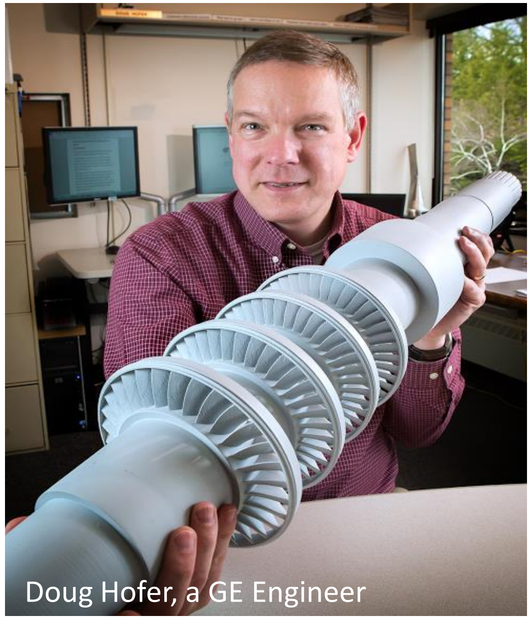
P31A – Missing components for a sCO2 power block

- Compressor - ✓
- Recuperator - ✓
- Cooling Tower - ✓
- Expander - ✗
- Generator - ✓



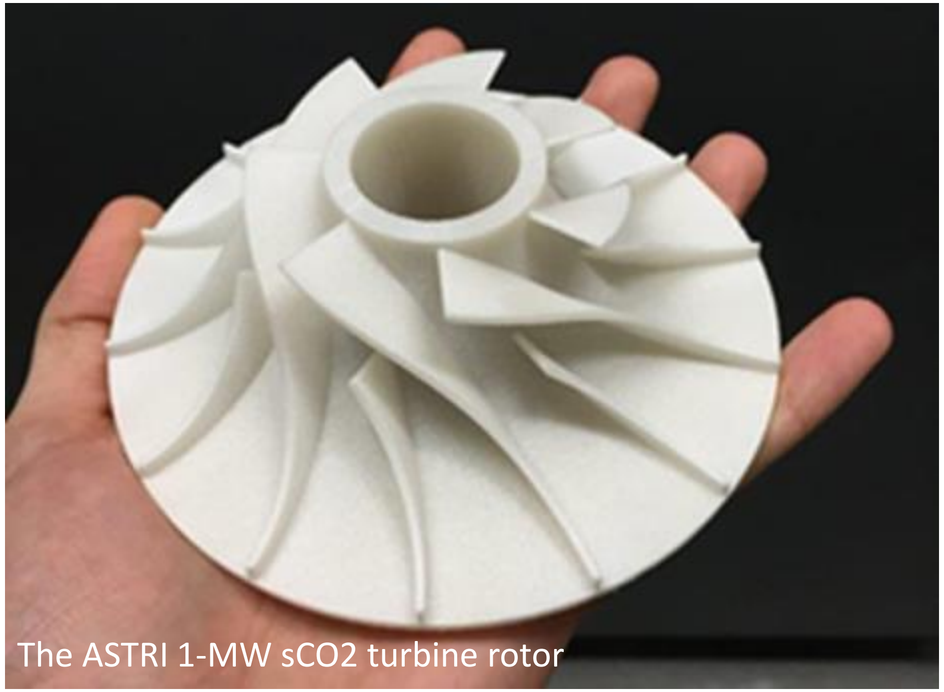
This is the present ASTRI plant configuration but we are considering other options to increase the efficiency.

P31A – Global Context


Doug Hofer, a GE Engineer

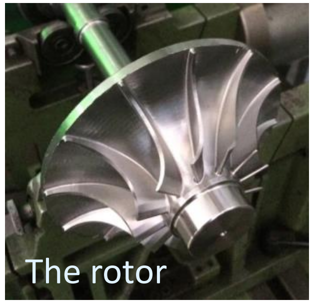
The GE Global Research is also developing a sCO_2 turbine. It is axial and therefore suitable for large plants (>50 MWe).

The ASTRI chose a radial turbine configuration to cover the range 1-30MWe. The ASTRI and the US turbines, in combination, will offer the benefits of the sCO_2 cycles to an entire size range of CST installations from 1-MWe to 100+ MWe.

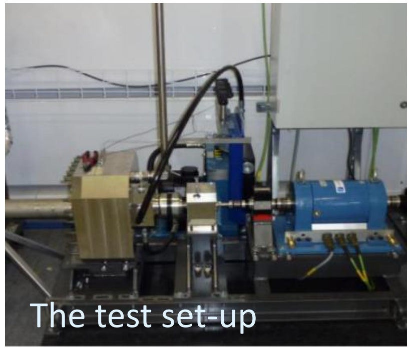

The ASTRI 1-MW sCO2 turbine rotor

China also started a supercritical CO_2 turbine project in 2015. China Academy of Sciences and Xi'an University are involved. Node 3 leader spent 4 months in China as the guest of a large Chinese manufacturer, who was interested in this technology.

P31A – Pinjarra Hills supercritical turbine test facility



The rotor



The test set-up

A small turbine was designed and built to validate design procedures to be tested on the above UQ turbine test rig.

Through these tests ASTRI is gaining the knowledge and capability to design a 25-MWe turbine.

Further testing is required for the new sCO_2 bearing and seal designs. The UQ test rig can handle the sCO_2 cycle pressures but not the sCO_2 cycle temperatures.

P31A – Why hybrid cooling?

- Using a wet cooling tower, the ASTRI plant would need 1.5 liters of water for every kWh generated
- At current Brisbane water prices, this adds 0.42 cents/kWh to the LCOE
- Water is more expensive and maybe unavailable away from the coast

- That is why the ASTRI target plant will use a dry cooling tower.
- The penalty is lost power on hot days of the summer
- The ASTRI plant will use water sprays to maintain the design output on hot days
- The unique ASTRI technologies
  - Inexpensive short towers
  - The protection against cross wind
  - Optimal water spray design
  - The use of saline water

P31A – Hybrid Cooling Tower Test Facility on UQ Gatton campus

Opening of the facility: The UQ ASTRI team; the Minister; the DVC

The 25-m tall natural draft dry cooling tower designed for a 1-MWe sCO_2 power block offers ASTRI a unique chance to develop and test hybrid cooling technologies.

Discussions with potential customers of the technology , including:

- Arrow
- Wannon Water
- Volcanex
- Ergon Energy
- Xatech

We are finalizing design details leading to a deployment contract with one of the above.

P31A – Protection of the IP

P31A is creating novel technology and valuable intellectual property.

Some of the IP is in the form of know-how and design techniques and is being protected by controlling the release of information through papers and other publications.

When appropriate, patents are taken:

- WO 2011011831 A9 – Thermal power plants
- PAT-02226-AU-01 – Supercritical CO2 turbine
- PAT-02225-AU-01 – Natural Draft Dry Cooling Tower

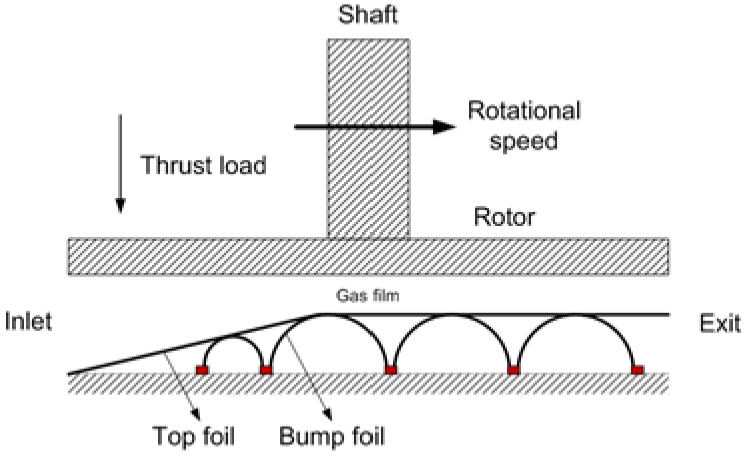
P31A – International Collaboration

- **Hybrid Cooling collaboration visits**
  - Desikhan Bharathan (NREL) was in UQ (Jun-Oct 2014)
  - Manuel Lucas (UMH-Spain) in UQ (Aug-Nov 2013) and also in Oct 2015
  - M Sadafi in VKI Belgium (2 months) & UMH-Spain(2 months) in 2015 on hybrid cooling
- **sCO2 turbine collaboration visits**
  - Clay Hearn (CEM, Uni Texas Austin) was in UQ in May-Oct 2014
  - Hal Gurgenci worked with the Chinese heavy equipment and turbine manufacturer CITIC on sCO_2 turbine manufacturing design (Mar-Jun 2014)
  - Ingo Jahn in Cambridge University (Jan-Jun 2016) on supercritical turbine design
- **Other sCO2 power block**
  - Thomas Eckert (Munich Uni) in UQ (Mar-Jun 2016) on supercritical flow modelling
  - Iman Abdi in MIT (six months in 2015) on turbine and tower flow visualisation
  - Luis Marin (Chile) in UQ (Mar-Jun2016) on supercritical HX
  - Pilar Orihuela (Uni Seville) in UQ (Jan-Apr 2016) on supercritical HX

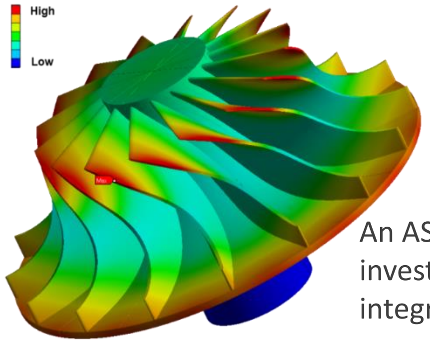
Note: Collaboration between the R&D teams ; not necessarily governed by a contract. A visit longer than two months and with the visitor working with the host on an ASTRI project , I count as collaboration.

P31A - Caveats

- **No** off-the-shelf bearing and seal technology exists for CO_2 at the target conditions:
  - T=610^{o}C and p=20 MPa
- Good ASTRI P31A progress towards appropriate bearing and seal designs
  - Using foil bearings and dry gas seals
  - Need to be validated in an appropriate test facility
    - A good area for US collaboration

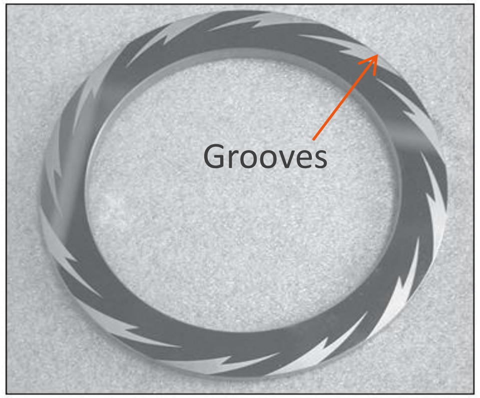


An ASTRI PhD student is simulating the operation of foil bearings in supercritical CO_2 conditions



An ASTRI student is investigating the mechanical integrity of the rotor designs

Another ASTRI student has been developing analysis techniques for dry gas seals in supercritical CO2 cycle conditions



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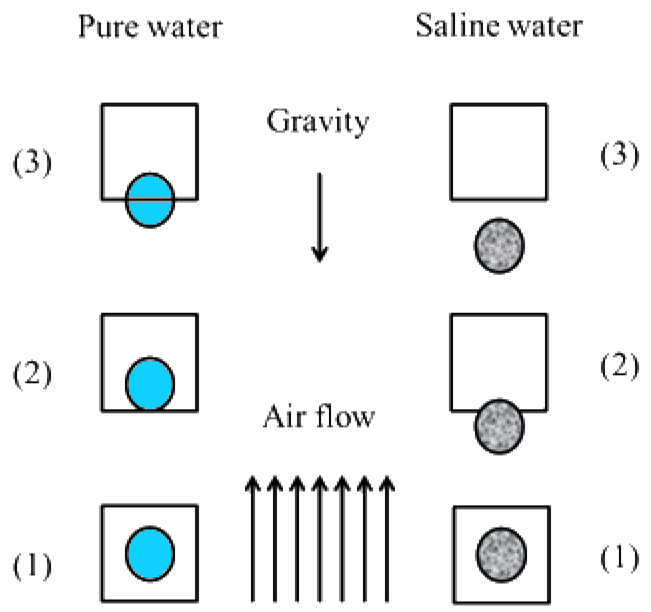
  - Using foil bearings and dry gas seals
  - Need to be validated in an appropriate test facility
    - A good area for US collaboration
- Hybrid cooling
  - The work by the ASTRI PhD students show the possibility of using saline water for cooling the inlet air on hot days in otherwise dry towers. This will be tested in the newly commissioned hybrid cooling tower test facility



Higher density of the saline water gives it more time to evaporate before it touches heat exchangers → reduced corrosion

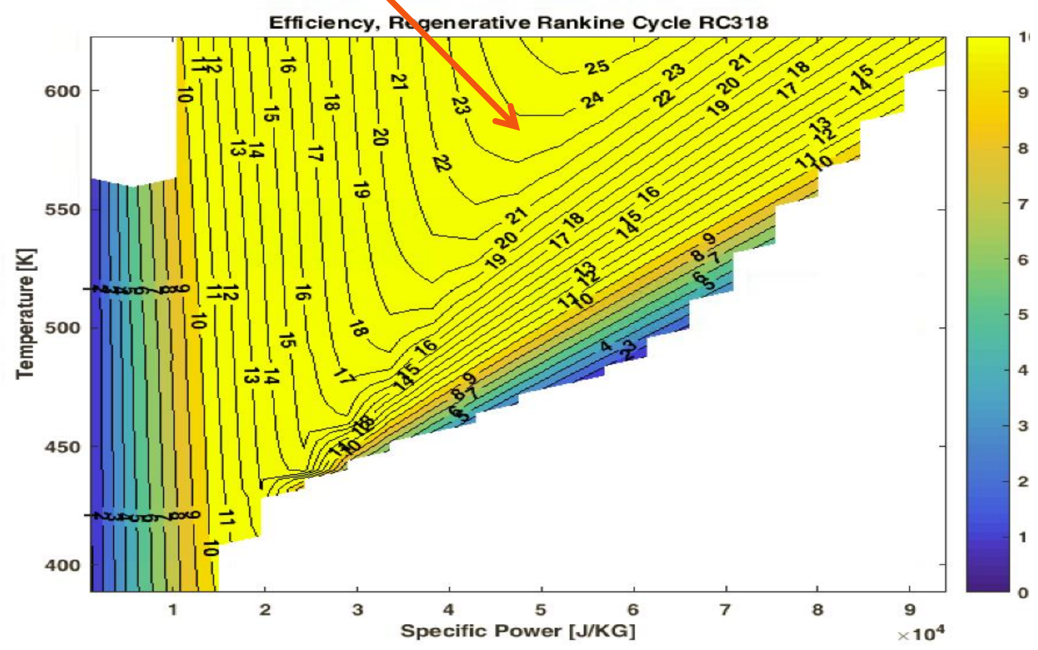
P32: Alternative power blocks

- The aim
  - To automate the selection of power blocks that provide the optimal cost and efficiency match to different CST application
- Why?
  - Different types of power block and different working fluids give different relative performance depending on scale and temperature
  - Changes in the technologies for solar receivers and thermal storage systems require new power block solutions to be found
- Our capability
  - Functional design specifications of power blocks incorporating turbine, compressor and heat exchanger units
  - Interaction with cost and performance models for the entire CST plant that account for working fluid and temperature changes

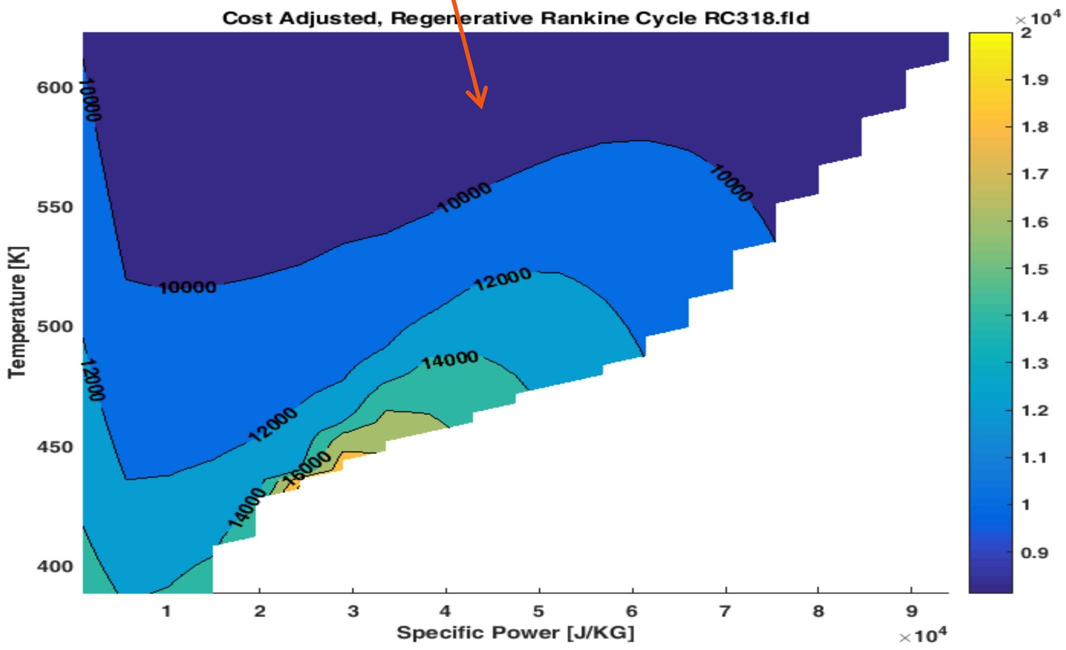
P32: Bottoming cycles

- Evaluating the best conditions and fluids for an Organic Rankine Cycle utilising the heat from a sCO_2 power block to enhance efficiency and storage utilisation

Contours of efficiency, %



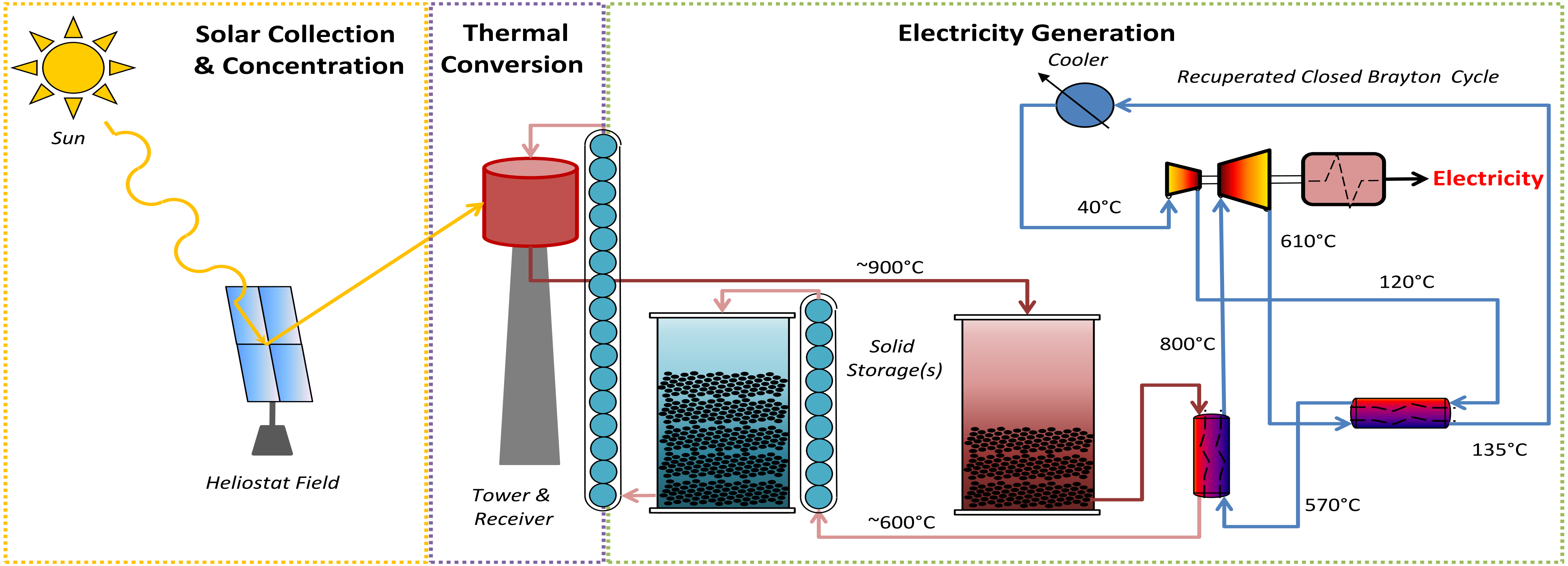
Contours of adjusted relative cost, $/kW



IMPORTANT – The highest efficiency configuration may not be the most cost-effective option if the costs start increasing nonlinearly at high temperatures.

P32: High temperature cycles

- Particle receivers and storage are expected to operate at temperatures >750°C, where steam and sCO_2 are expected to cause severe materials problems
- Inert gas closed cycles are a potential solution, utilising He or SF_6 at temperature up to 900°C and with efficiencies exceeding 48%



Node 3 - Future Directions

- Keep sharpening our cost estimations and pursue cost reducing innovations
- Validate our bearing and seal designs in real supercritical CO_2 cycle conditions
- Build a small proof-of-concept supercritical CO_2 CST plant (~1-MWe)
- Find a partner for manufacturing our sCO_2 turbine
- Develop a more efficient compressor for the 25-MWe ASTRI target plant
- Demonstrate how saline water can be used in hybrid cooling
- Expand scope of power block optimisation tools to include all proposed CST options

Summary

- The ASTRI sCO_2 turbine technology is unique and enables commercial CST in 1-30 MWe.
- ASTRI technology complements the US projects appropriate at scales >100-MWe.
- When proven, the ASTRI technology will provide a real commercial alternative to diesel electricity in Australian remote communities and mining sites.
- The natural draft hybrid cooling technology for small power plants has already been demonstrated on the UQ Gatton campus and is receiving significant commercial interest.
  - Power generation without consuming water
  - Lower parasitic losses and lower O&M
- The option to use saline water will further enhance the CST applicability in remote areas by making use of the brackish underground aquifers.

Acknowledgements

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Thank you