

THE CRITICALITY OF CO₂ FOR CSP

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Chief Research Scientist, Solar Technology
29th September 2016

1ST EUROPEAN SEMINAR ON SUPERCRITICAL CO₂ (SCO₂) POWER SYSTEMS
www.csiro.au



People 5319

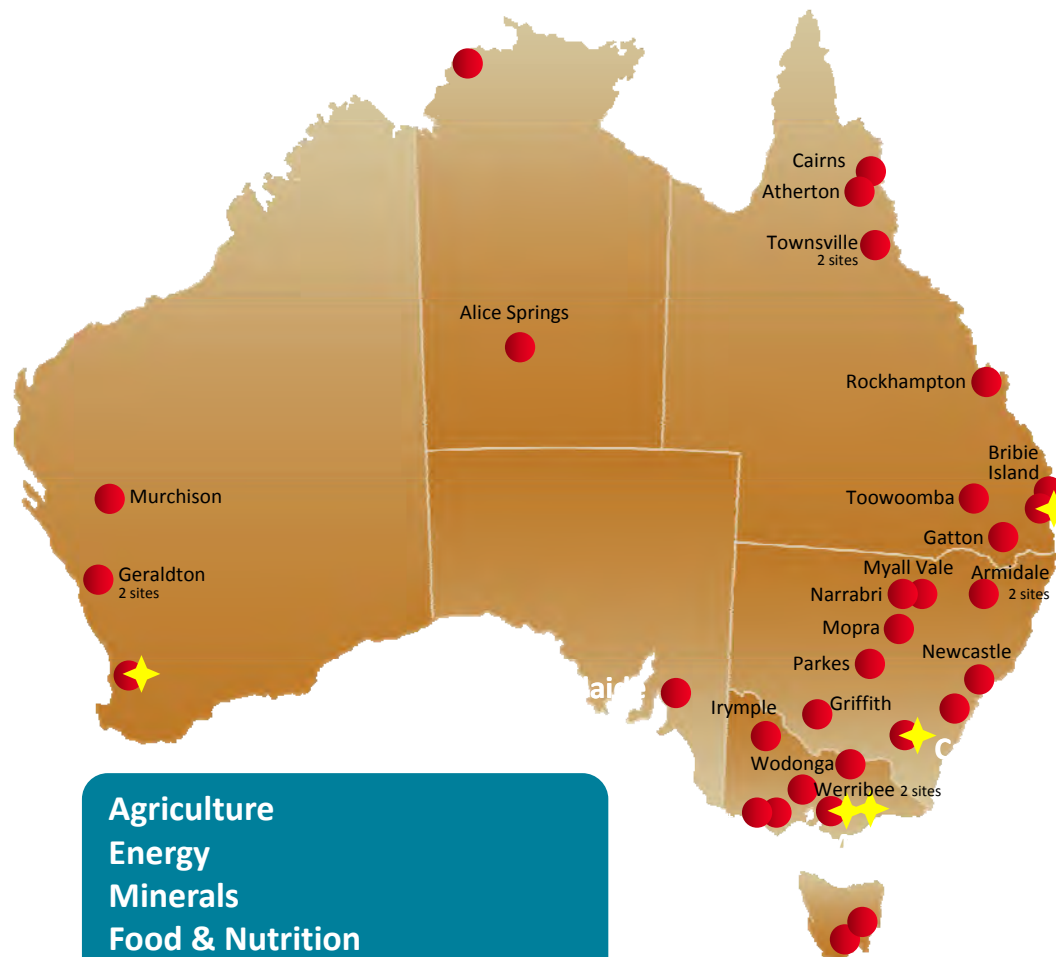
Locations 55

Business units 9

Budget \$1B+

Industry 2800+

**Top 1% global
research org.**



Agriculture
Energy
Minerals
Food & Nutrition
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Data61

CSIRO



AGRICULTURE



HEALTH & BIOSECURITY



LAND AND WATER



FOOD AND NUTRITION



DATA61



MANUFACTURING



OCEANS AND ATMOSPHERE



MINERAL RESOURCES



ENERGY

Big ideas start here



Fast WLAN

Wireless Local Area Network



POLYMER BANKNOTES



AEROGARD



BARLEYmax™



RELENZA FLU TREATMENT



TOTAL WELLBEING DIET



HENDRA VACCINE



EXTENDED WEAR CONTACTS



SOFTLY WASHING LIQUID



SELF TWISTING YARN

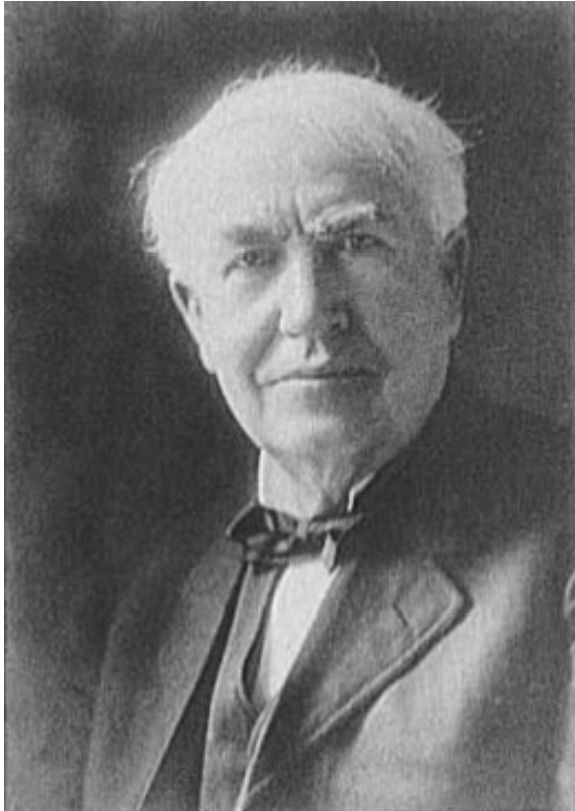


RAFT POLYMERISATION



NOVACQ™ PRAWN FEED

Thomas Edison



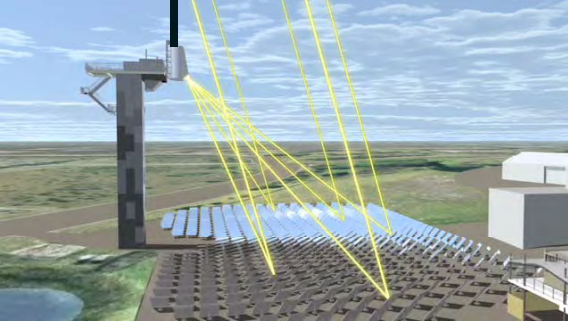
“I'd put my *money* on the sun and solar energy. What a source of power! I hope we don't have to wait 'til oil and coal run out before we tackle that.”

(1847-1931)

Rapid commercial CSP deployment in last several years

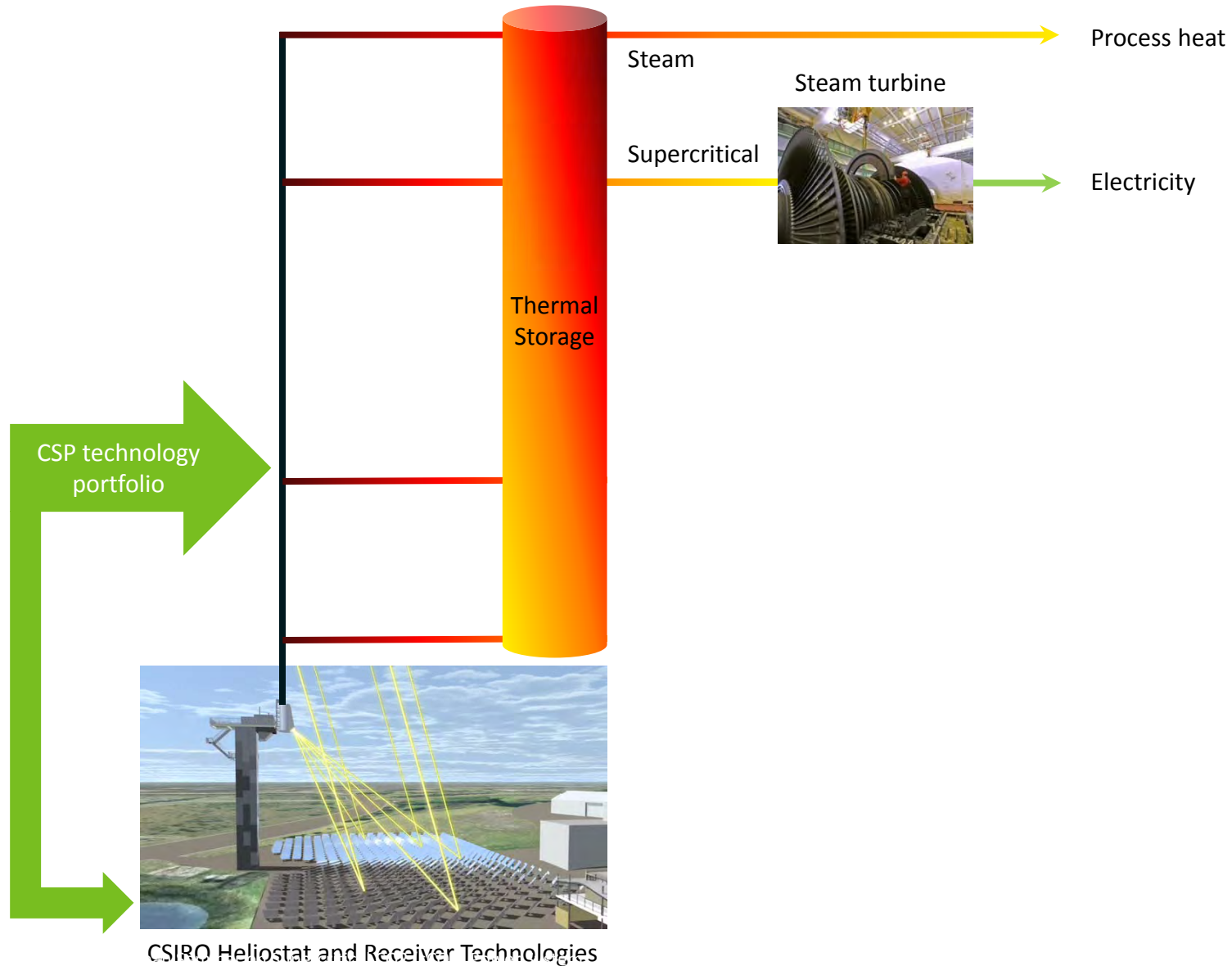


Targeted portfolio of CSP Research Activities

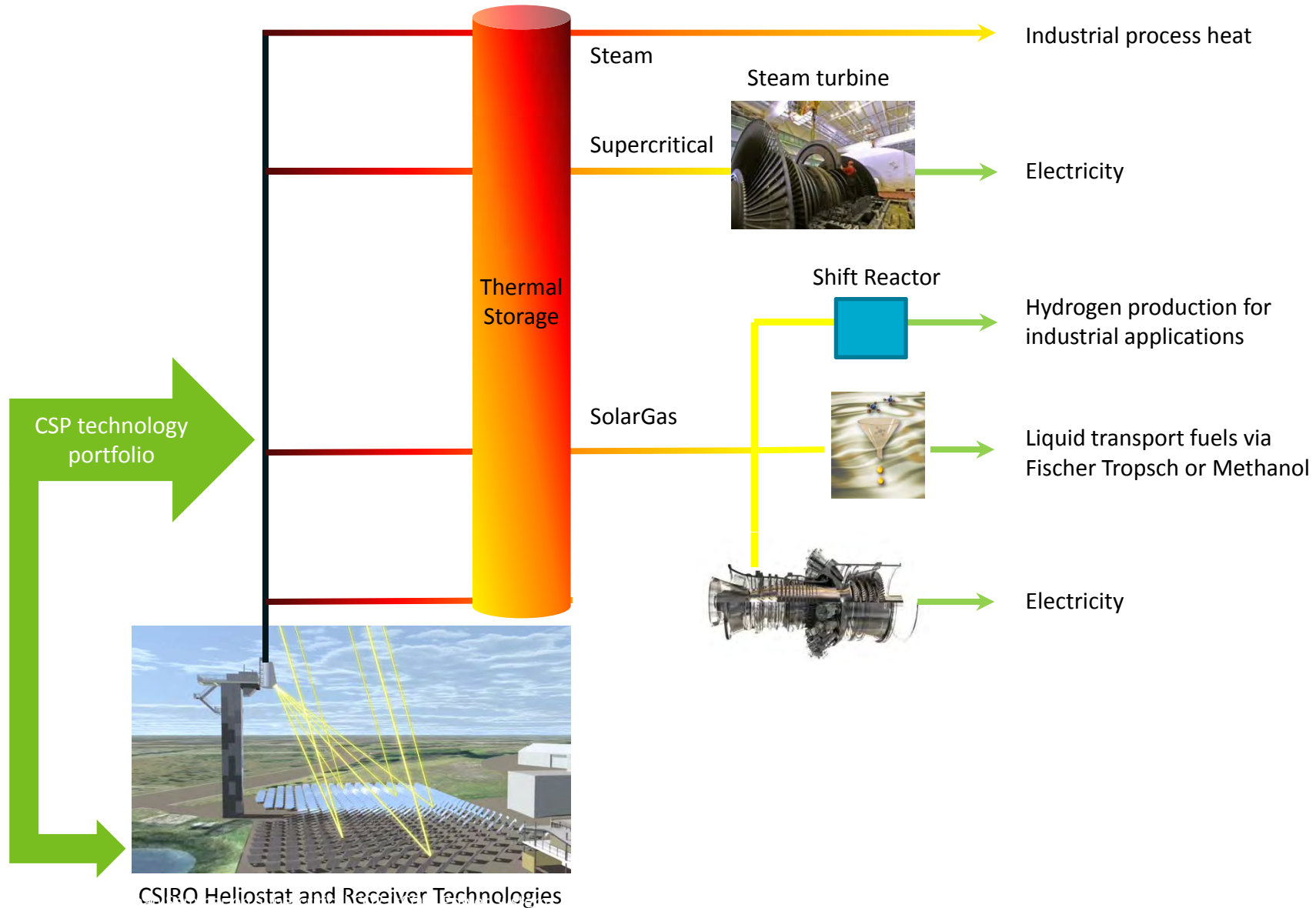


CSIRO Heliostat Technology

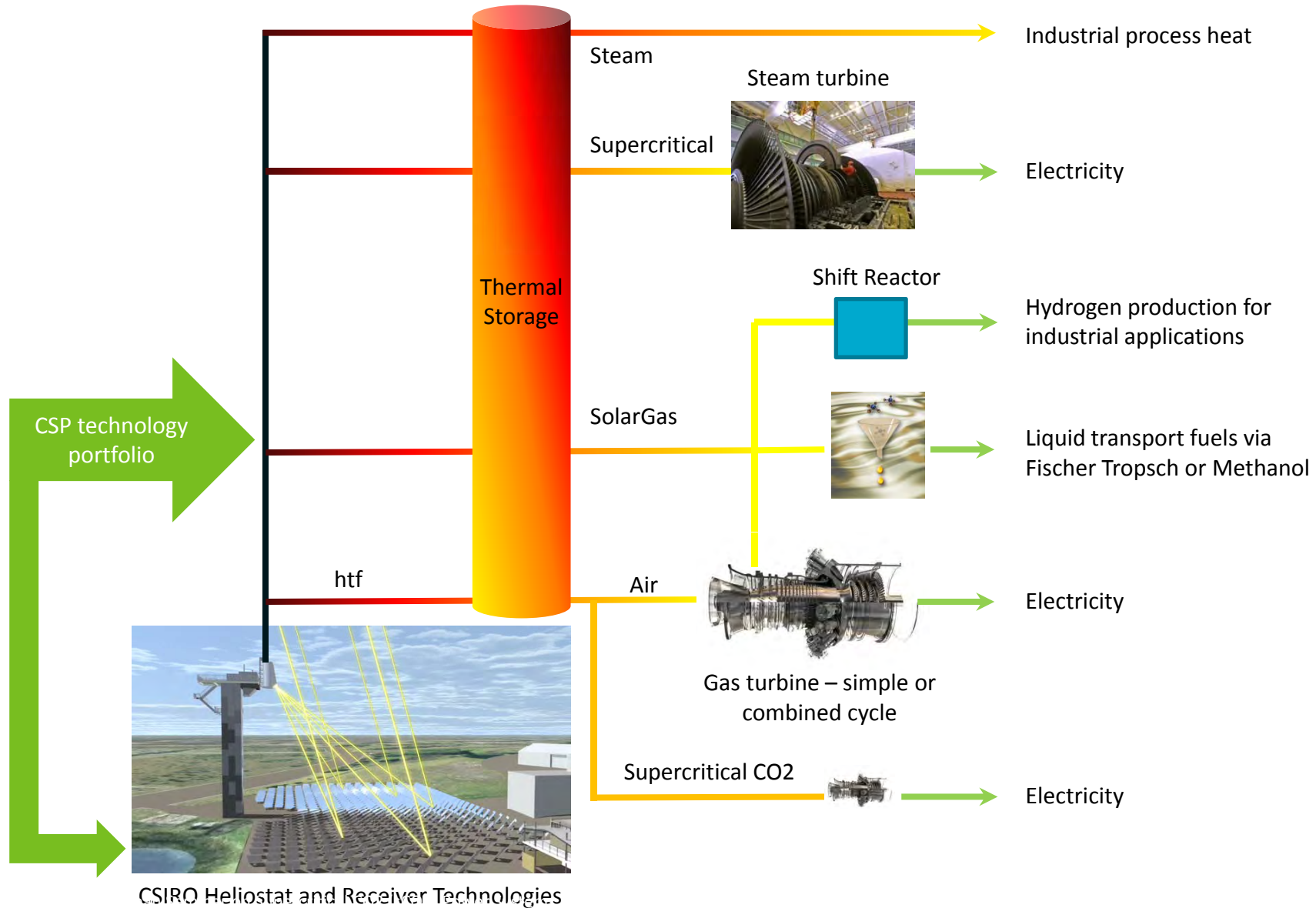
Targeted portfolio of CSP Research Activities



Targeted portfolio of CSP Research Activities



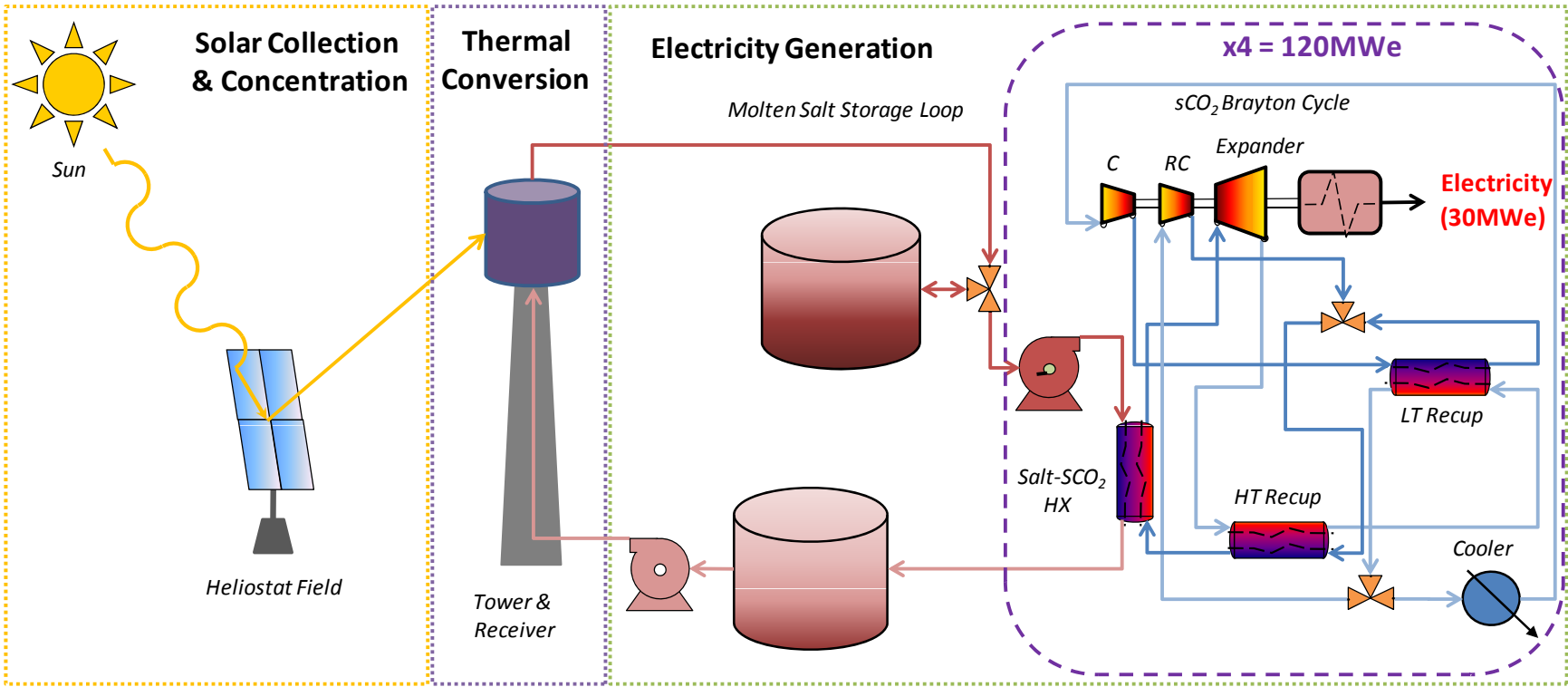
Targeted portfolio of CSP Research Activities



NATIONAL SOLAR ENERGY CENTRE



CSP-driven s-CO2 cycle – “near” term



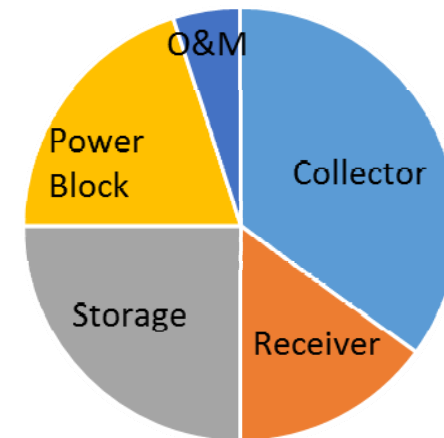
Complex (often fun) multi-variable optimization

Relatively conventional issues:

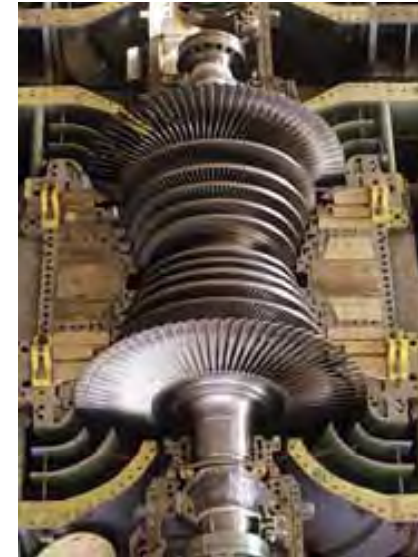
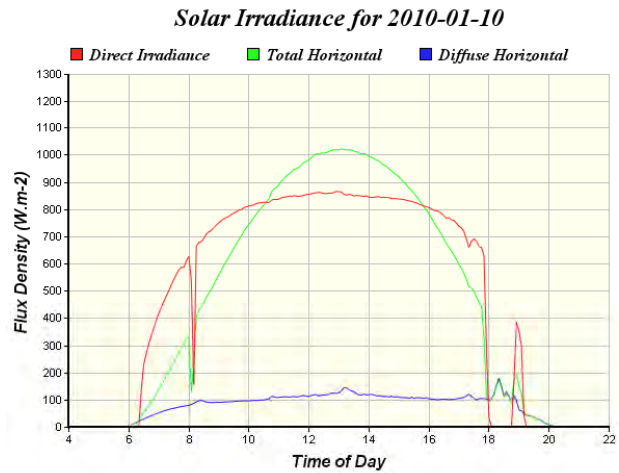
Capacity vs \$/kW vs efficiency

- Normal steam turbine demands $> 50\text{MWe}$; adding storage means very large receiver; significant investment in single projects
- Efficiency is king

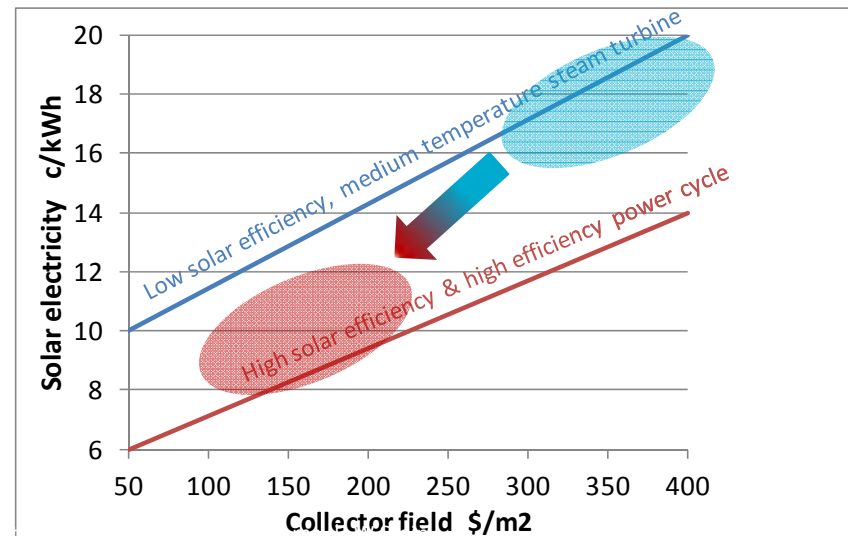
Contribution to LCOE



The fundamentals of reducing CSP cost



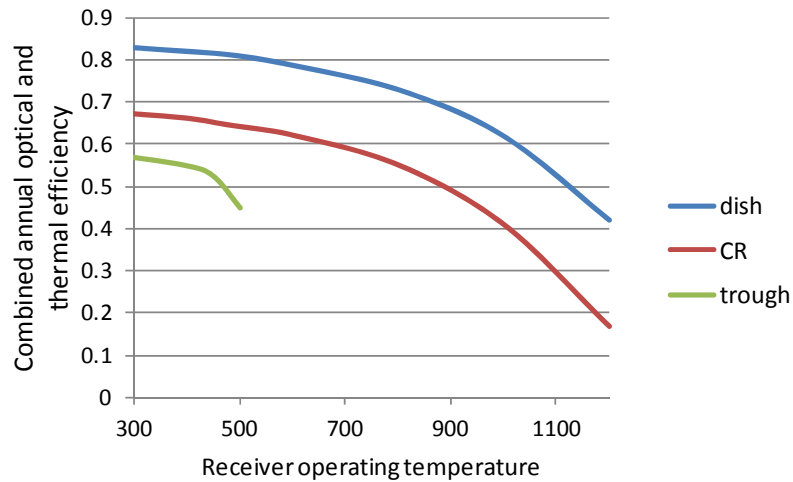
We know the resource



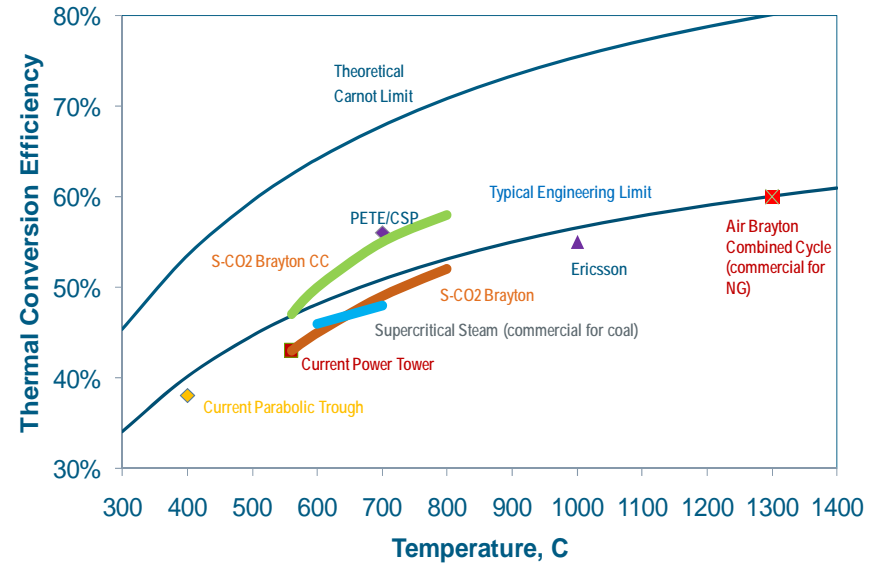
We know the cost and performance of turbines/ heat engines

The fundamentals of reducing CSP LCOE

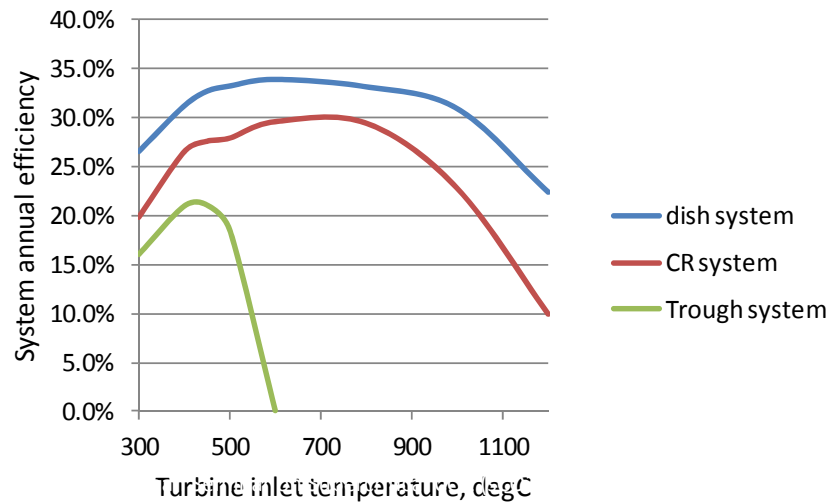
Annual collector efficiency



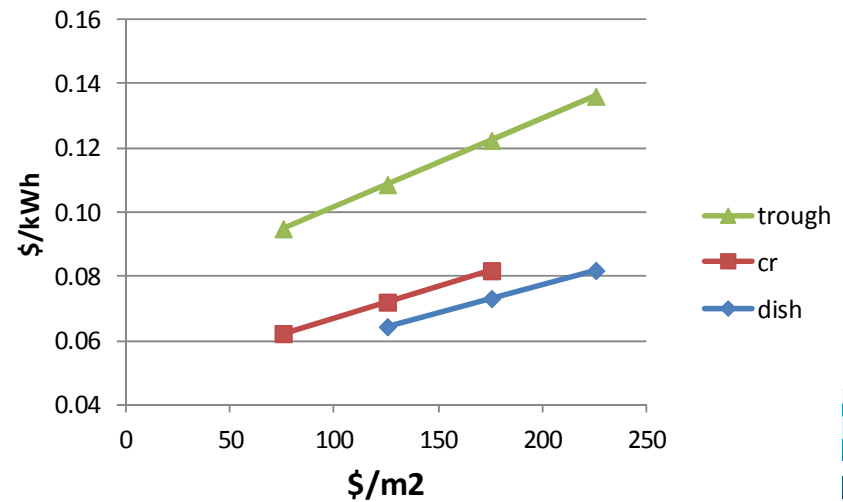
Turbine efficiency



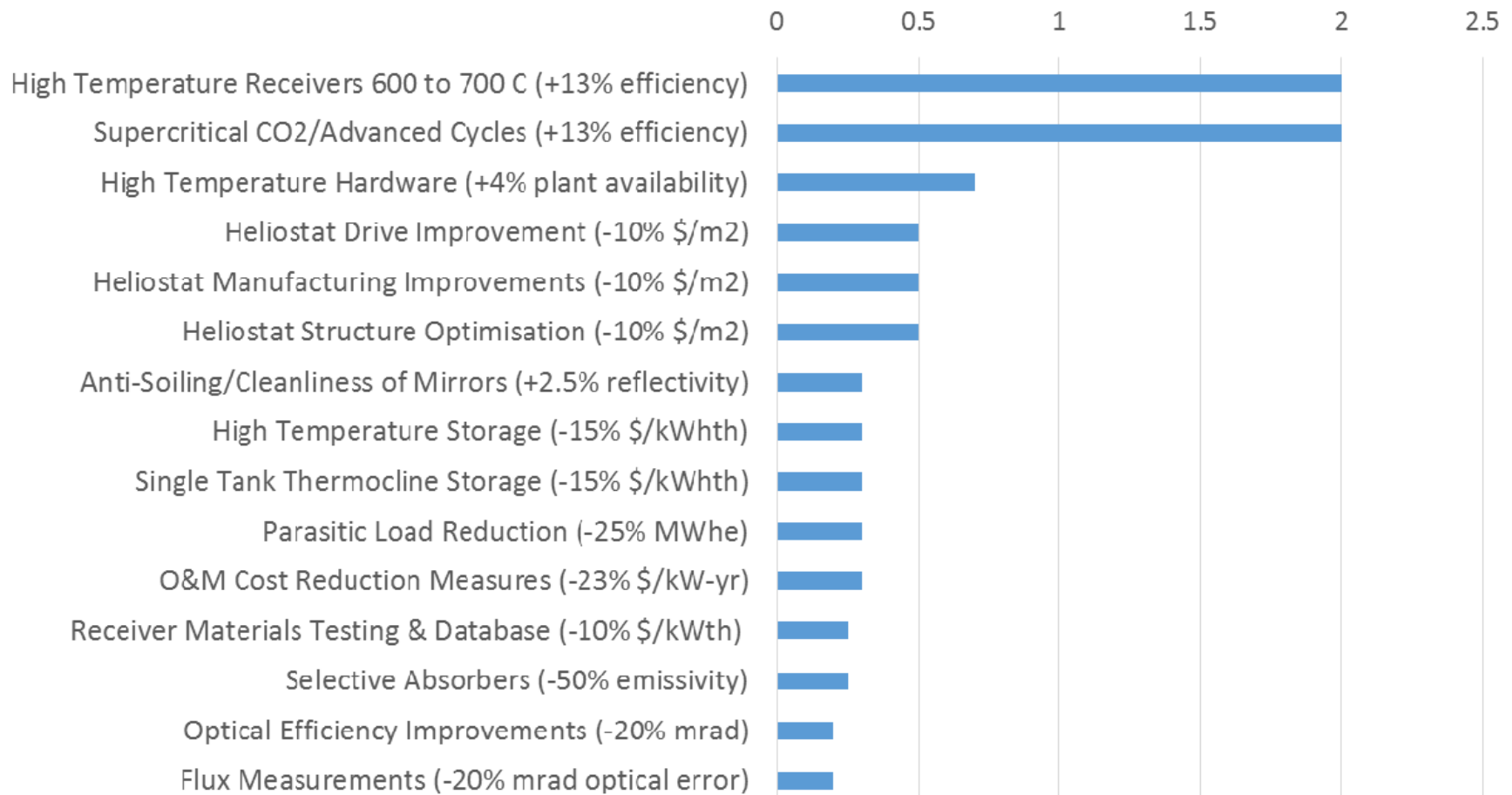
CSP system efficiency



CSP system cost



Solar tower cost reduction priorities



Complex multi-variable optimization

Interaction with other components:

Thermal or thermochemical storage

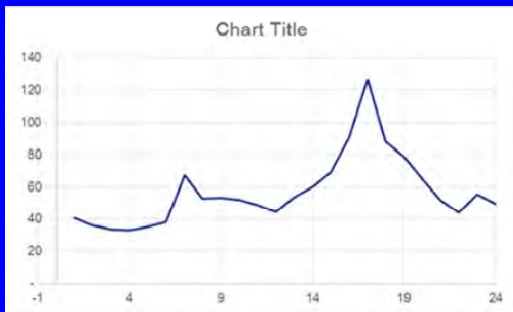
- “Conventional” sensible molten storage works well with a Rankine cycle but more difficult with small ΔT of s-CO₂

Cost of storage (\$/kWhth) needed to meet LCOE target

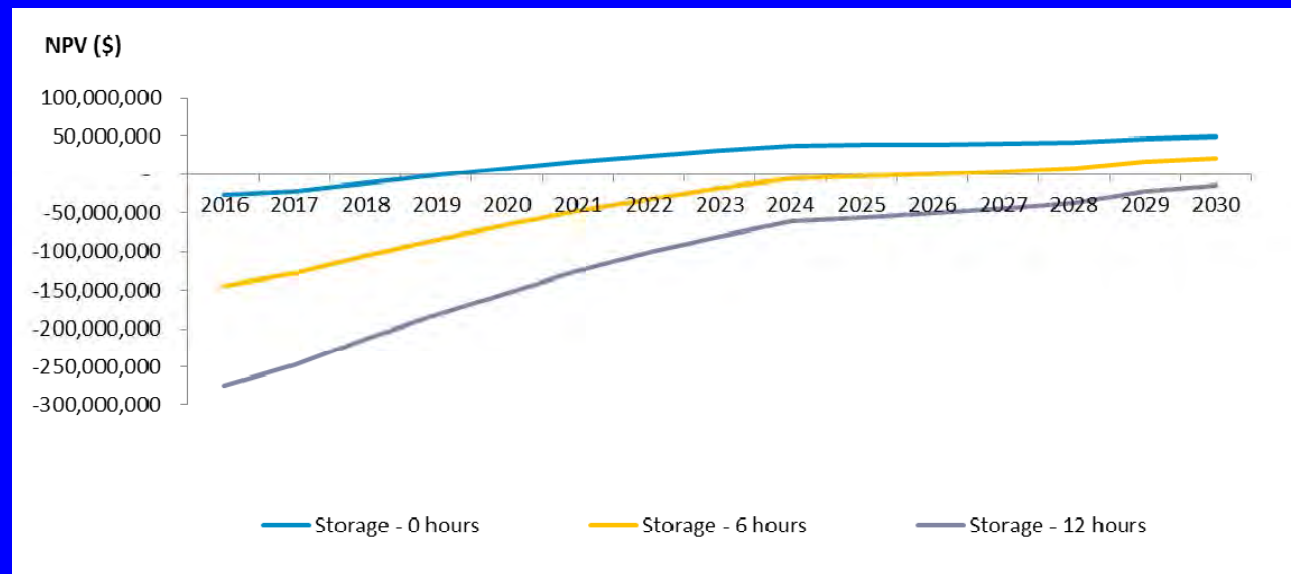
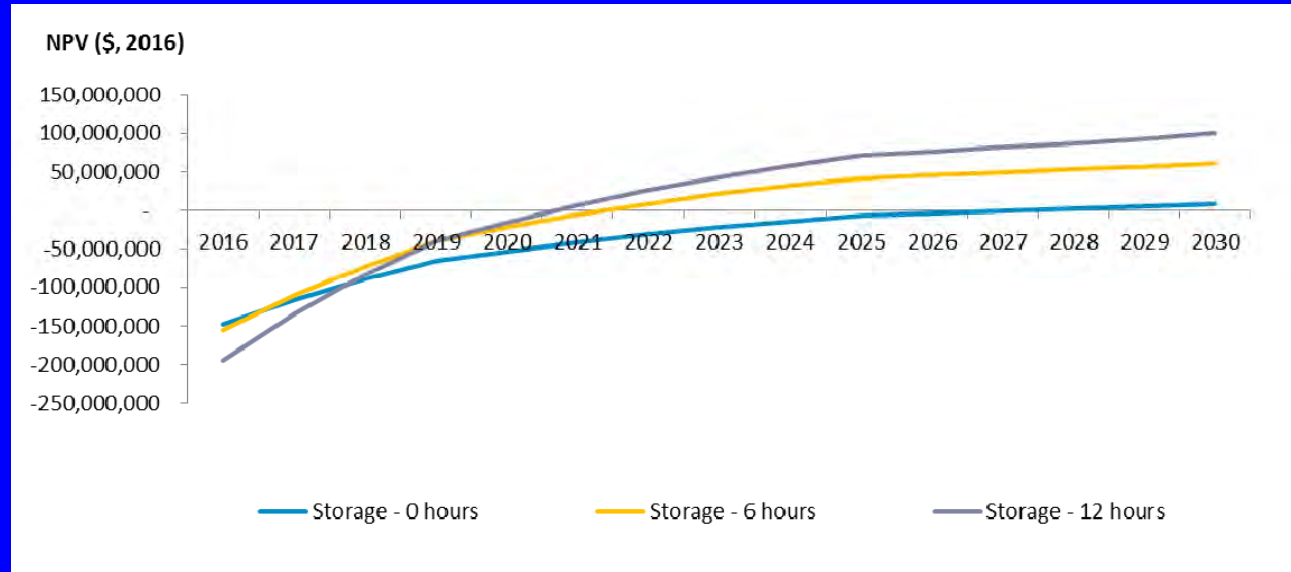
TARGET	CYCLE TEMPERATURE (°C)			
	560	610	700	1000
18c/kWh	\$234	\$259	\$208	-\$49
12c/kWh	\$101	\$118	\$53	-\$236



NPV for CSP and thermal storage



NPV for PV and battery storage



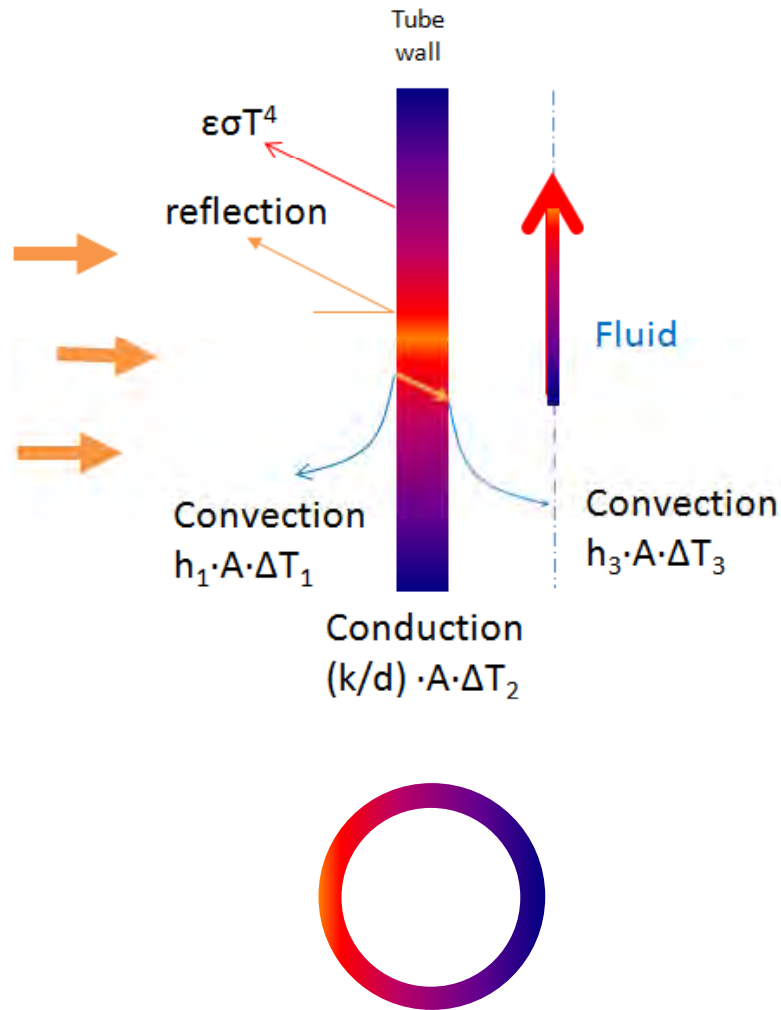
Complex multi-variable optimization

Interaction with other components:

Receiver design impacted by:

- Flux control
- Thermal loss mechanisms
- Material thermo-physical properties
- Material chemical/ metallurgical properties

Uncontrolled solar flux (or temperature)



Causes:

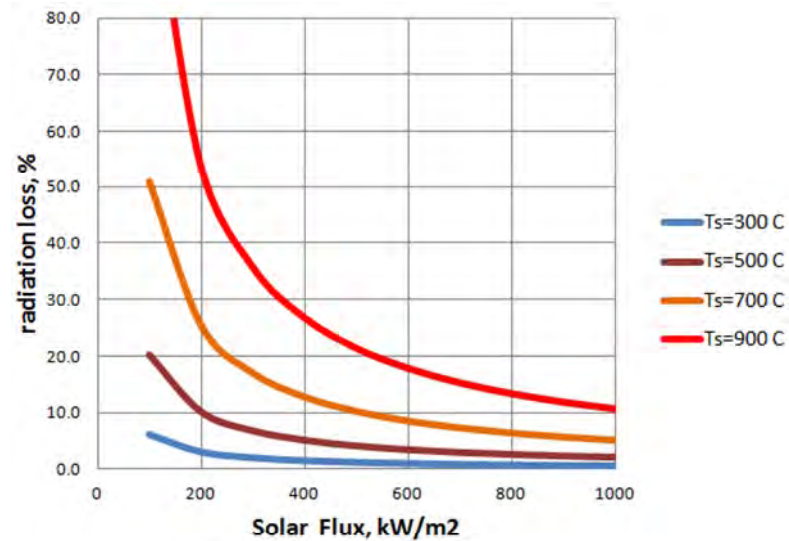
- Sun location
- Limit of optic control
- Receiver geometry
- Field geometry
- Tower shading
- Heat transfer problem
- Other unknowns

Consequences:

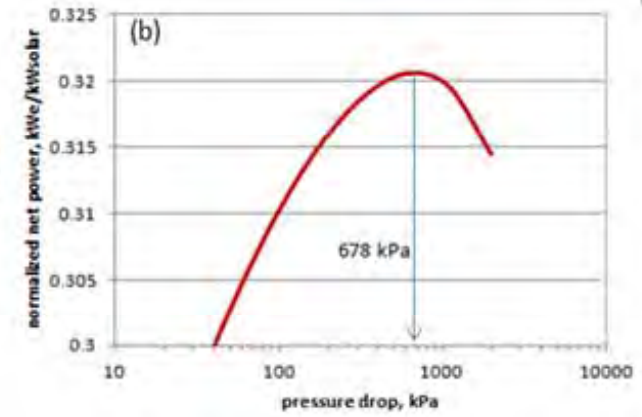
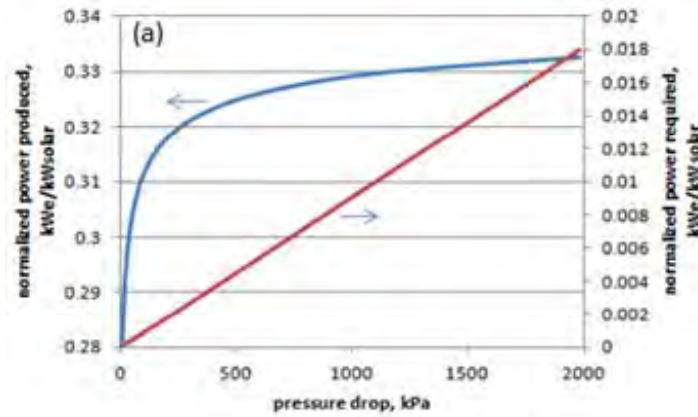
- Inefficient heat transfer
- Hot and cold spots
- Material failure
- OP condition limited

Solutions:

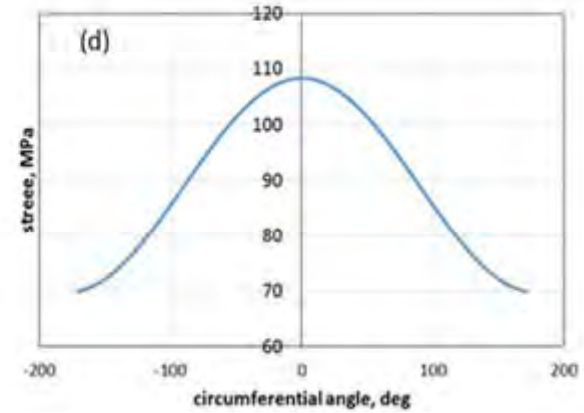
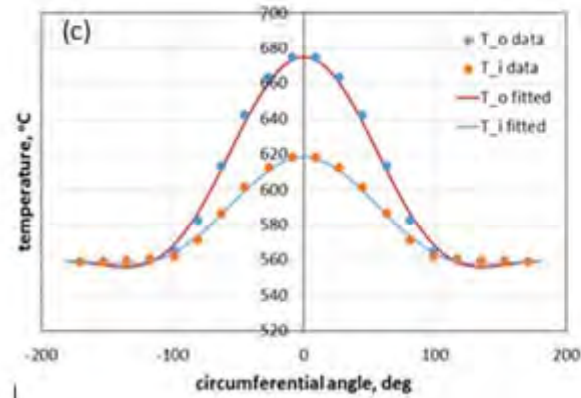
- Flux distribution control
- High accuracy heliostat
- Enhancing heat transfer
- Beam redirection



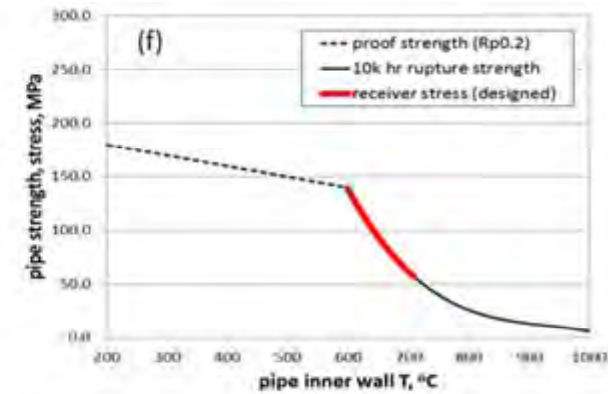
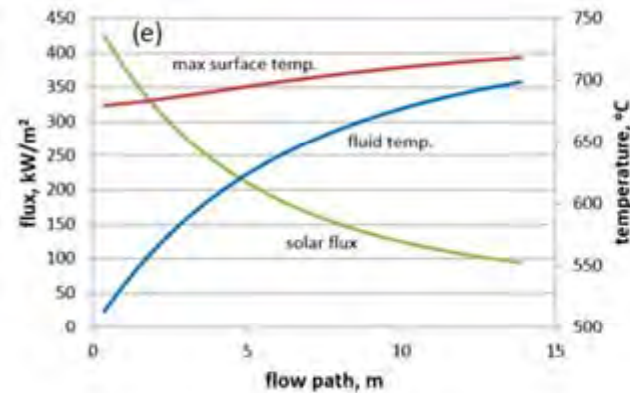
Turbulence & dP Opt.



Pipe Stress Clc.



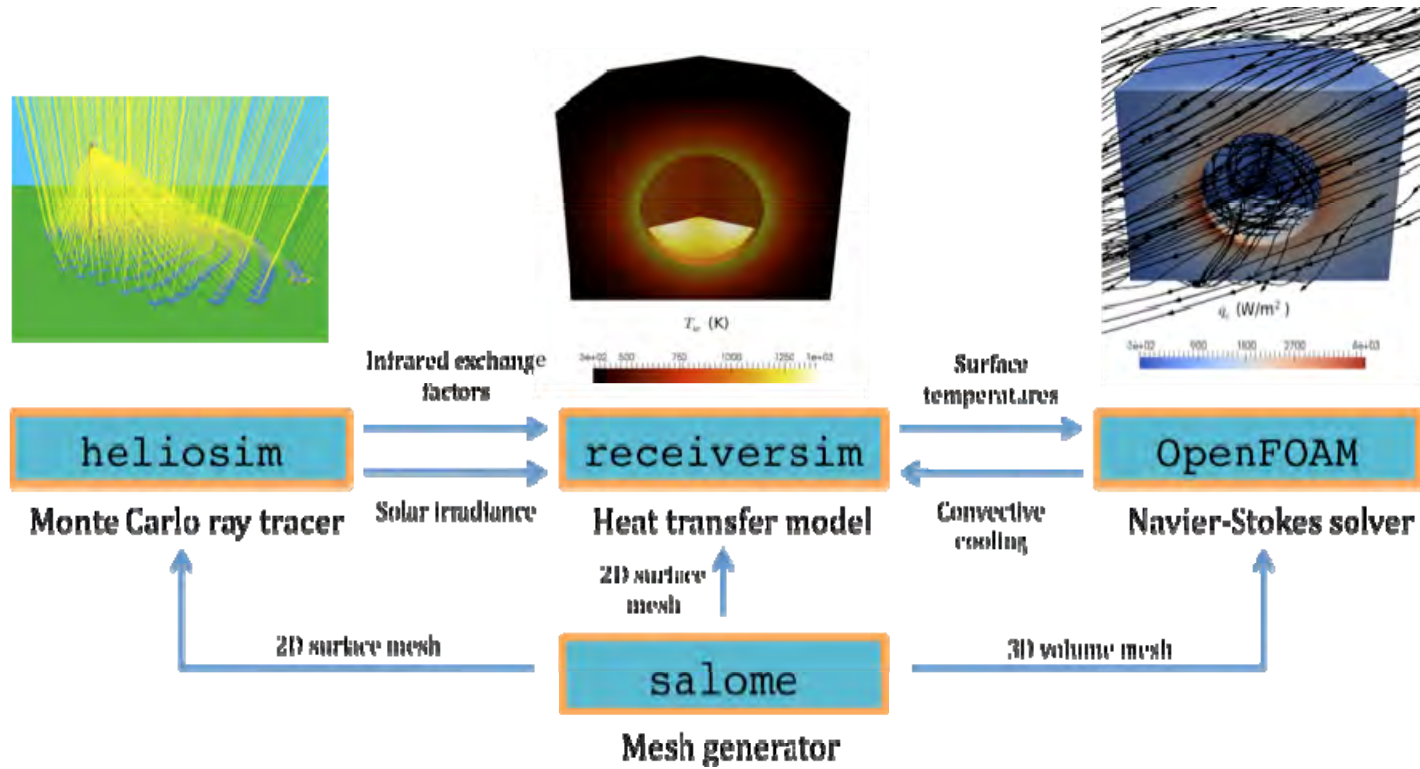
Flux Distribution Opt.





CSIRO

Combined Design/Optimization



Receiver Activities in CSIRO

type	capacity	condition	design	status	
1	Solar Gas receiver/reactor	200kW _{th}	10bar / 760°C	CSIRO	tested
2	SC-Steam receiver	300kW _{th}	230bar / 560°C	CSIRO	tested
3	Air receiver 1	600kW _{th}	5bar / 800°C	MHI	tested
4	Air receiver 2 (HX device)	10kW _{th}	8bar / up to material limit	CSIRO	tested
5	Air receiver 3	90kW _{th}	5bar / 900°C	CSIRO	tested
6	CO ₂ receiver	250kW _{th}	10bar / 750°C	Abengoa	tested
7	Supercritical CO ₂ receiver	250kW _e	200bar / 700°C	CSIRO	installed
8	Sodium receiver	TBD	700°C	CSIRO	various studies
9	Particle receiver	Design	800°C	CSIRO	various studies
10	Bladed receiver	TBD	TBD	ANU	various studies



CSIRO s-CO₂ activities

IN-FIELD PILOT

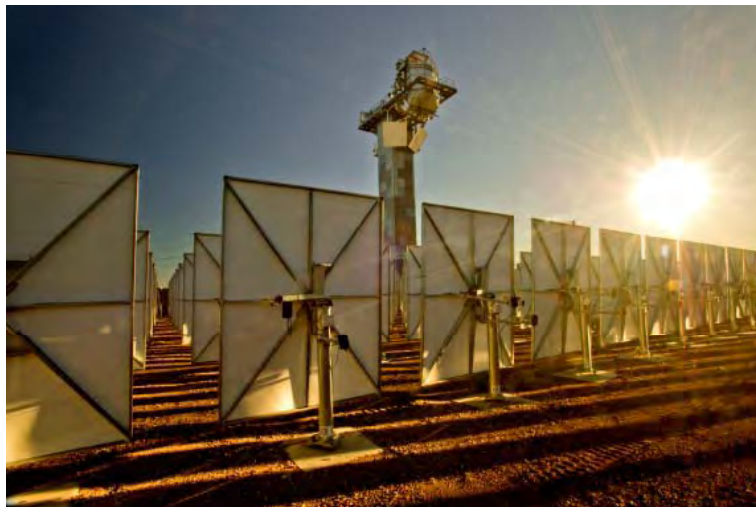
- Completed fabrication of s-CO₂ test loop and solar receiver, bop rated for up to 720°C and 30MPa output though most receiver testing will be at ≈20MPa.
- System operated at supercritical conditions (on gas heater) for commissioning
- Plumbing allowance made for a future small turbine.

MATERIALS EXPERIMENTS

- High temperature materials “lifing” experiments and creep calculations for s-CO₂ >700°C, >25MPa

SYSTEM & PROCESS MODELLING

- The material, component and system knowledge gained will be used for development of a solar s-CO₂ demonstration project.



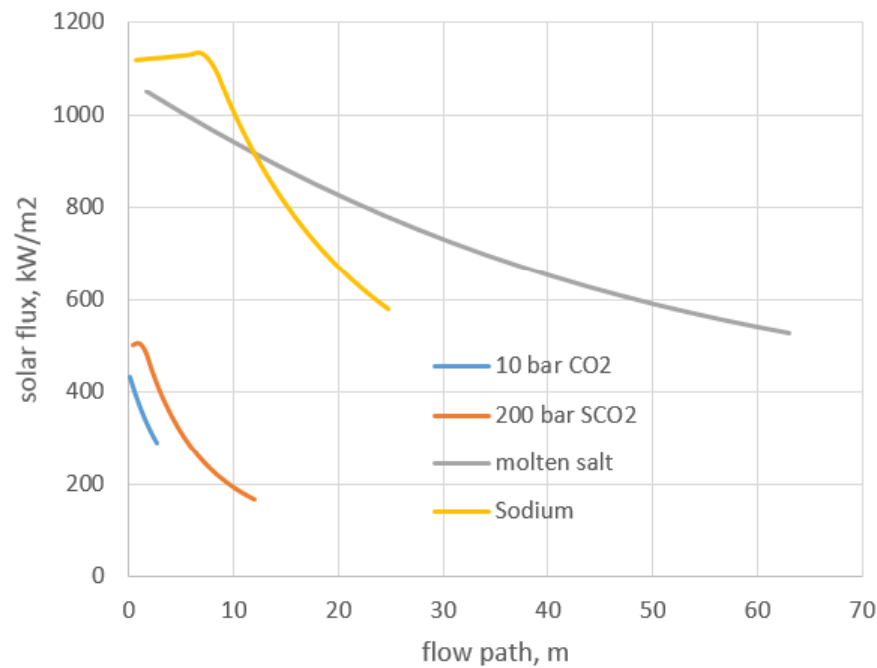
30MPa

S-CO₂ System Demonstration



Receiver Heat transfer with Different Fluids

Ideal condition satisfying ASME max allowable stress of Haynes 230



	10 bar CO2	200 bar sCO2	High T Chloride molten salt	Sodium
Pipe size	3/8" sch10	3/8" sch80	1" sch5	1" sch5
opt. DP, kPa	50	684	1200	160
pipe length for 500->700 C, m	2.712	12.33	64.57	25.33
flow rate per pipe, kg/s	0.051	0.199	5.755	2.849
capacity per pipe, kW	12	50	1382	665
Ave. fluid h W/m²K	1144	5578	8952	28281
efficiency	73.2	77.2	86.2	87.8

- External tubular receiver
- Receiver inlet/outlet: 500C/700C
- Reflectivity: 0.07, Emissivity: 0.85

s-CO₂ Solar thermal Receiver



s-CO₂ solar receiver



First operation of s-CO₂ receiver and bop



Material compatibility with s-CO₂ - Experimental apparatus

Laboratory air counter-flow in



Three zones furnace heating elements

Test tube specimen S-CO₂ flow out

Alumina tube enclosure



Laboratory air counter-flow out

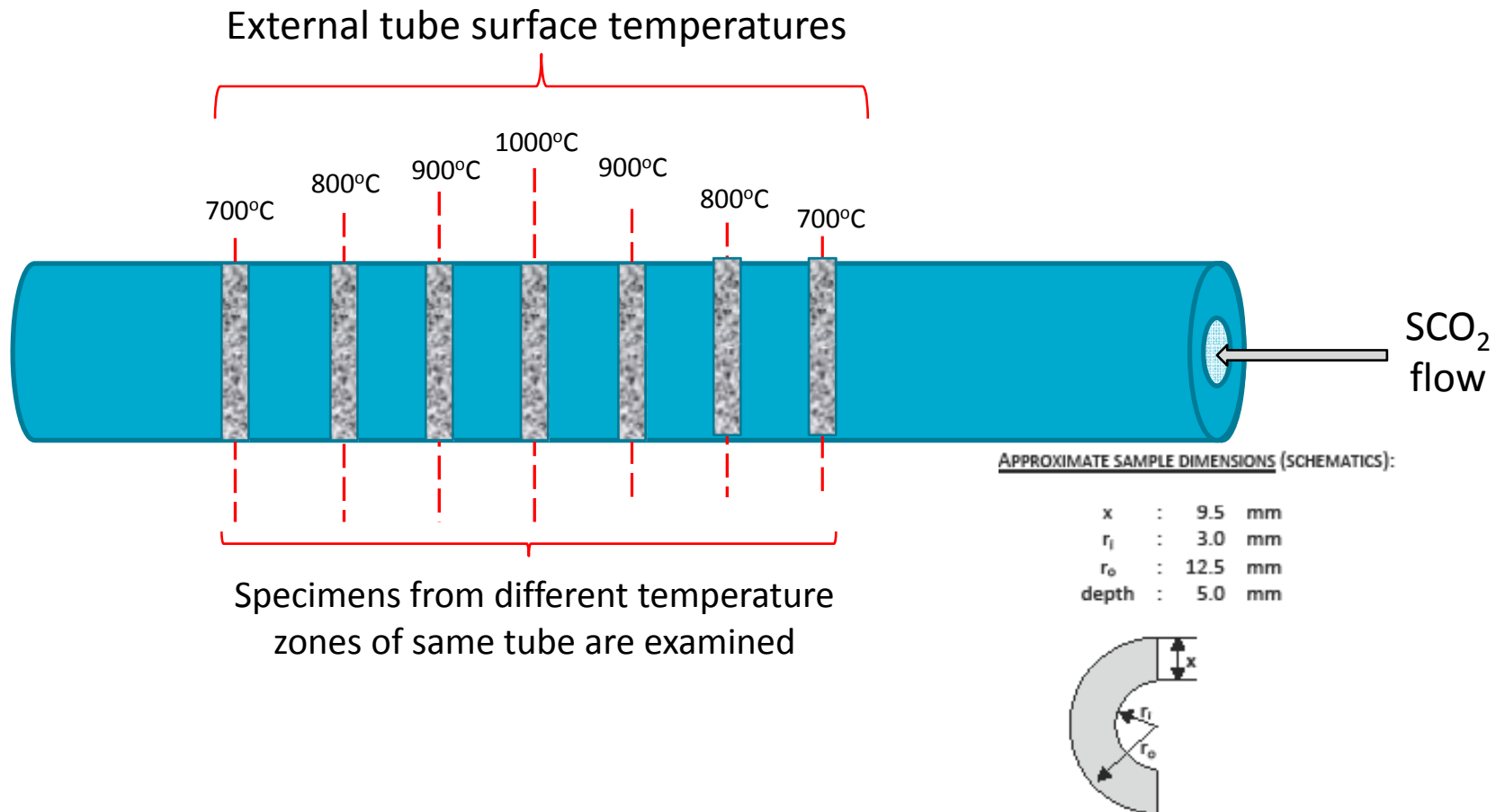
External 253MA protective jacket and air cooled flange



Test tube specimen S-CO₂ flow in

Typical experiment in progress

Test specimen and tube temperature zones Schematics

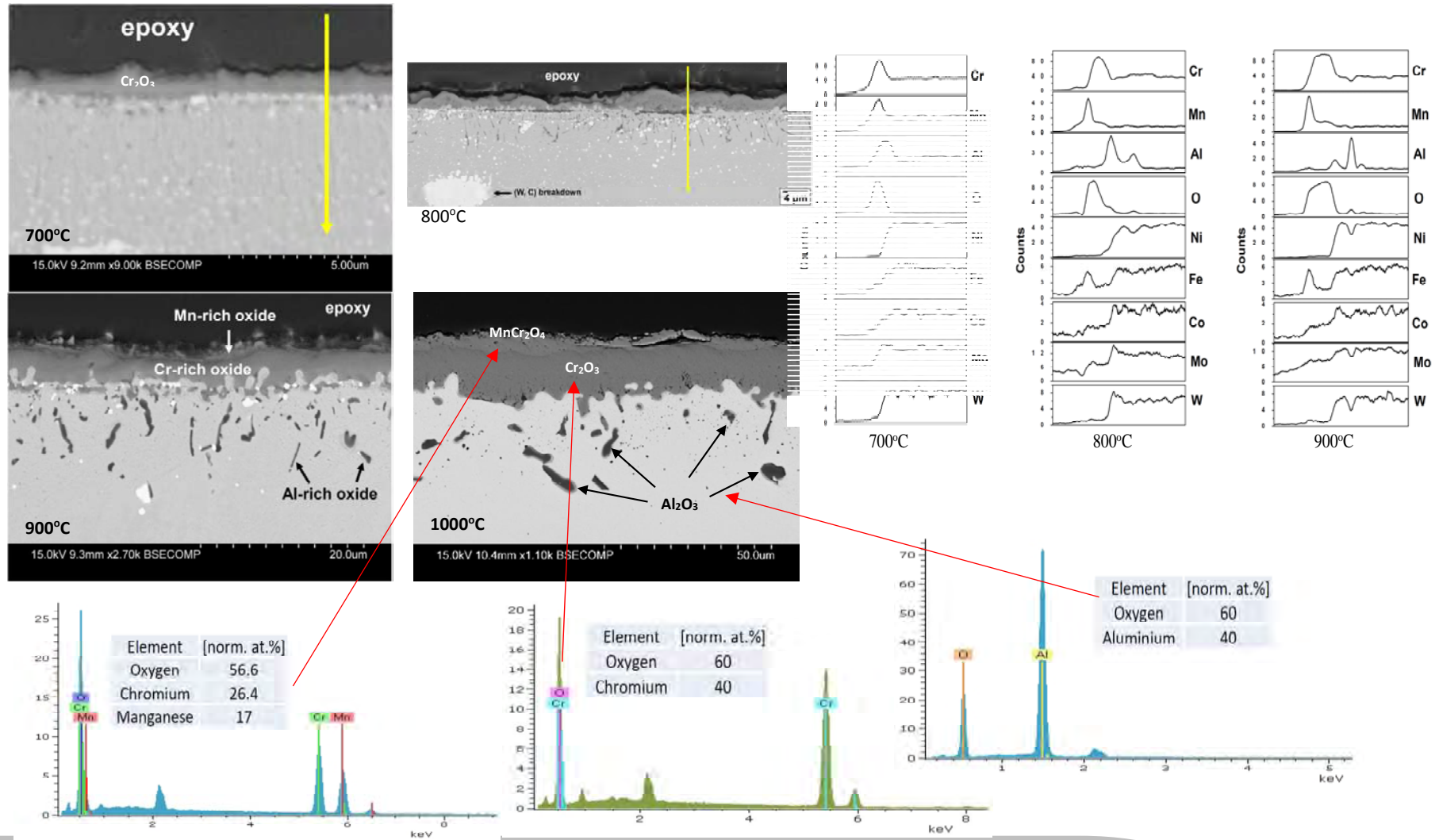


Ni-based alloys evaluated

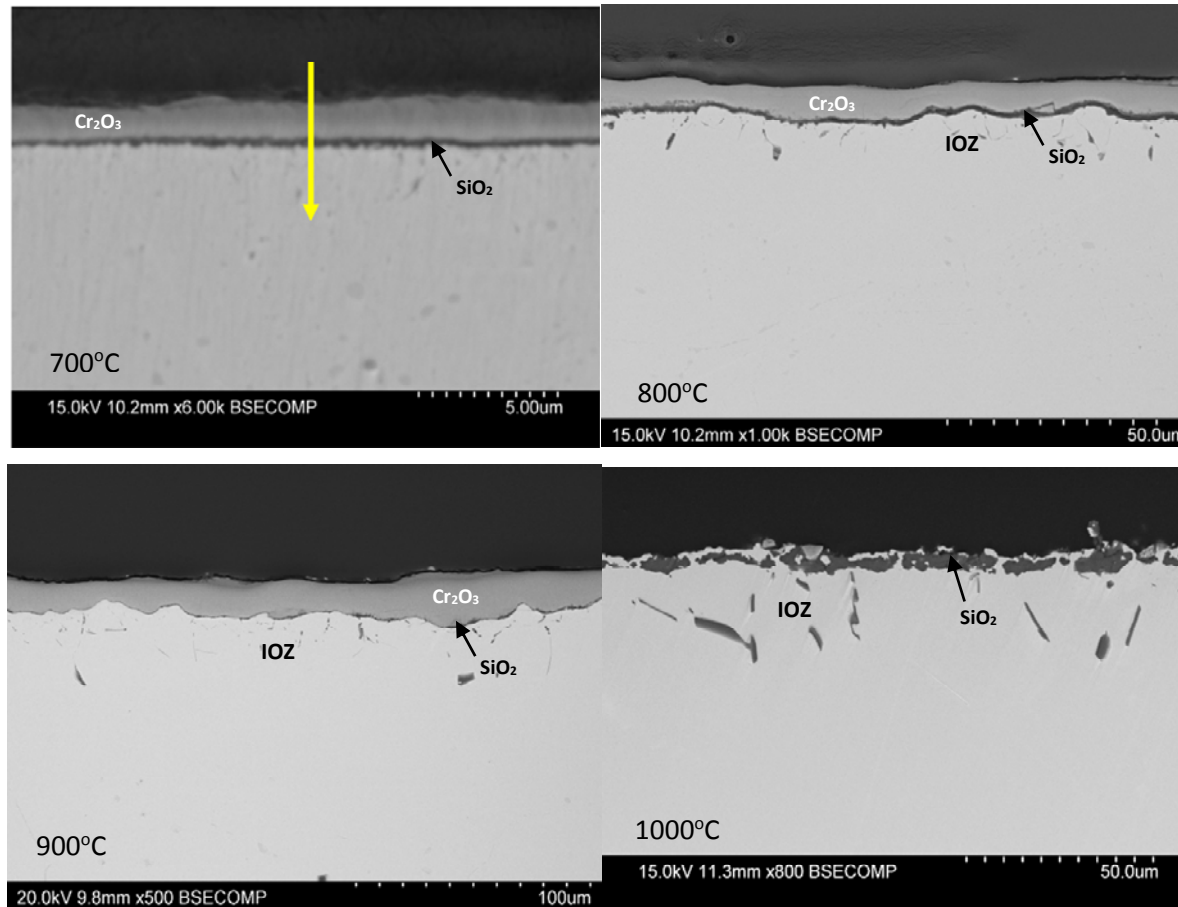
- Alloys sourced from Haynes International - Subjected to 1000 h continuous corrosion test.
- Tubular samples of each alloy internally pressurised by flowing SCO_2 .
- Exposed to SCO_2 at 20 MPa over a temperature range 700°C - 1000°C.
- Composition of alloys tested as per the table.

Alloy type	Nominal composition - maximum wt%										
	Ni	Cr	Co	Mo	Ti	Al	Fe	Mn	Si	C	other
Haynes 282	bal	19	10.2	8.46	2.19	1.38	0.39	0.03	0.05	0.063	0.005 B
Haynes 188	23	22	bal	--	--	--	2.64	0.85	0.25	0.111	14.3 W 0.007 P 0.002 B
Haynes HR120	37	25	0.12	0.21	--	0.05	bal	0.69	0.52	0.062	0.564 Nb 0.1 W 0.07 Cu
Haynes HR160	bal	28	30.1	0.14	0.55	--	0.27	0.47	2.58	0.054	0.1 W 0.05 Nb
Haynes 230	bal	22	0.13	1.36	0.01	0.44	2.00	0.50	0.44	0.100	14.2 W 0.013 La

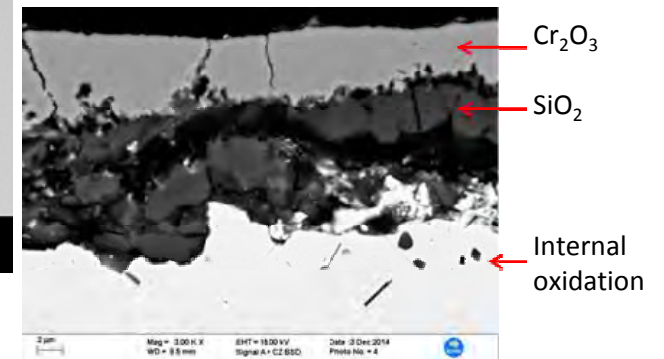
Corrosion results Haynes 230



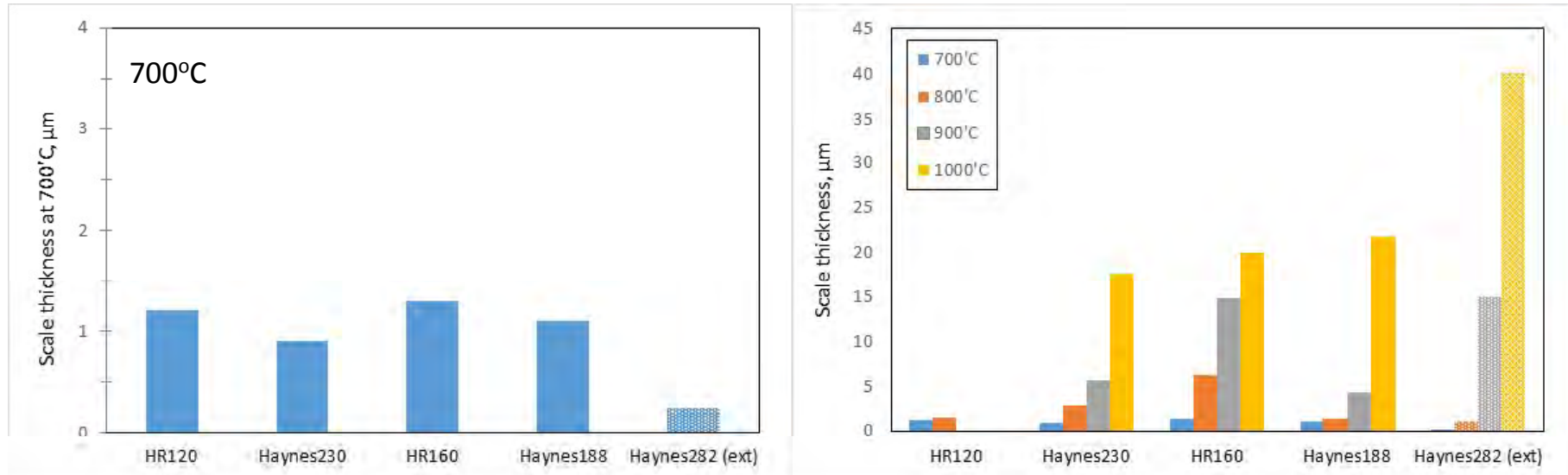
Corrosion results HR160 - 700 to 1000°C



- Two-layered scales on the specimens reacted at 700-900°C, but only the darker oxide remains on the alloy after reaction at 1000°C.
- Intense scale breakage occurred at 1000°C as detailed by the SEM high magnification micrograph of a section of the internal surface of the tube that retained the chromia scale.
- Internal oxidation zone (IOZ) in the specimens reacted at 800-1000°C but not at 700°C.



Scale development – Effect of temperature



- At 700°C, after 1000 h exposure the scale thicknesses for HR120 and HR160 are 1.2 and 1.3 μm, for Haynes 230 and 188 are 0.9 and 1.1 μm respectively and for alloy Haynes282, 0.25 μm.
- All alloys tested are suitable for application at 700°C, and ranked in the following order; Haynes282 > Haynes230, Haynes188, HR120 > HR160.
- At temperatures higher than 700°C, the alloys develop significantly larger scale.
- At 800°C and above, the alloys presented sub-scale internal oxidation, the exceptions were Haynes188 and alloy HR120 at 800°C which are deemed suitable for application at this temperature. In both of these the protective Cr₂O₃ scale was supported by a semi-continuous SiO₂ layer.

Summary of main findings to date – “Lifing” experiments for s-CO₂ materials

- The alloys developed protective chromia-rich scales and at temperature > 800°C - a significant internal oxidation zone.
- Chromium-rich carbides precipitated within the alloys leaving a subsurface carbide free zone (CFZ) resulting in carbides enrichment at the core.
- Ageing of the alloys at 1000°C in air, revealed natural carbides in the grain boundaries as a consequence of annealing due to long time at temperature. These were not related to reaction with sCO₂.
- The extent of corrosion due to exposure to s-CO₂ varied with temperature and presented different characteristics depending on alloy composition.
- Internal attack (subsurface degradation) in the temperature range 800-1000°C appears greater than the metal loss due to oxide scale formation. The former being 50-75% of the total corrosion affected zone.

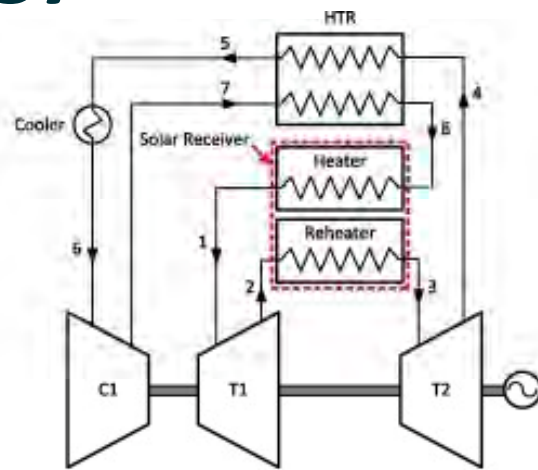
Next steps:

- Additional candidate materials; extended testing of most prospective materials; refinement of theoretical modelling; augmentation of lab facilities, autoclaves, etc.
- Development of testing of rotating components under high flow conditions

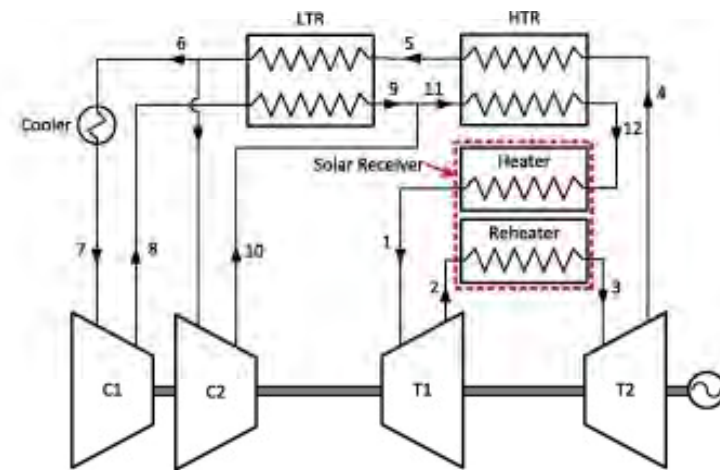
Subsurface Degradation

- Subsurface internal alloy degradation can be more significant than metal wastage due to scaling. This reinforces the importance of subsurface characterization in study of corrosion.
- The present findings demonstrate the potential shortcomings associated with evaluation of alloy corrosion resistance on the basis of scaling behaviour alone. Subsurface attack by corroding fluid must be thoroughly evaluated before deciding on best alloy for purpose.

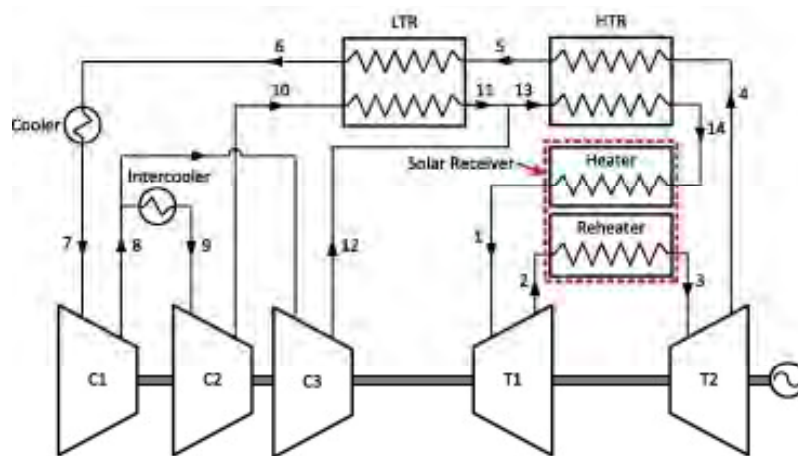
Exergy Model Development



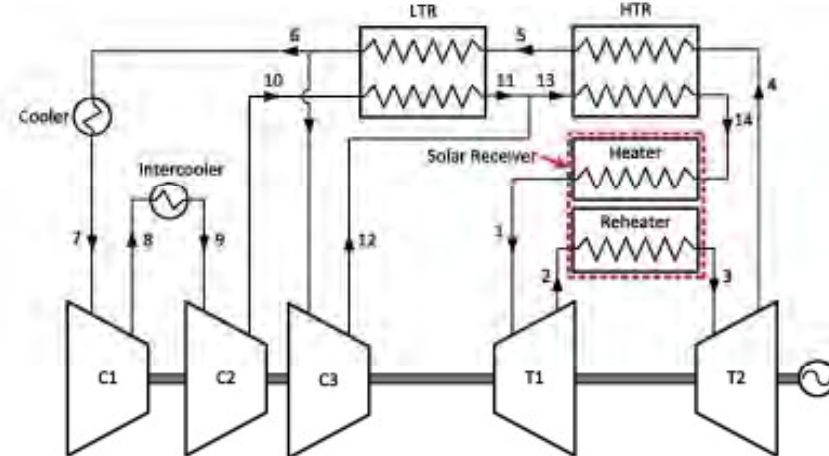
(a)



(b)



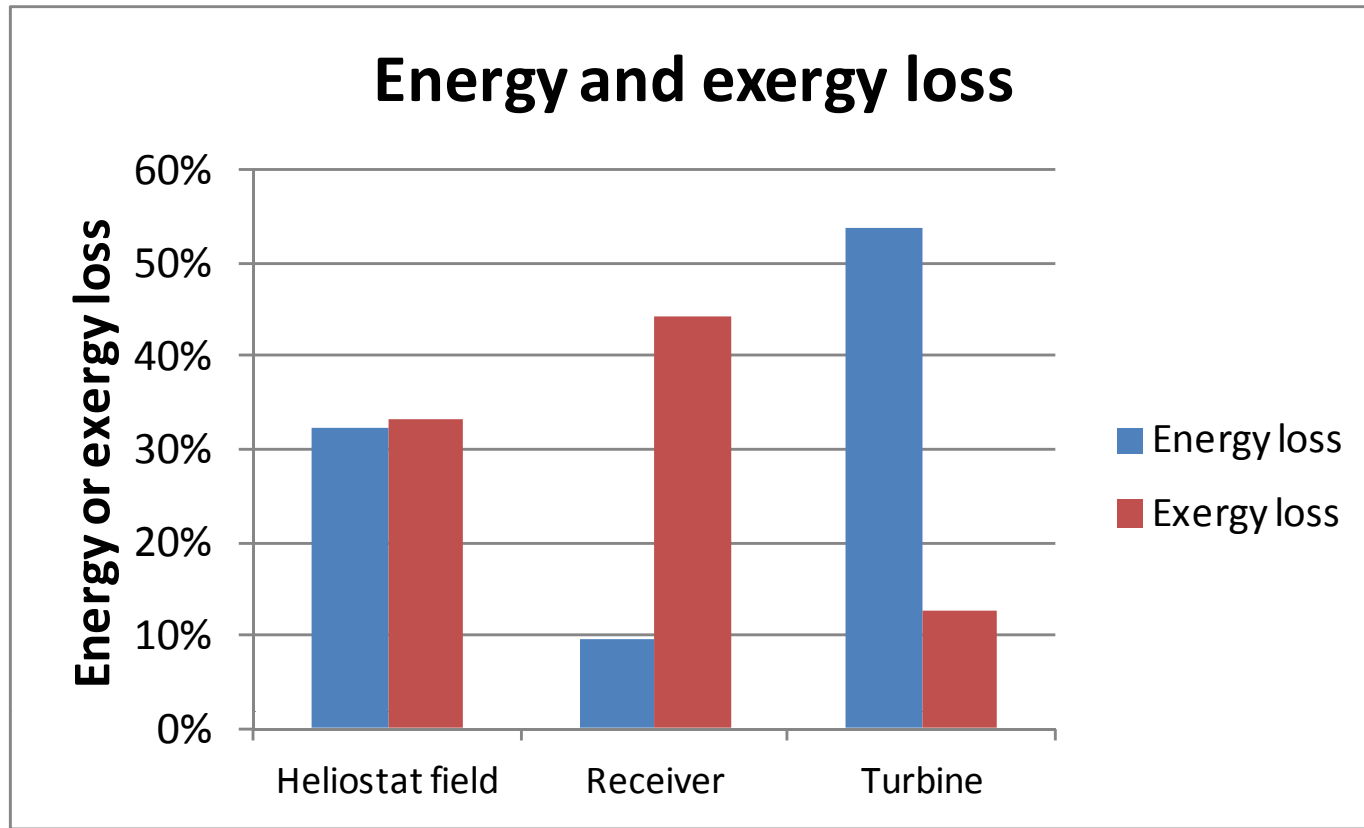
(c)



(d)

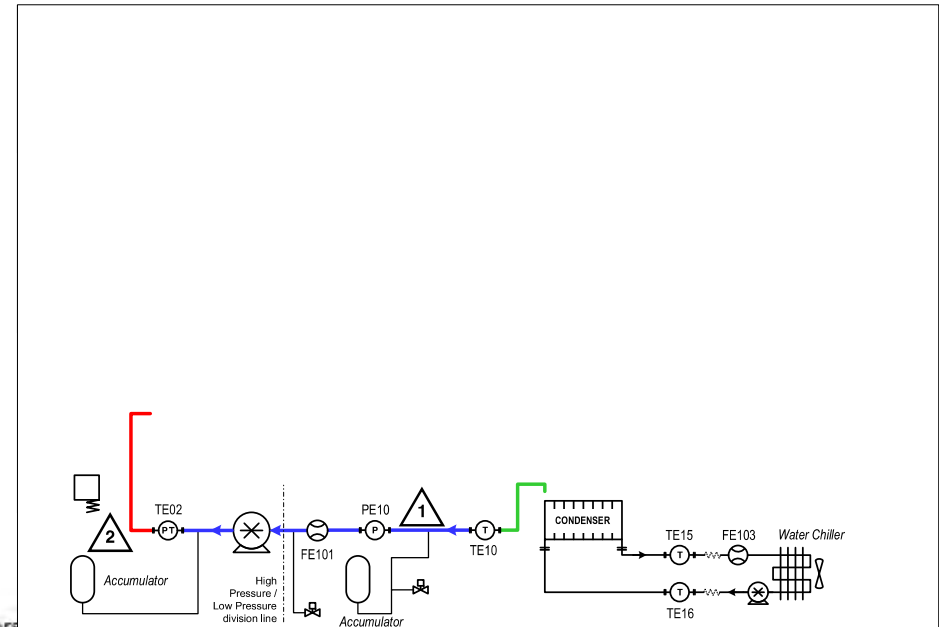
Applied Energy, Volume 148, 15 June 2015, Pages 348-365

Where can we make most thermodynamic impact?



High Pressure Test Loop

- Multiple Loop Configurations
Recuperated / Non Recuperated
- Expansion valve or turbine mode
- Allows testing at similar (scaled)
conditions



Capabilities:

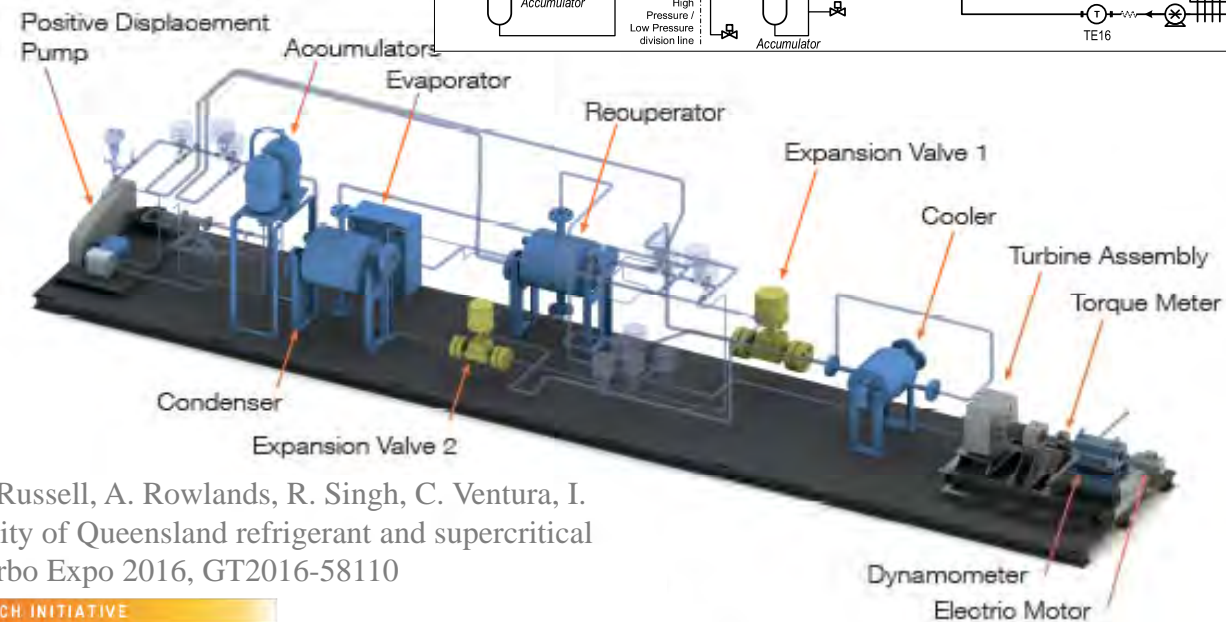
Flow Rate:

3 L/s (soon 30 L/s)

Power: 60 kWt

Temperature Limit : 250° C

Pressure Limit: 20 MPa



B. Twomey, A. Nagy, H. Russell, A. Rowlands, R. Singh, C. Ventura, I. Jahn (2016). The University of Queensland refrigerant and supercritical CO2 test loop, ASME Turbo Expo 2016, GT2016-58110

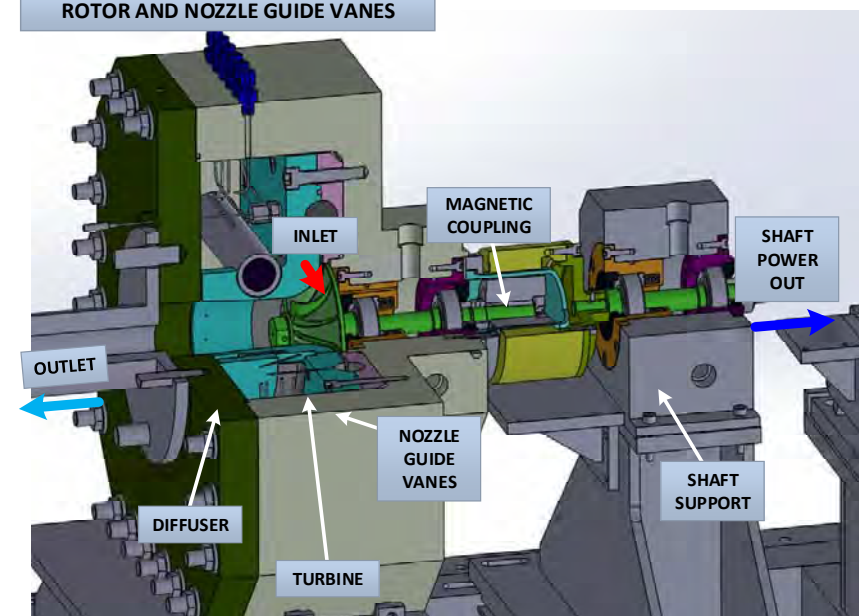
UQ 7kW R245fa turbine

- Stepping stone towards a radial sCO₂ turbine
- Verification of design tools and methods
- Rotor stator geometry defined using in-house design tools
- CFD to estimate rotor loads
- Flexible housing to iterate rotor and stator design

→ Validation of Tools and Methods



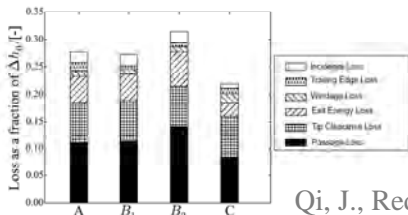
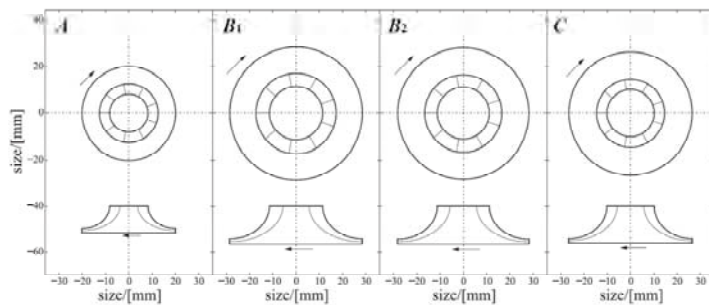
Speed: 32 000 RPM
Power: 7 kW
Temperature: 150° C
Pressure Ratio: 3.76



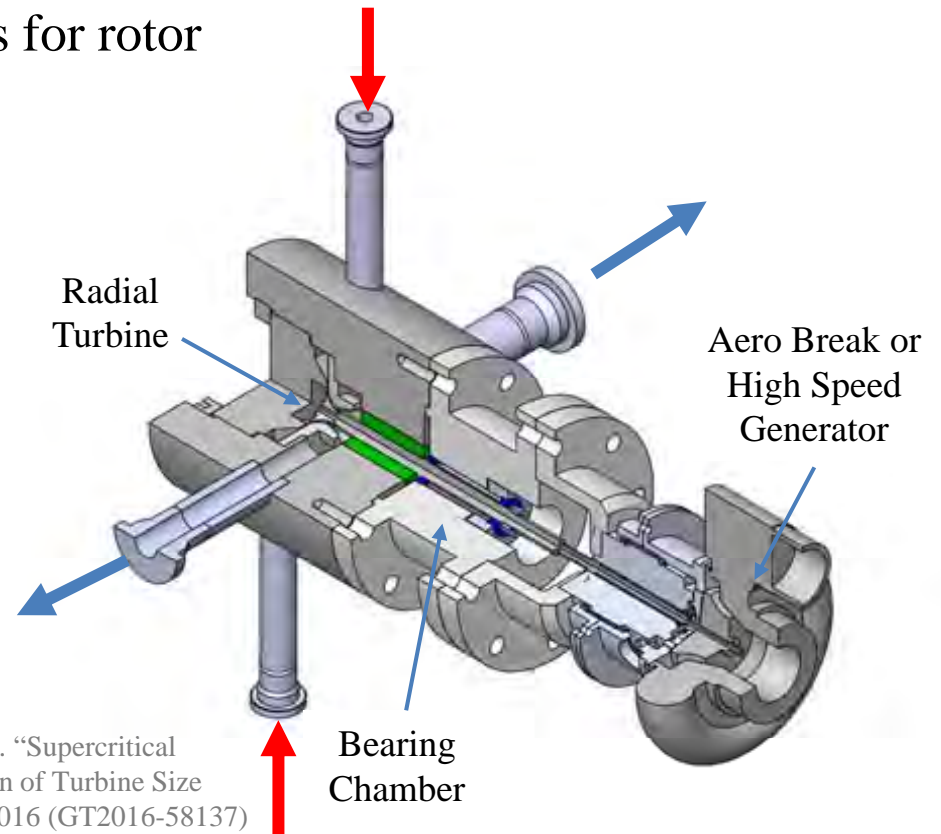
100kW sCO₂ turbine

- Concept for family of turbines
Power Range: 0.25 MW → 10 MW
- Scalable Rotor and Casing design
- Design selection based on in-house tools for rotor geometry, volutes, etc...
- Manufacture to commence in 2017

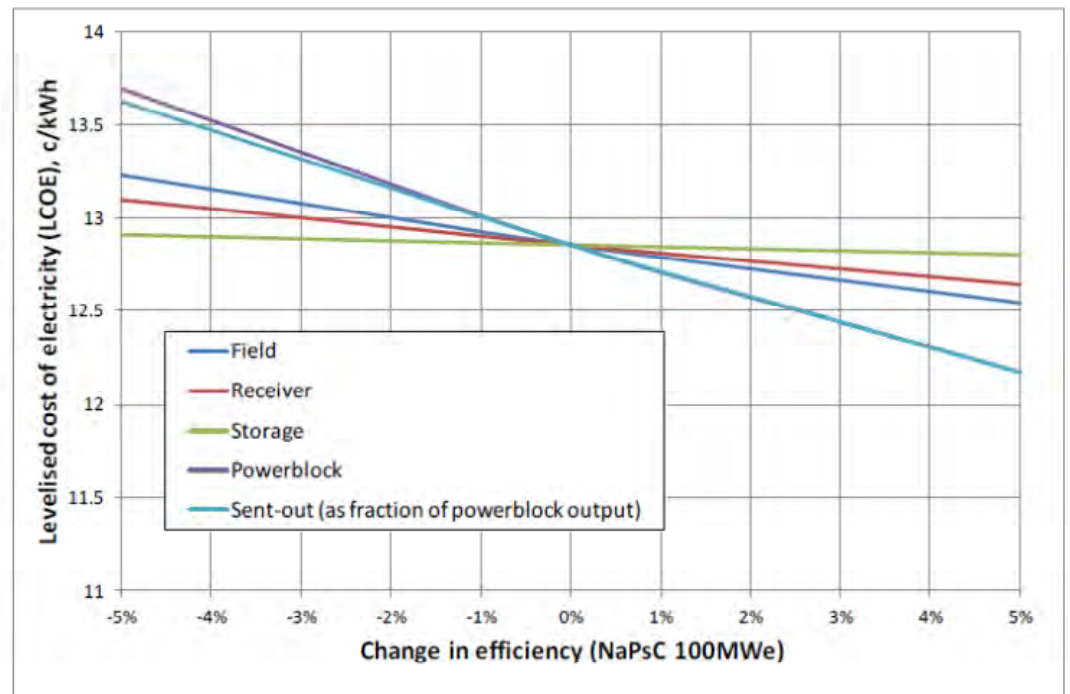
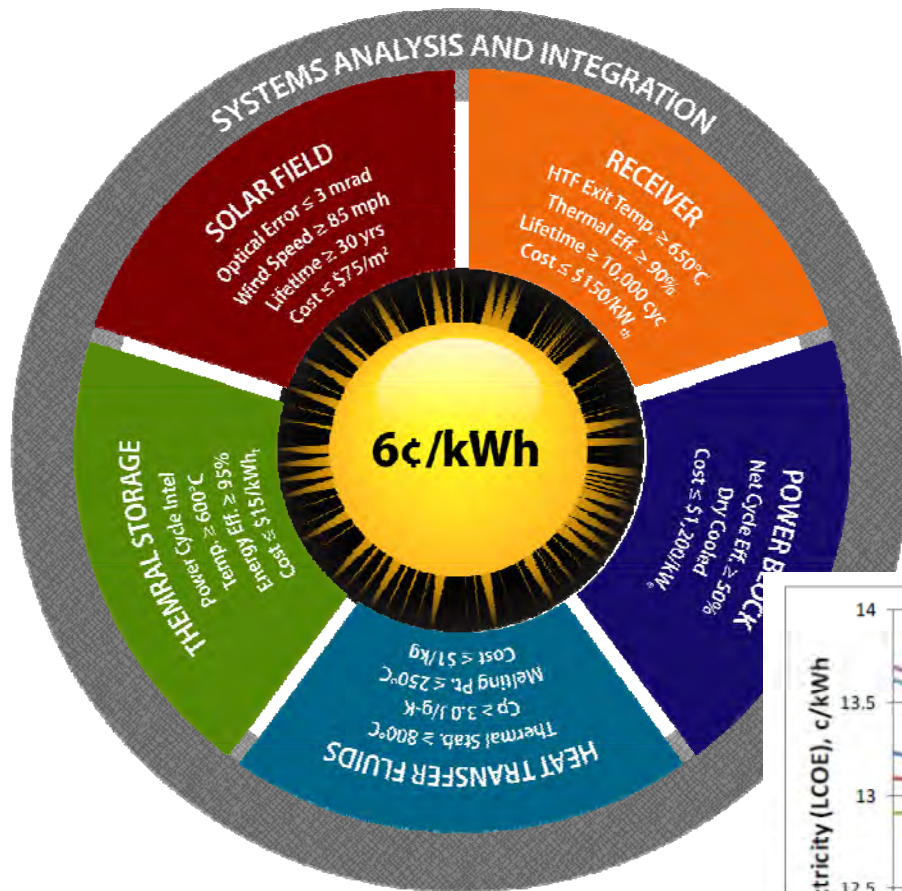
Operation Conditions:
 P_{IN} : 20 MPa
 T_{IN} : 550-600° C
 Pressure Ratio: 2.2 – 2.5



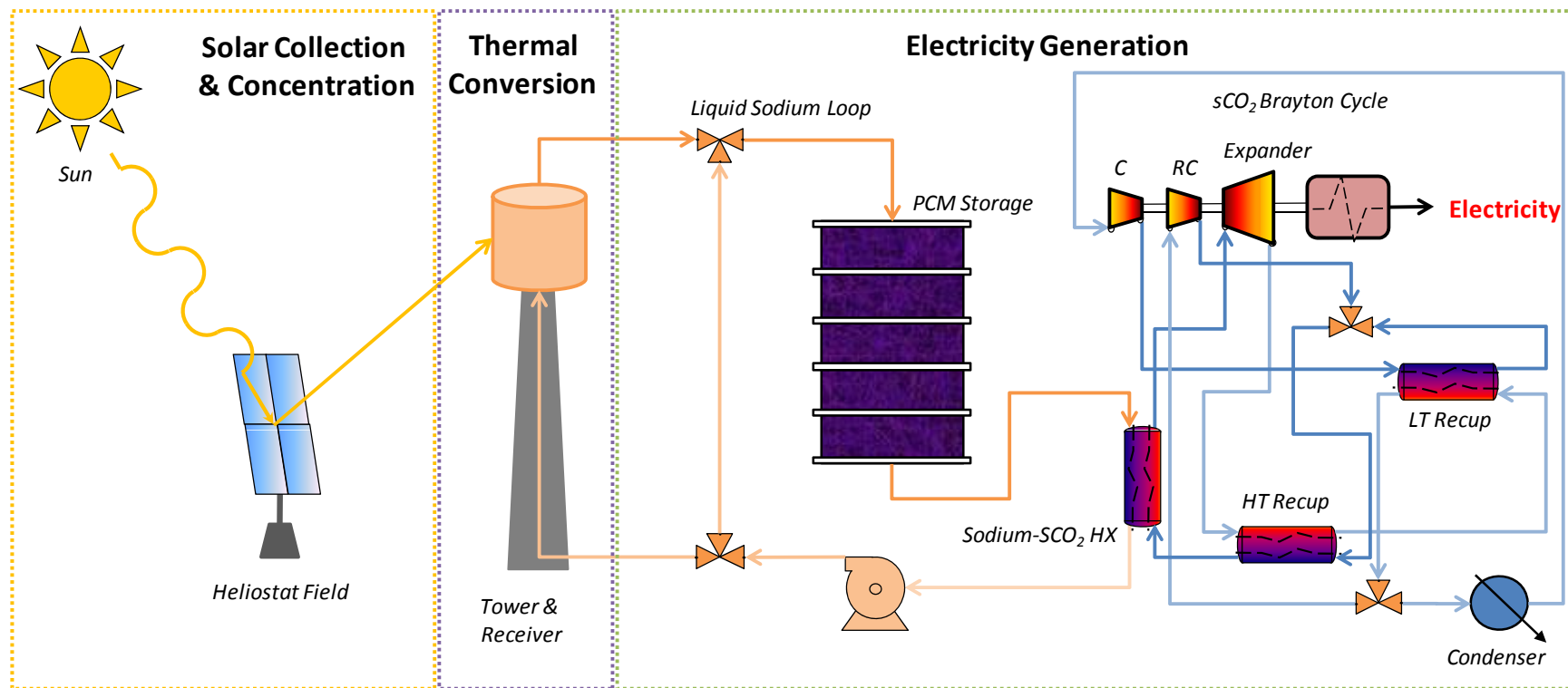
Qi, J., Reddell, T., Qin, K., Hooman, K., Jahn, I. 2016. "Supercritical CO₂ Radial Turbine Design Performance as a Function of Turbine Size parameters". Proceedings of the ASME Turbo Expo 2016 (GT2016-58137)

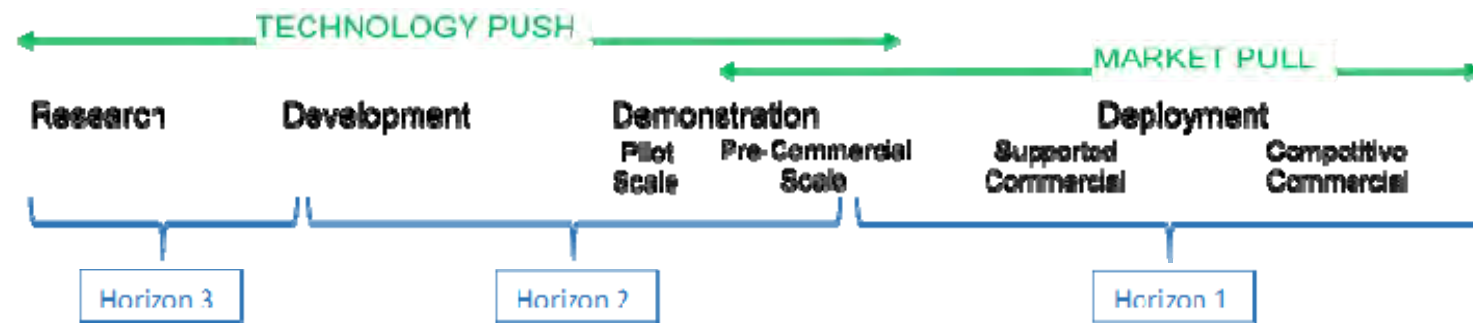


Component cost and performance targets



CSP-driven s-CO₂ cycle - Advanced





	Today	5 years	10 years
H1	<ul style="list-style-type: none"> Tower, salt receiver, 2-tank salt storage, sub-crit. steam turbine, including hybrids. >1. Innovation hub – integrated with above Industrial heat opportunities, incl hybrids 	<ul style="list-style-type: none"> Tower, salt receiver, 2-tank salt storage, 540°C s-CO₂ turbine Innovation hub (already existing) Demonstration scale solar fuels Heat supply incl hybrid with biomass/gas/coal 	<ul style="list-style-type: none"> Tower with advanced heliostats, hi temp htf receiver, hi temp storage, hi temp s-CO₂ turbine Expanded/ refurbished Innovation hub Commercial solar fuels Hazardous waste/ environmental remediation project
H2	<ul style="list-style-type: none"> Pilot testing of advanced htf in tubular receiver, eg Na; hi temp salt; watching brief on particle receivers Test small (≈100kW_e) med temp s-CO₂ turbine on-sun in loop for process optimisation ≈ 1 MWh_{th} hi temp storage test, with above Heliostat longitudinal trials Proving of modeling/ analytical tools Pilot scale solar fuels 	<ul style="list-style-type: none"> Pilot testing of high temperature htf in tubular receiver, eg Na; hi temp salt Participate in global particle receiver trials Test small hi temp s-CO₂ turbine on-sun in loop for process optimisation. ≈ 1 MWh_{th} storage test integrated with above receiver - PCM or thermochemical cycle Pilot scale novel concentrator test Diagnostic tools for all components Environmental remediation; hazardous waste 	<ul style="list-style-type: none"> On-sun pilot testing of advanced receiver integrated with thermochemical storage test loop – at scale on Innovation Hub Globally embedded research teams and components, ie Australian CSP technology deployed in numerous research facilities assisted by researcher two-way sharing Assistance to competitive Australian manufacturing for components, including s-CO₂ turbines Zero O&M heliostats
H3	<ul style="list-style-type: none"> Novel thermochemical cycles for long term storage – candidate materials Next gen reflectors Materials for hi temp receivers and storage (htf, containment, protection - seeding, coatings) Reduced reflector O&M Advanced measurement tools 	<ul style="list-style-type: none"> Novel thermochemical cycles for long term storage – pre-pilot loop Next gen concentrators Very high flux/ high heat transfer/ low loss receivers/ reactors, including hi temp selective surfaces Heat nine receivers 	<ul style="list-style-type: none"> Fuels from thermally-driven atmospheric CO₂ reduction cycles Thermionics ??

Today

H1

- Tower, salt receiver, 2-tank salt storage, sub-crit. steam turbine, including hybrids. >1.
- Innovation hub – integrated with above
- Industrial heat opportunities, incl hybrids

H2

- Pilot testing of advanced htf in tubular receiver, eg Na; hi temp salt; watching brief on particle receivers
- Test small ($\approx 100\text{kW}_e$) med temp s-CO₂ turbine on-sun in loop for process optimisation
- $\approx 1\text{ MWh}_{th}$ hi temp storage test, with above
- Heliostat longitudinal trials
- Proving of modelling/ analytical tools
- Pilot scale solar fuels

H3

- Novel thermochemical cycles for long term storage – candidate materials
- Next gen reflectors
- Materials for hi temp receivers and storage (htf, containment, protection - seeding, coatings)
- Reduced reflector O&M
- Advanced measurement tools

5 years

H1

- Tower, salt receiver, 2-tank salt storage, 540°C s-CO₂ turbine
- Innovation hub (already existing)
- Demonstration scale solar fuels
- Heat supply incl hybrid with biomass/gas/coal

H2

- Pilot testing of high temperature htf in tubular receiver, eg Na; hi temp salt
- Participate in global particle receiver trials
- Test small hi temp s-CO₂ turbine on-sun in loop for process optimisation.
- $\approx 1\text{ MWh}_{th}$ storage test integrated with above receiver - PCM or thermochemical cycle
- Pilot scale novel concentrator test
- Diagnostic tools for all components
- Environmental remediation; hazardous waste

H3

- Novel thermochemical cycles for long term storage – pre-pilot loop
- Next gen concentrators
- Very high flux/ high heat transfer/ low loss receivers/ reactors, including hi temp selective surfaces
- Heat pipe receivers

5 years

H1

- Tower, salt receiver, 2-tank salt storage, 540°C s-CO₂ turbine
- Innovation hub (already existing)
- Demonstration scale solar fuels
- Heat supply incl hybrid with biomass/gas/coal

H2

- Pilot testing of high temperature htf in tubular receiver, eg Na; hi temp salt
- Participate in global particle receiver trials
- Test small hi temp s-CO₂ turbine on-sun in loop for process optimisation.
- ≈ 1 MWh_{th} storage test integrated with above receiver - PCM or thermochemical cycle
- Pilot scale novel concentrator test
- Diagnostic tools for all components
- Environmental remediation; hazardous waste

H3

- Novel thermochemical cycles for long term storage – pre-pilot loop
- Next gen concentrators
- Very high flux/ high heat transfer/ low loss receivers/ reactors, including hi temp selective surfaces

- Heat pipe receivers

10 years

H1

- Tower with advanced heliostats, hi temp htf receiver, hi temp storage, hi temp s-CO₂ turbine
- Expanded/refurbished Innovation hub
- Commercial solar fuels
- Hazardous waste/ environmental remediation project

H2

- On-sun pilot testing of advanced receiver integrated with thermochemical storage test loop – at scale on Innovation Hub
- Globally embedded research teams and components, ie Australian CSP technology deployed in numerous research facilities assisted by researcher two-way sharing
- Assistance to competitive Australian manufacturing for components, including s-CO₂ turbines
- Zero O&M heliostats

H3

- Fuels from thermally-driven atmospheric CO₂ reduction cycles
- Thermionics
- ??

Thank you

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