THE CRITICALITY OF CO_2 FOR CSP

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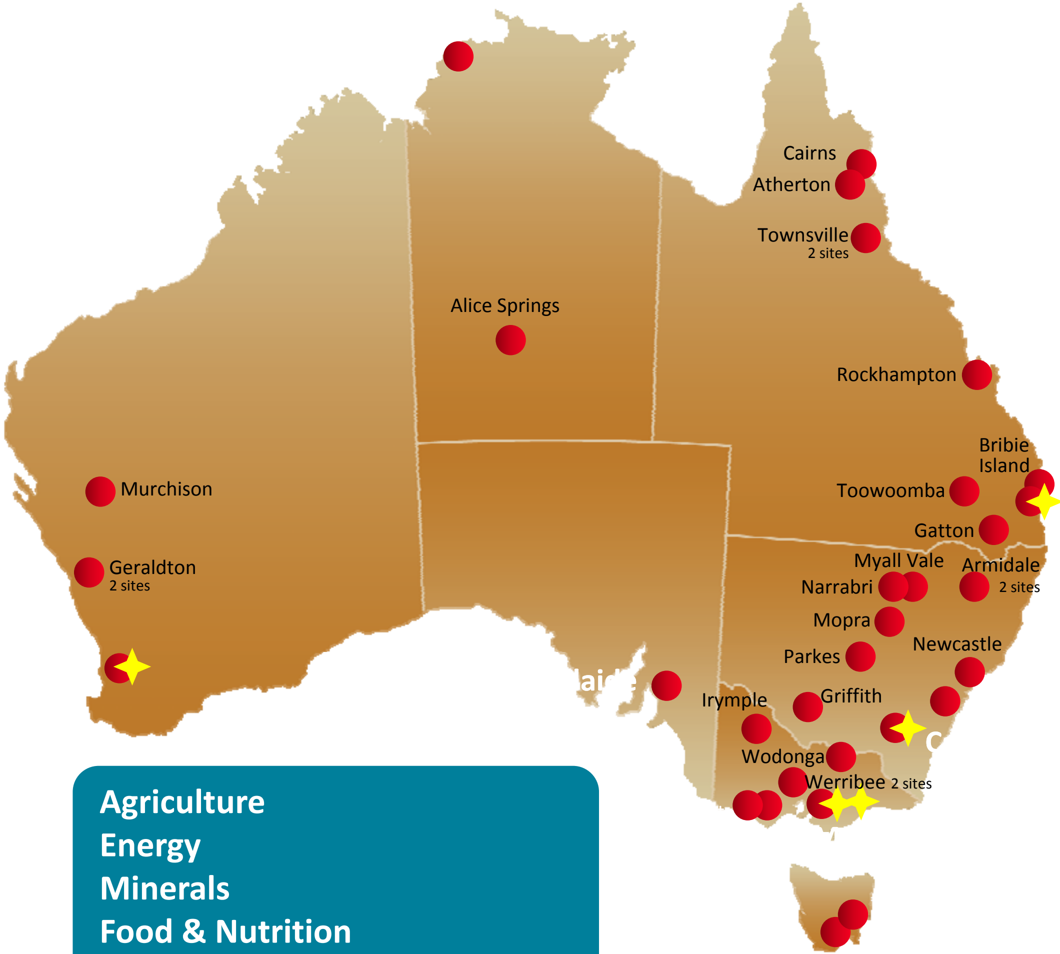
29th September 2016

People	**5319**
Locations	**55**
Business units	**9**
Budget	**$1B+**
Industry	**2800+**

Top 1% global research org.



- Agriculture
- Energy
- Minerals
- Food & Nutrition
- Oceans & Atmosphere
- Land & Water
- Health & Biosecurity
- Manufacturing
- 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

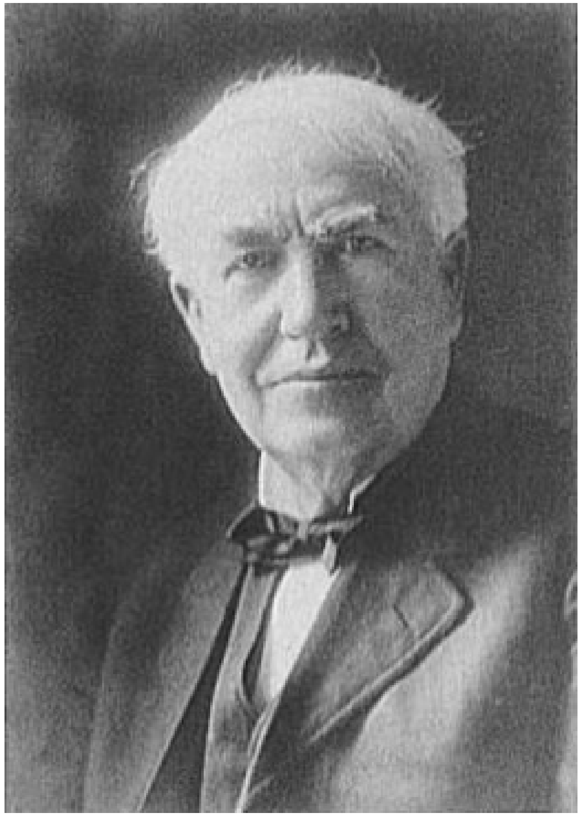
SOFTLY WASHING LIQUID

SELF TWISTING YARN

RAFT POLYMERISATION

NOVACQ™ PRAWN FEED

Thomas Edison



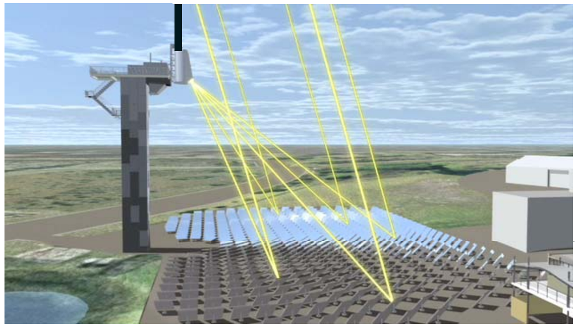
“I'd put my *money* on the sun and solar energy. What a source of power! I hope we don't have to wait 'til oil and coal run out before we tackle that.”

(1847-1931)

Rapid commercial CSP deployment in last several years

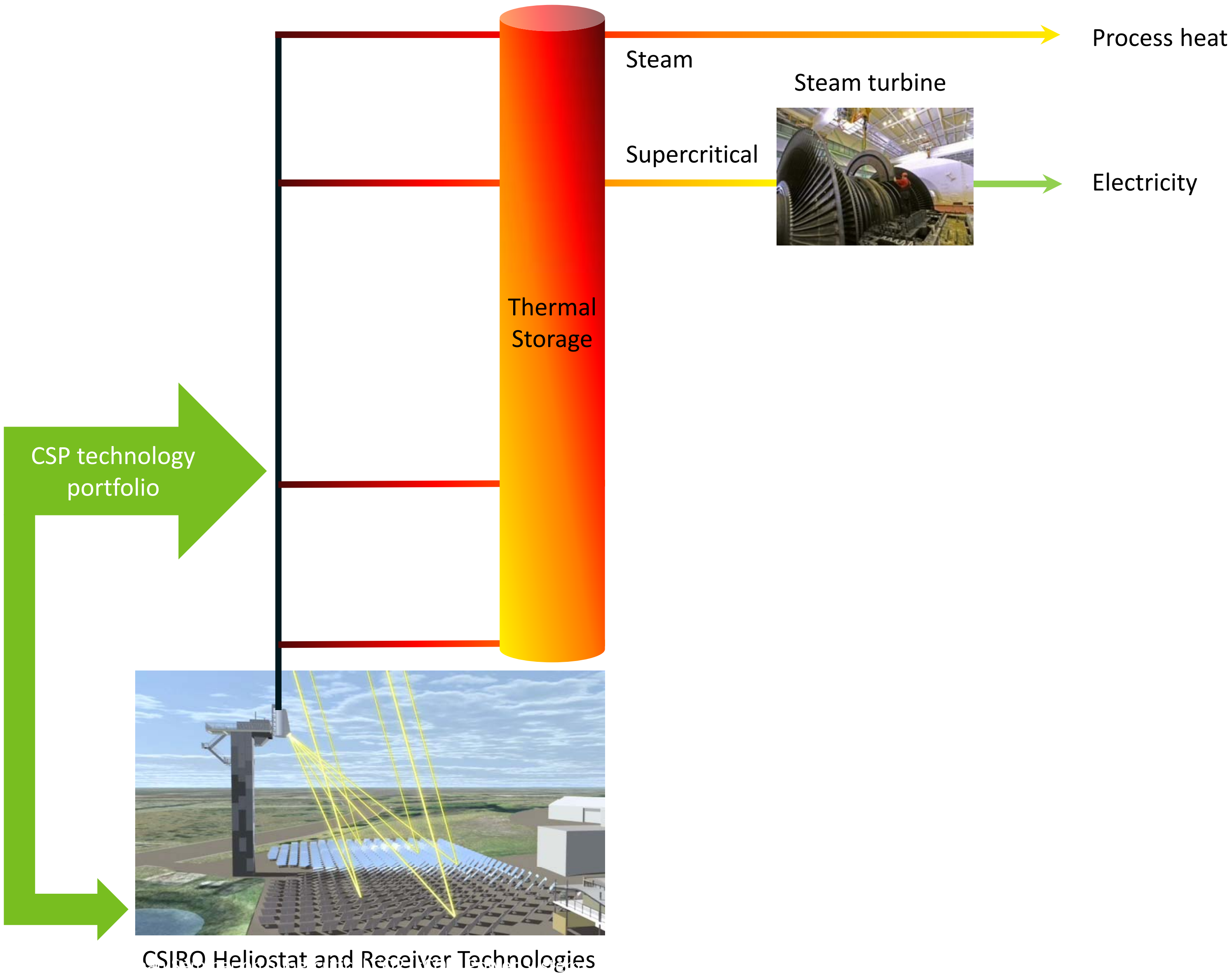
Targeted portfolio of CSP Research Activities

CSP technology portfolio

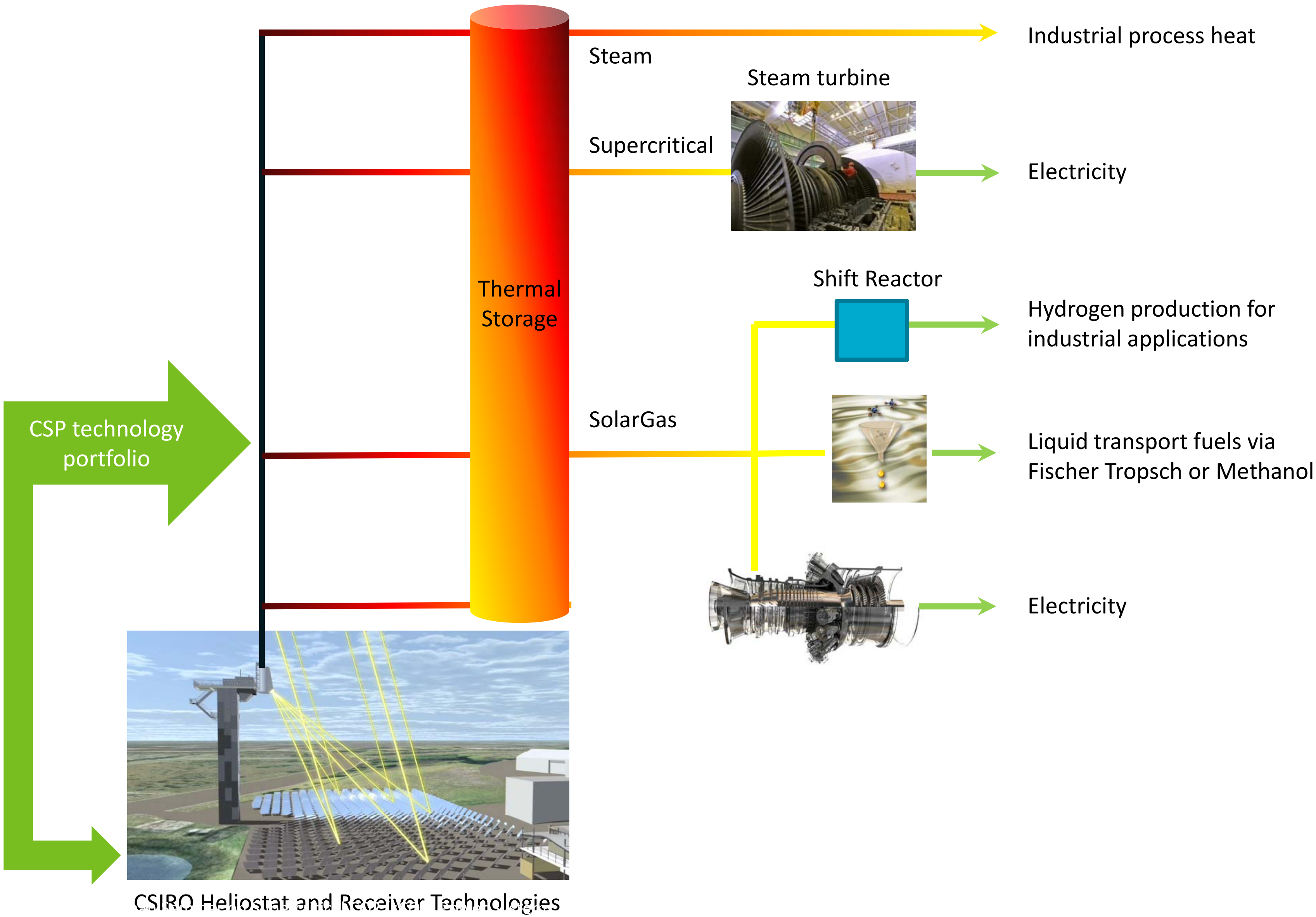


CSIRO Heliostat Technology

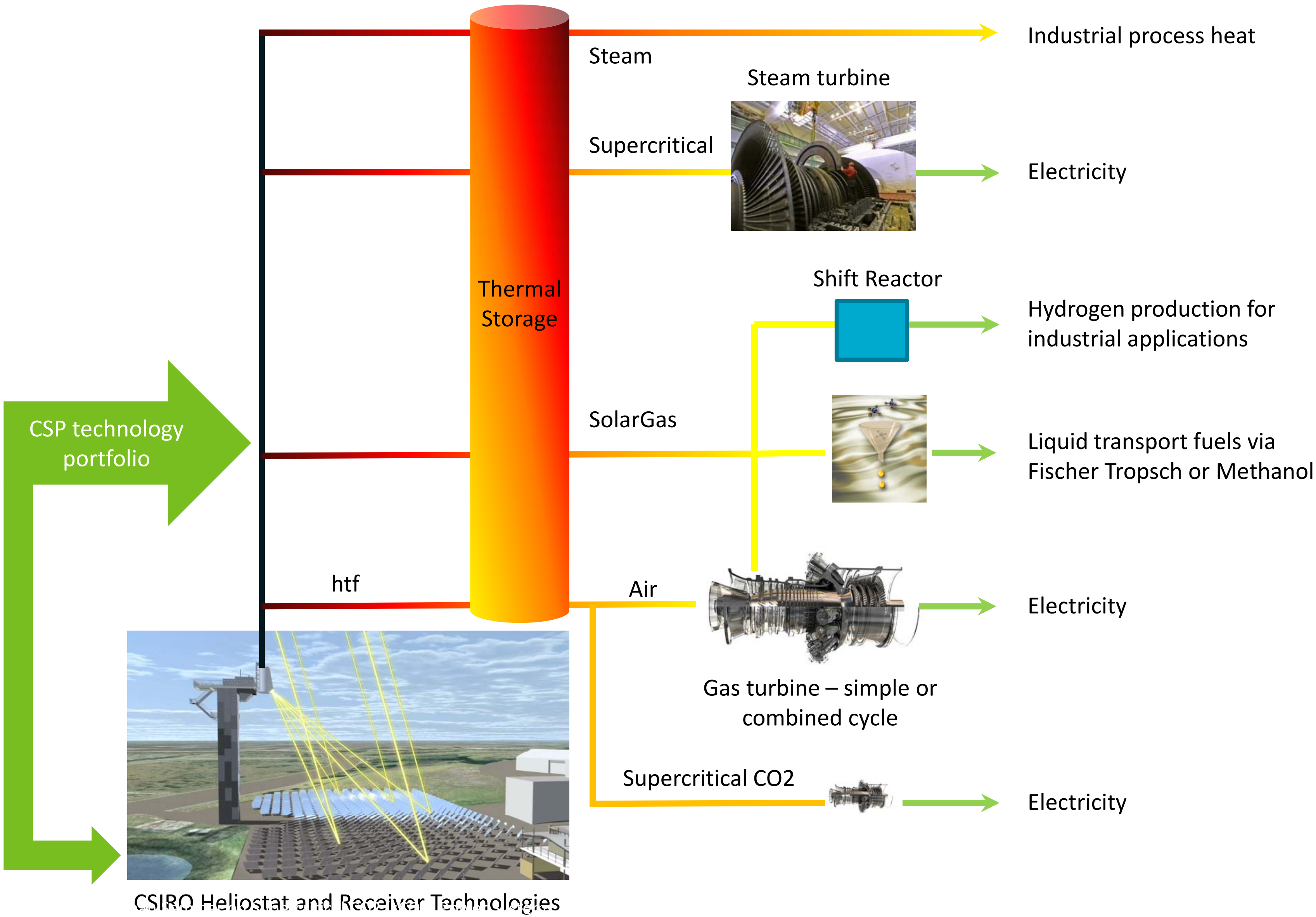
Targeted portfolio of CSP Research Activities



Targeted portfolio of CSP Research Activities

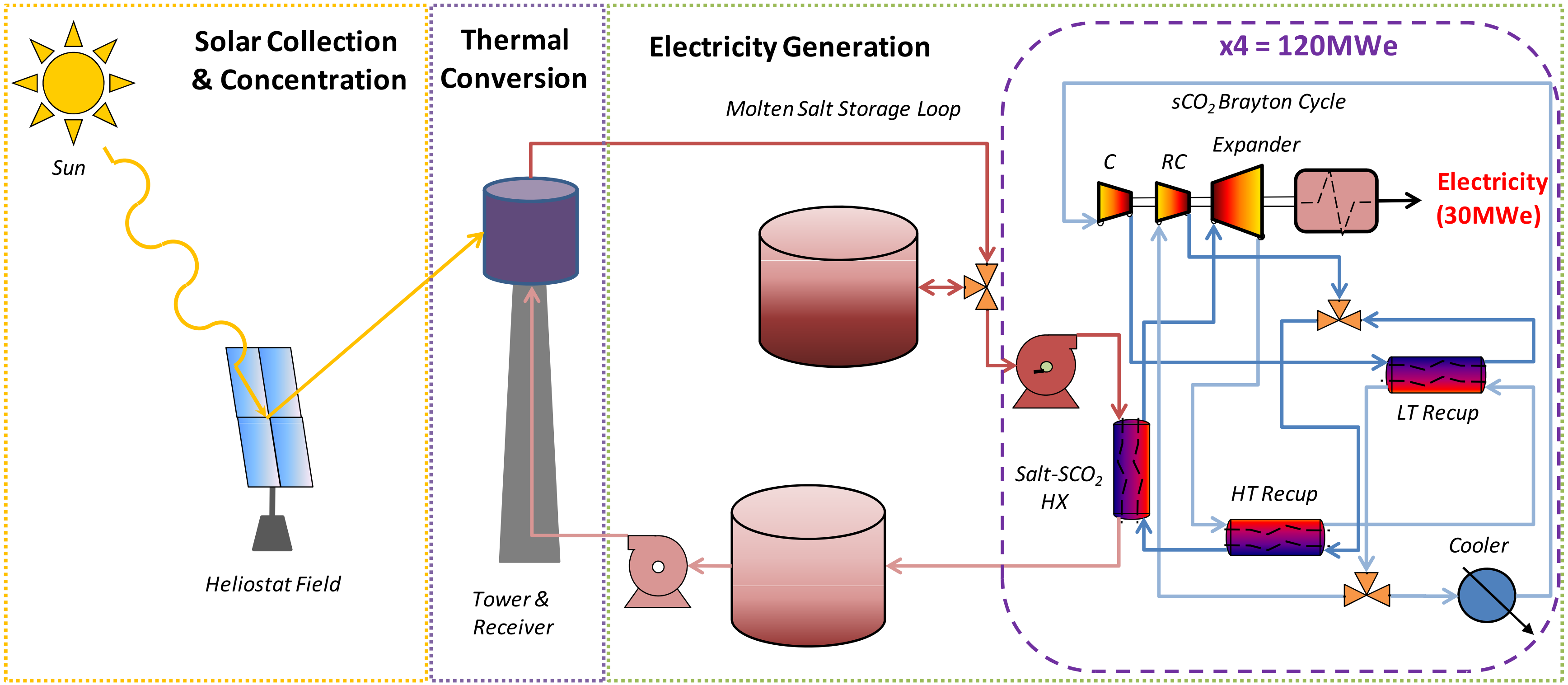


Targeted portfolio of CSP Research Activities




NATIONAL SOLAR ENERGY CENTRE

CSP-driven s-CO2 cycle – “near” term

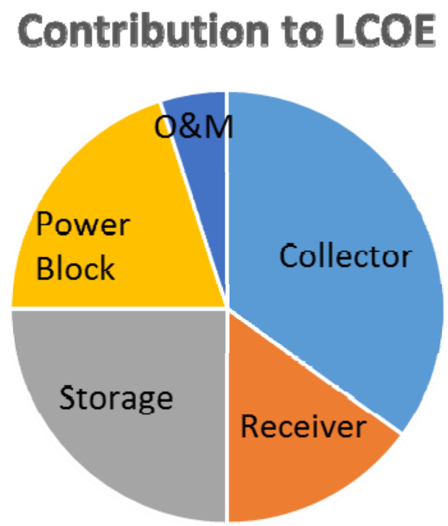


Complex (often fun) multi-variable optimization

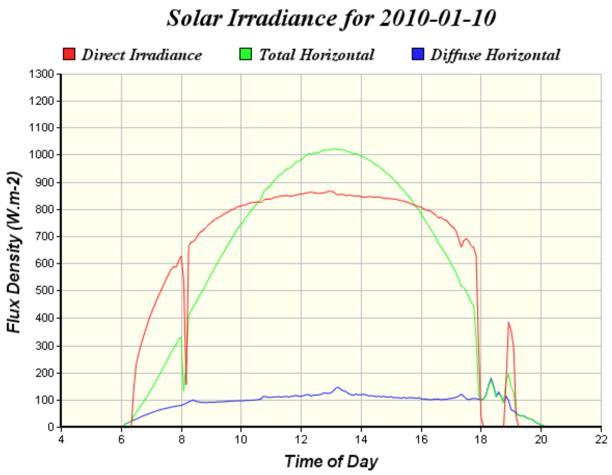
Relatively conventional issues:

Capacity vs $/kW vs efficiency

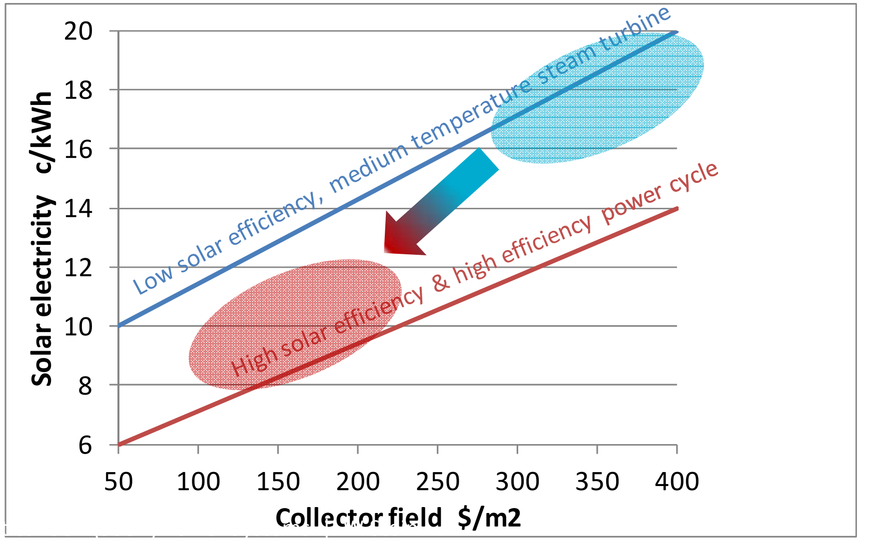
- Normal steam turbine demands > 50MWe; adding storage means very large receiver; significant investment in single projects
- Efficiency is king



The fundamentals of reducing CSP cost

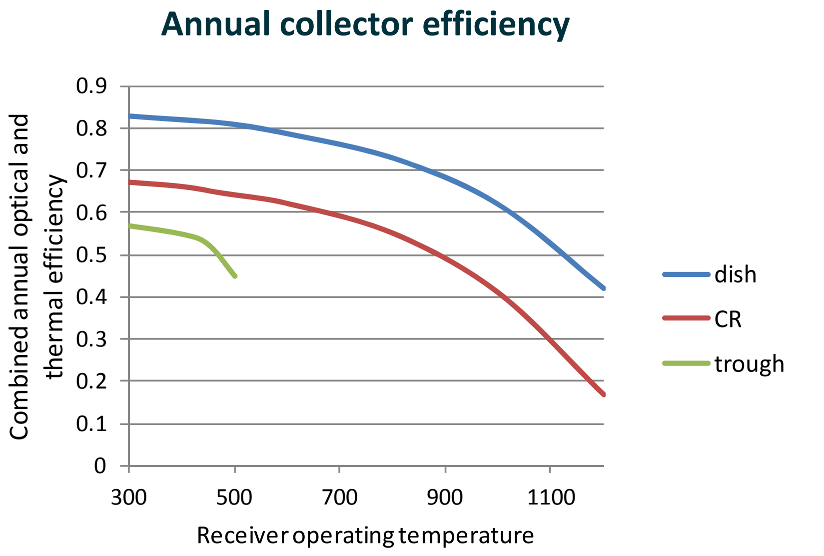


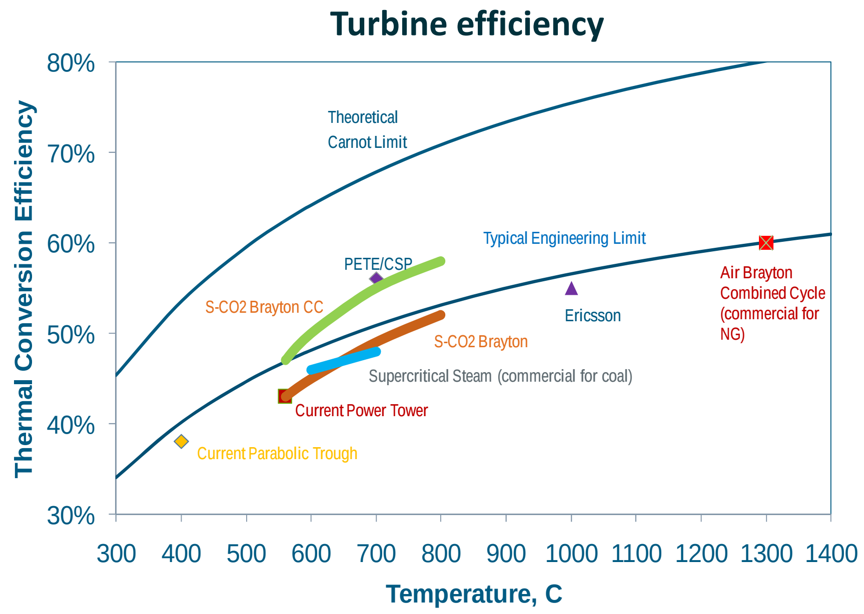
We know the resource

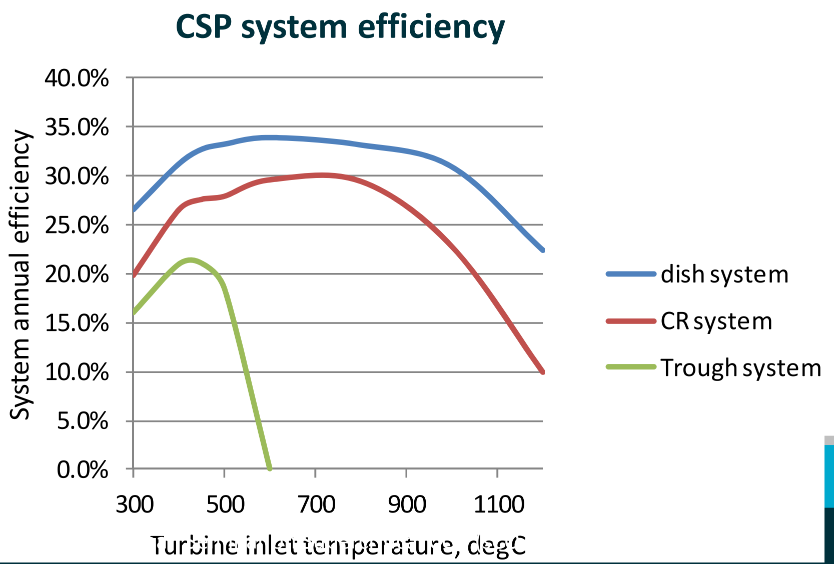


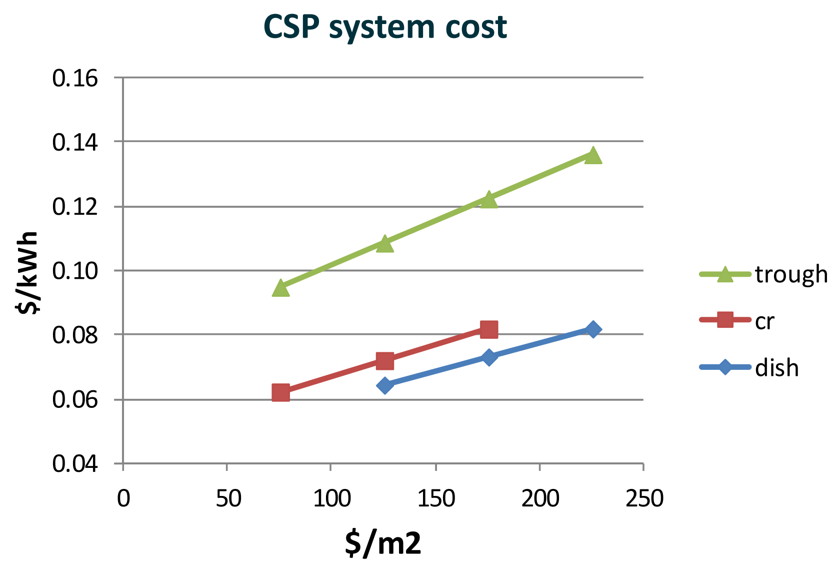
We know the cost and performance of turbines/ heat engines

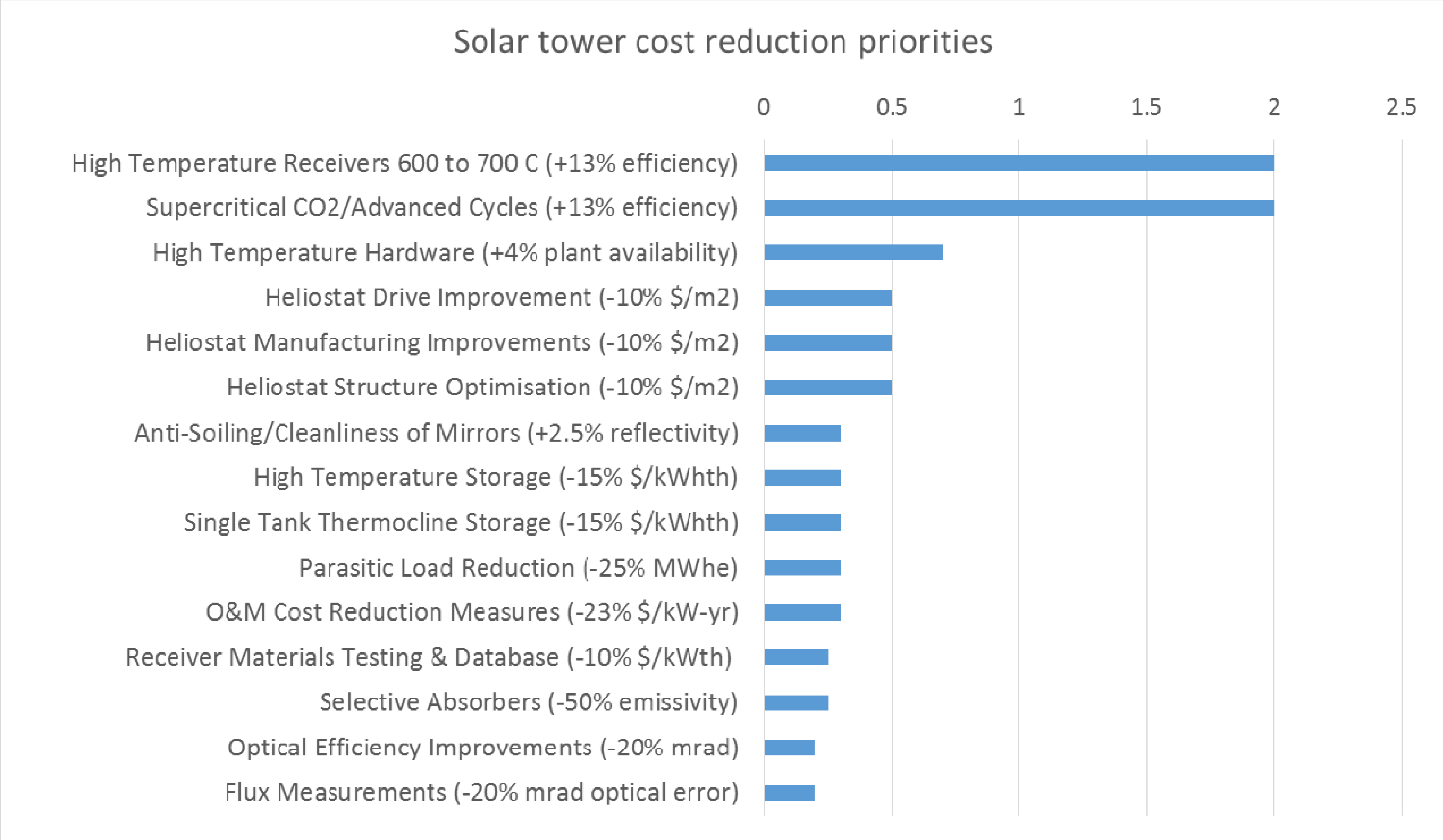
The fundamentals of reducing CSP LCOE











Solar tower cost reduction priorities
0
0.5
1
1.5
2
2.5
High Temperature Receivers 600 to 700 C (+13% efficiency)
Supercritical CO2/Advanced Cycles (+13% efficiency)
High Temperature Hardware (+4% plant availability)
Heliostat Drive Improvement (-10% $/m2)
Heliostat Manufacturing Improvements (-10% $/m2)
Heliostat Structure Optimisation (-10% $/m2)
Anti-Soiling/Cleanliness of Mirrors (+2.5% reflectivity)
High Temperature Storage (-15% $/kWhth)
Single Tank Thermocline Storage (-15% $/kWhth)
Parasitic Load Reduction (-25% MWhe)
O&M Cost Reduction Measures (-23% $/kW-yr)
Receiver Materials Testing & Database (-10% $/kWth)
Selective Absorbers (-50% emissivity)
Optical Efficiency Improvements (-20% mrad)
Flux Measurements (-20% mrad optical error)

Complex multi-variable optimization

Interaction with other components:

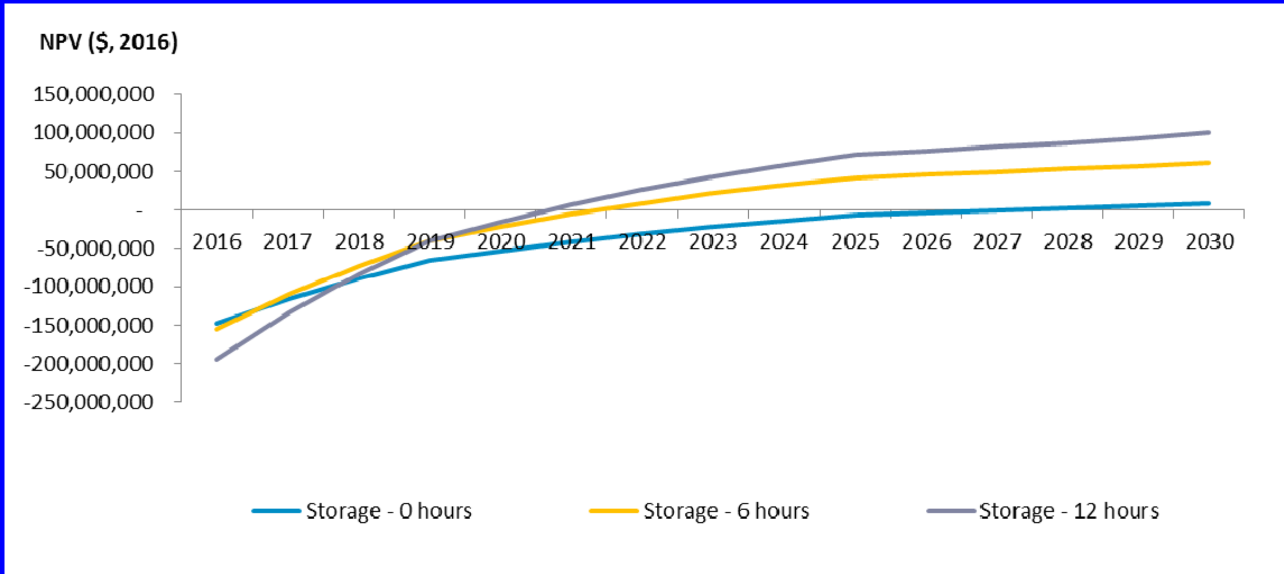
Thermal or thermochemical storage

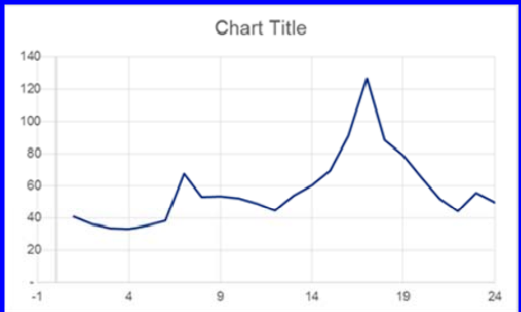
- “Conventional” sensible molten storage works well with a Rankine cycle but more difficult with small ΔT of s-CO2

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

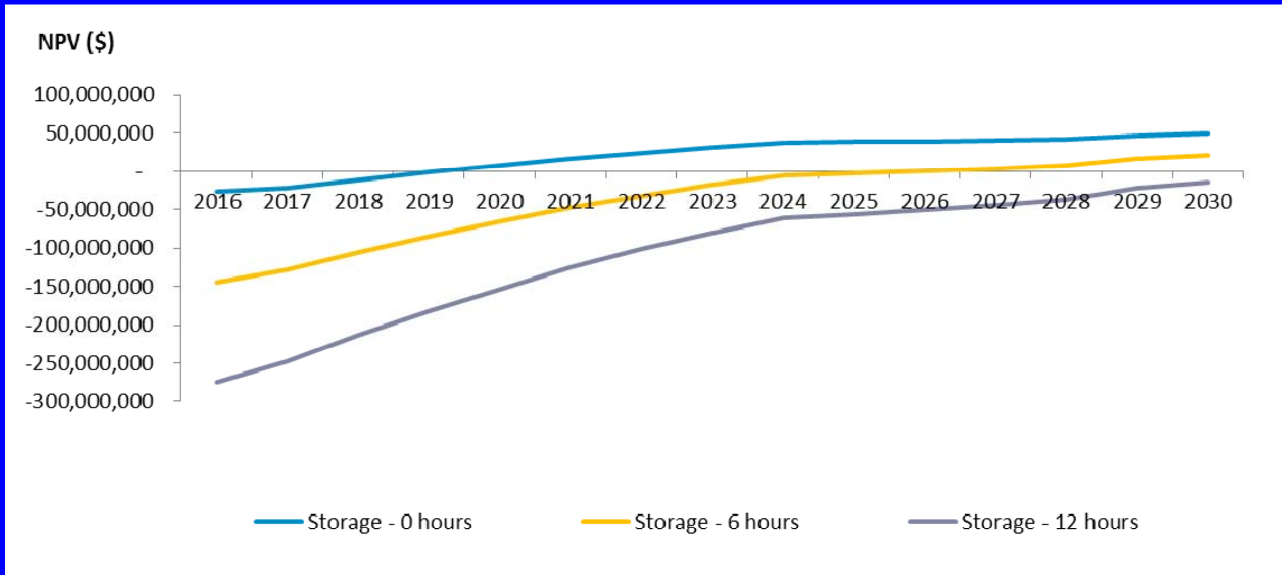
TARGET	CYCLE TEMPERATURE (°C)			
	560	610	700	1000
18c/kWh	$234	$259	$208	-$49
12c/kWh	$101	$118	$53	-$236

NPV for CSP and thermal storage





NPV for PV and battery storage



Deloitte.

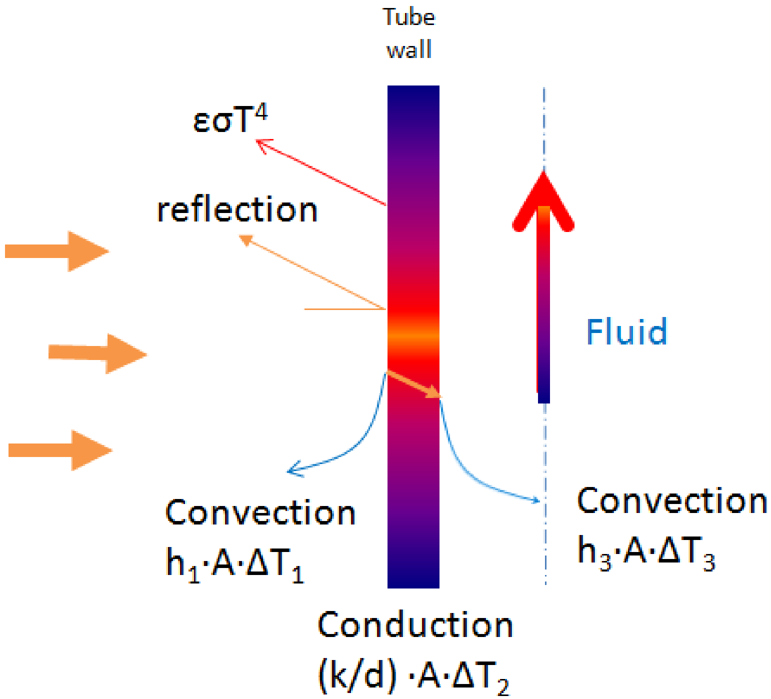
Complex multi-variable optimization

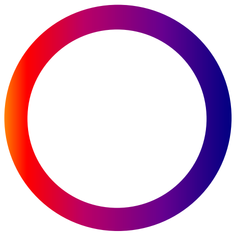
Interaction with other components:

Receiver design impacted by:

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

Uncontrolled solar flux (or temperature)

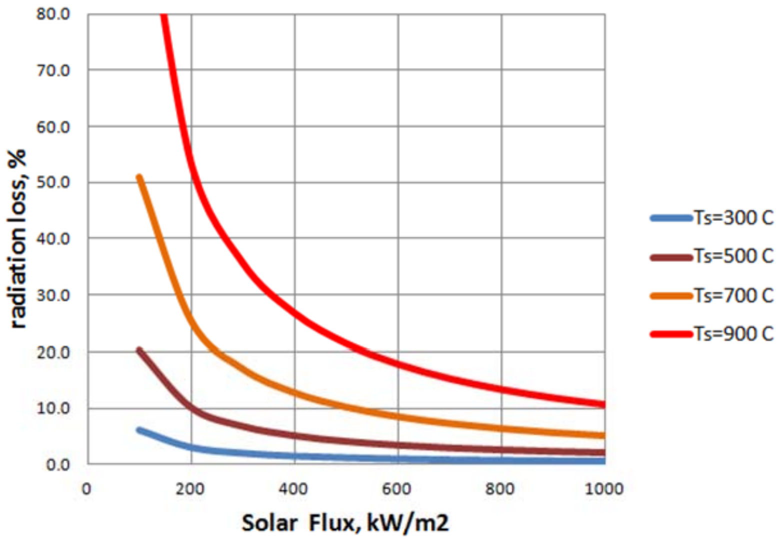




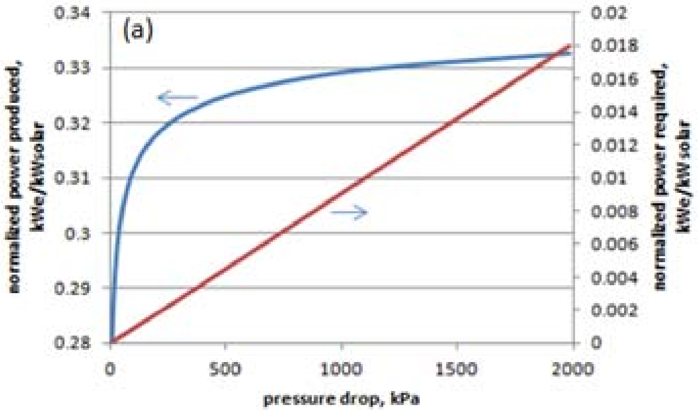
Causes:
Sun location
Limit of optic control
Receiver geometry
Field geometry
Tower shading
Heat transfer problem
Other unknowns

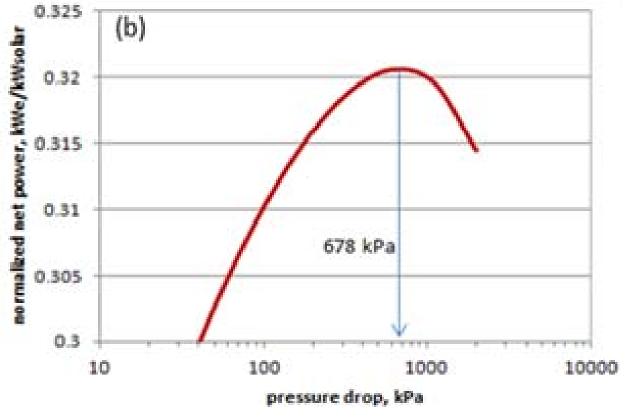
Consequences:
Inefficient heat transfer
Hot and cold spots
Material failure
OP condition limited

Solutions:
Flux distribution control
High accuracy heliostat
Enhancing heat transfer
Beam redirection

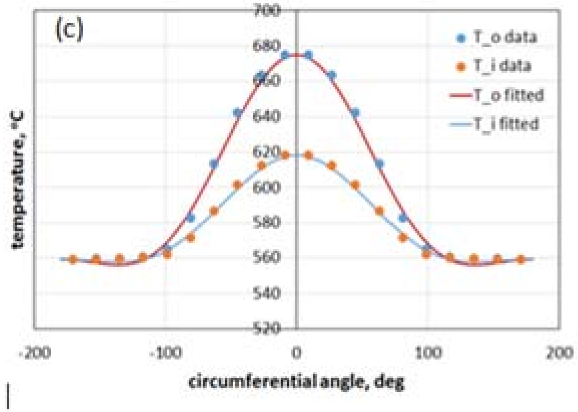


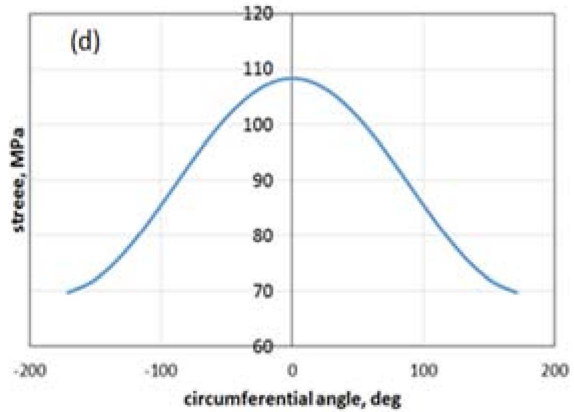
Turbulence & dP Opt.



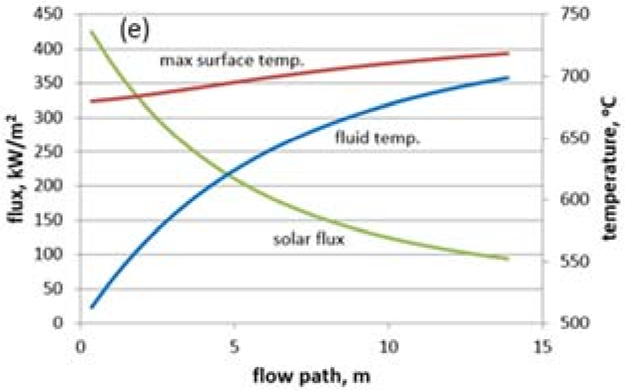


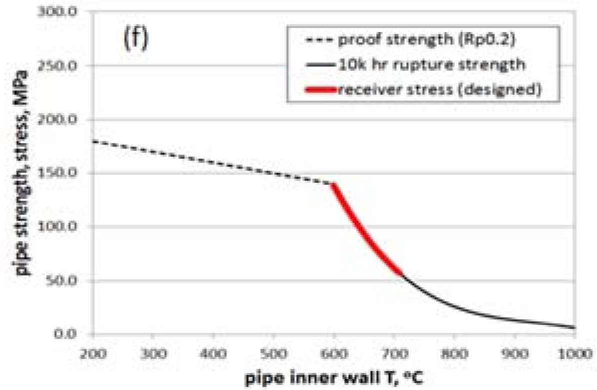
Pipe Stress Clc.



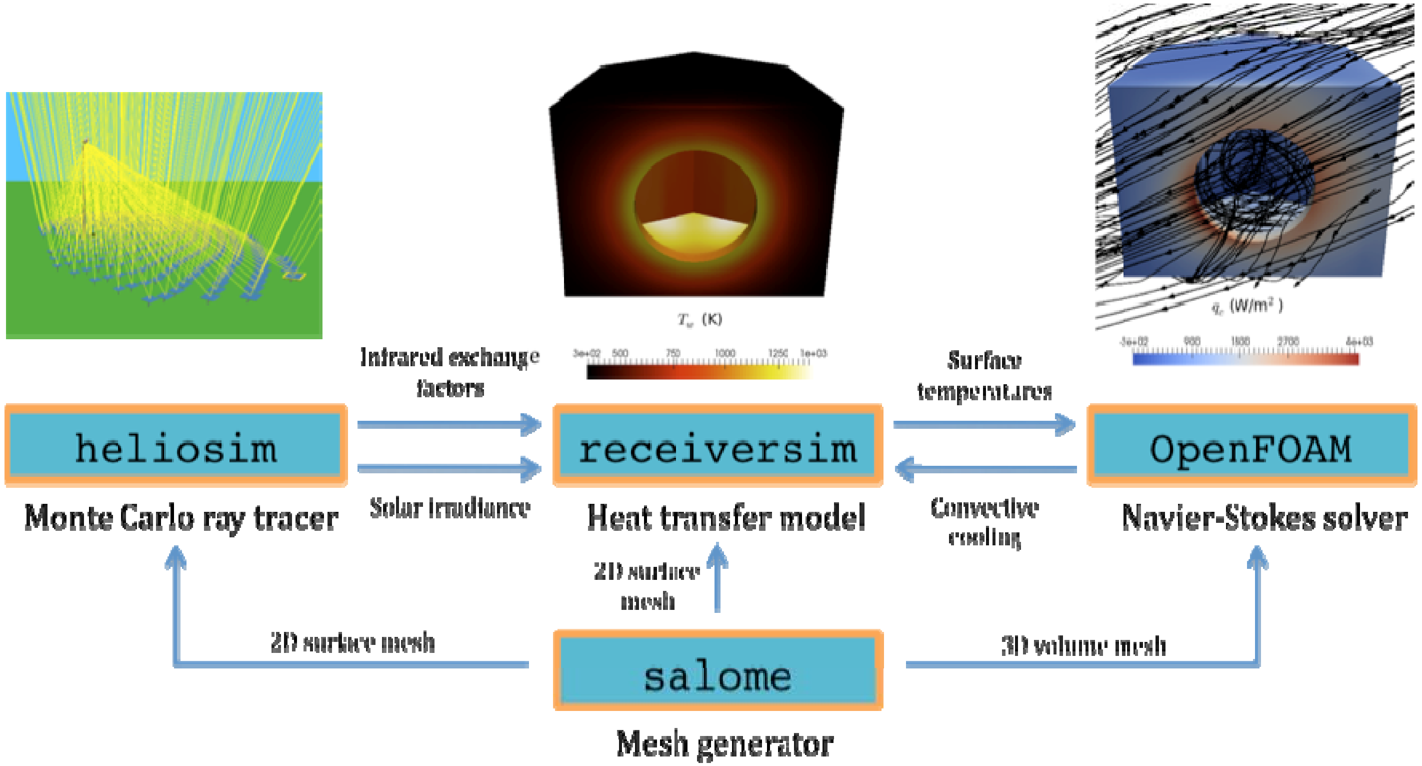


Flux Distribution Opt.



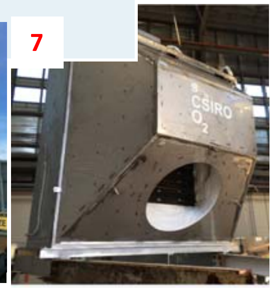


Combined Design/Optimization



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-CO_2 activities

IN-FIELD PILOT

- Completed fabrication of s-CO_2 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-CO_2 >700°C, >25MPa

SYSTEM & PROCESS MODELLING

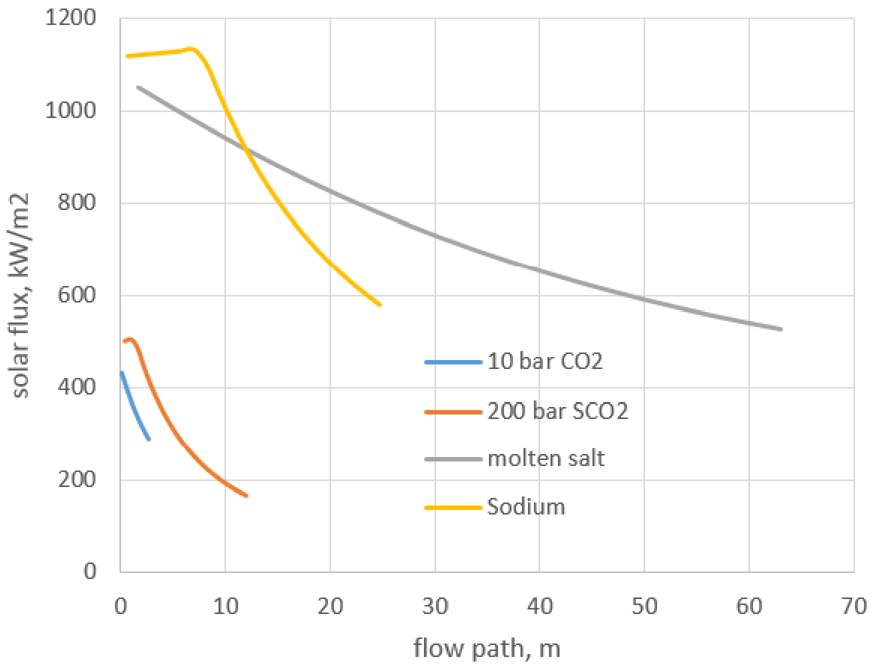
- The material, component and system knowledge gained will be used for development of a solar s-CO_2 demonstration project.

30MPa

S-CO_2 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-CO_2 Solar thermal Receiver

s-CO_2 solar receiver

First operation of s-CO2 receiver and bop

Material compatibility with s-CO_2 - Experimental apparatus

Laboratory air counter-flow in

Three zones furnace heating elements

Laboratory air counter-flow out

Test tube specimen S-CO2 flow out

Alumina tube enclosure

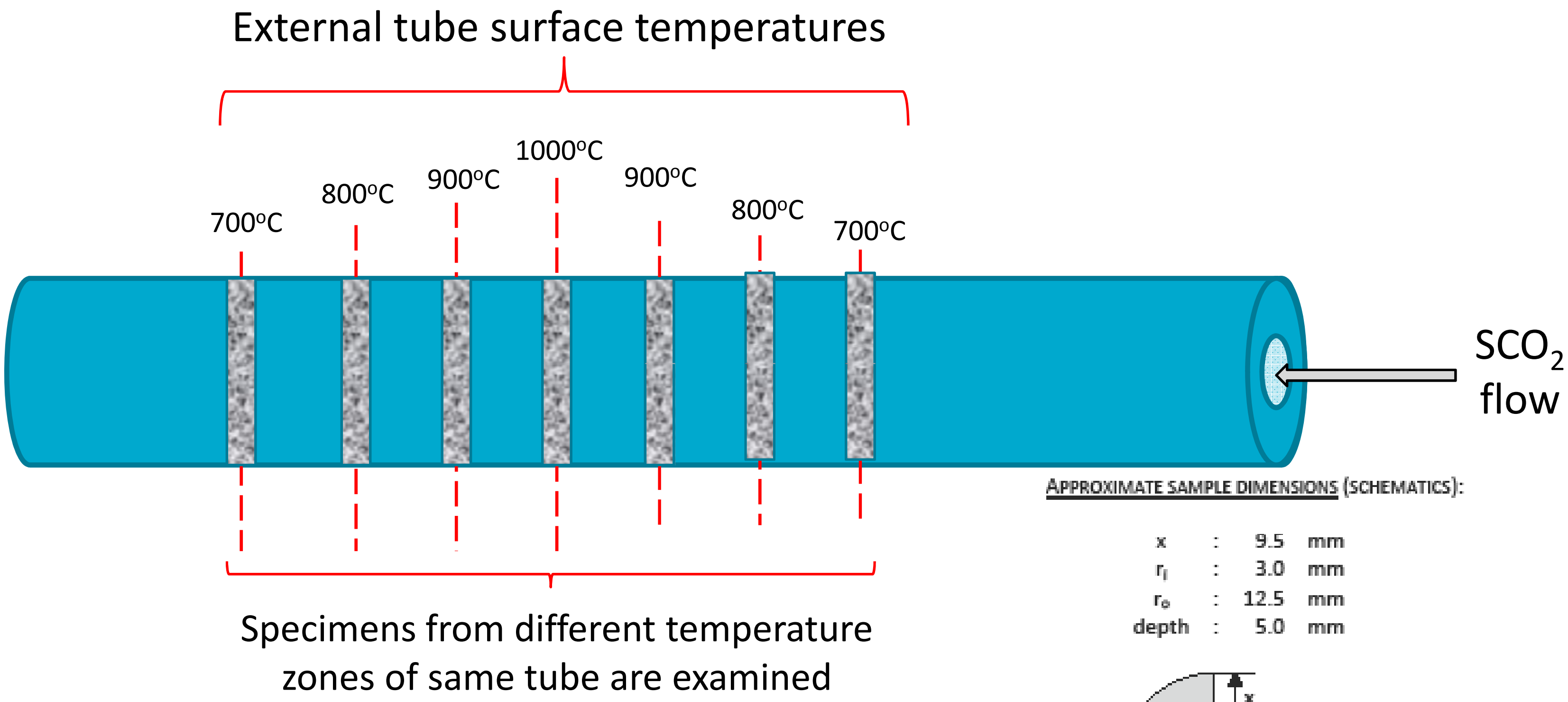
External 253MA protective jacket and air cooled flange

Test tube specimen S-CO2 flow in

Typical experiment in progress

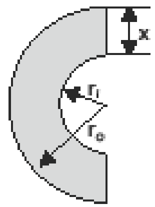
CSIRO

Test specimen and tube temperature zones
Schematics



APPROXIMATE SAMPLE DIMENSIONS (SCHEMATICS):

x	:	9.5	mm
r_i	:	3.0	mm
r_o	:	12.5	mm
depth	:	5.0	mm

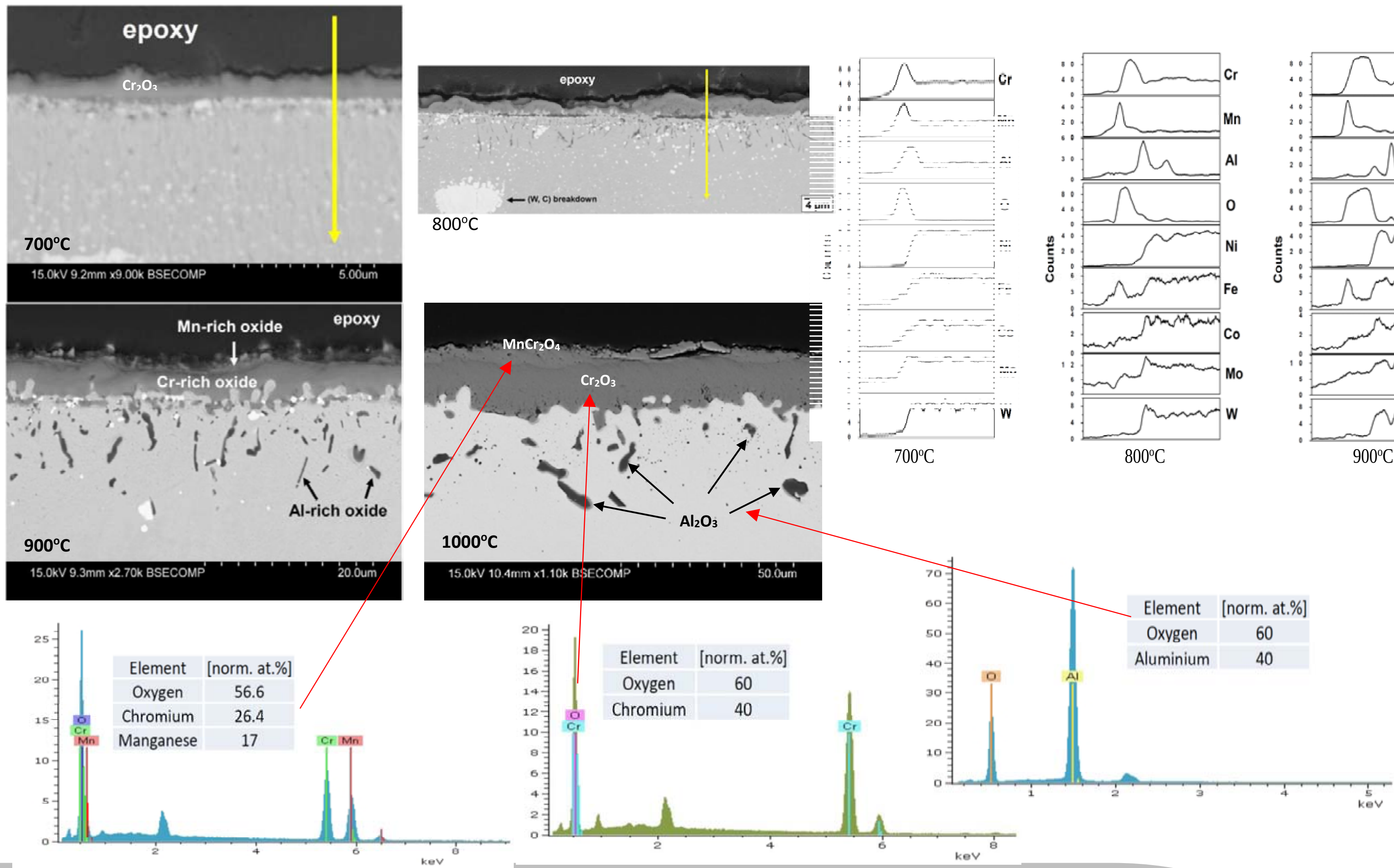


Ni-based alloys evaluated

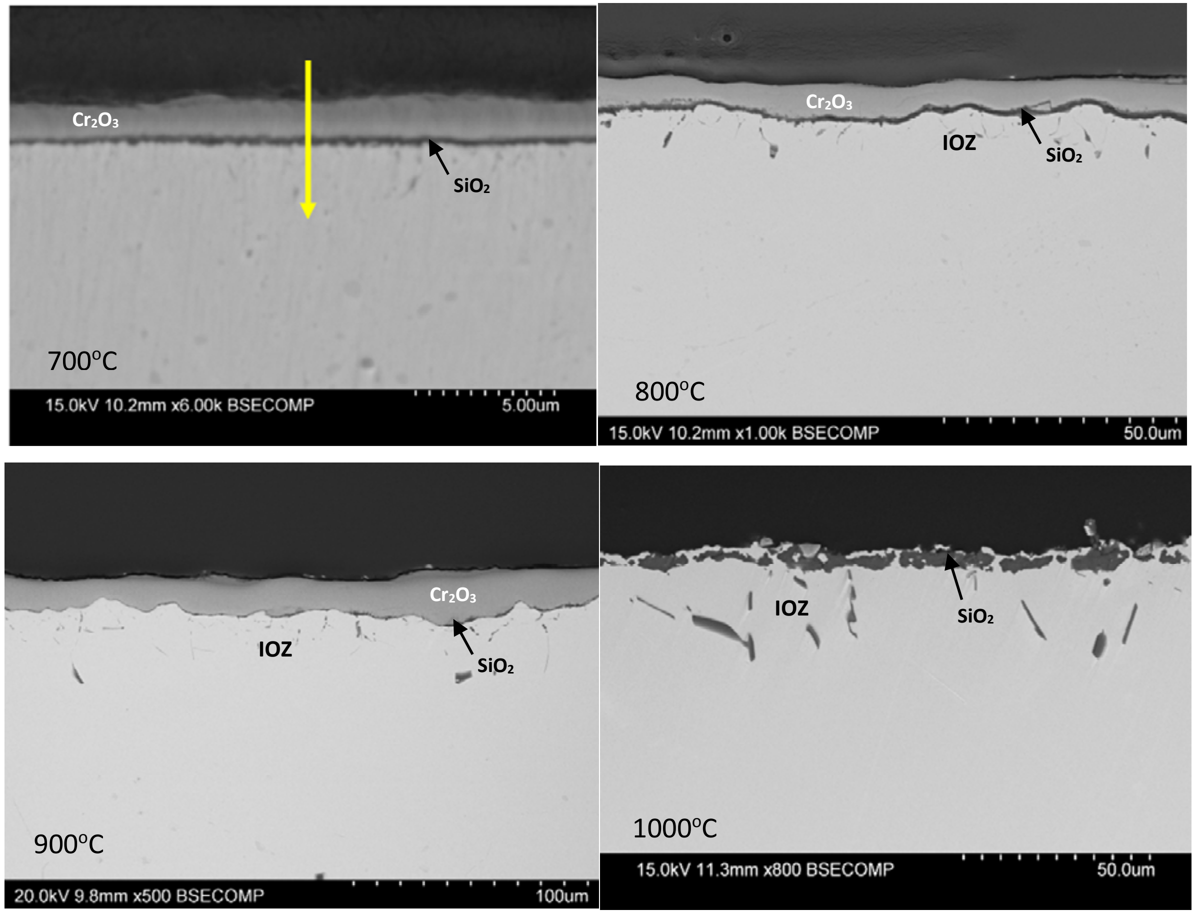
- Alloys sourced from Haynes International - Subjected to 1000 h continuous corrosion test.
- Tubular samples of each alloy internally pressurised by flowing SCO_2.
- Exposed to SCO_2 at 20 MPa over a temperature range 700ºC - 1000ºC.
- Composition of alloys tested as per the table.

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

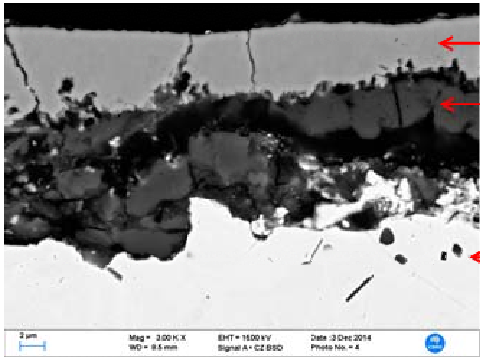
Corrosion results Haynes 230



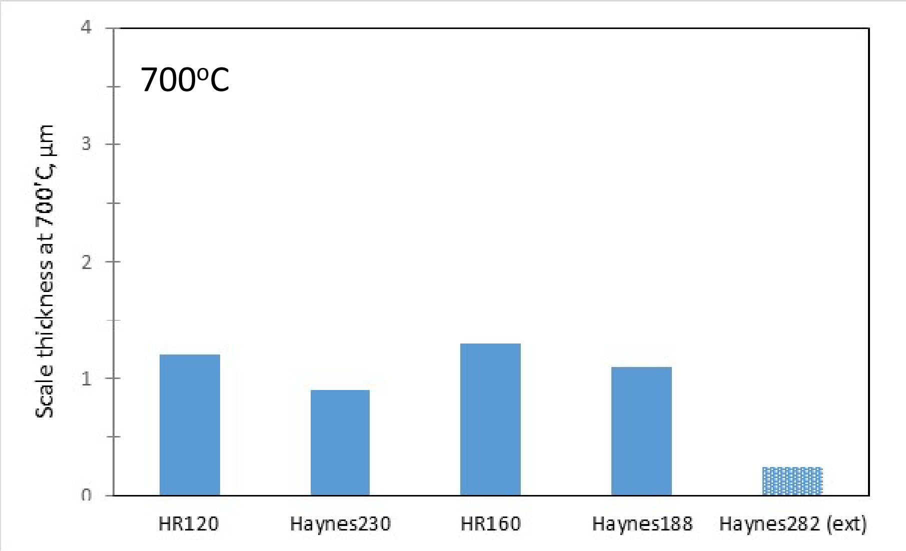
Corrosion results HR160 - 700 to 1000°C

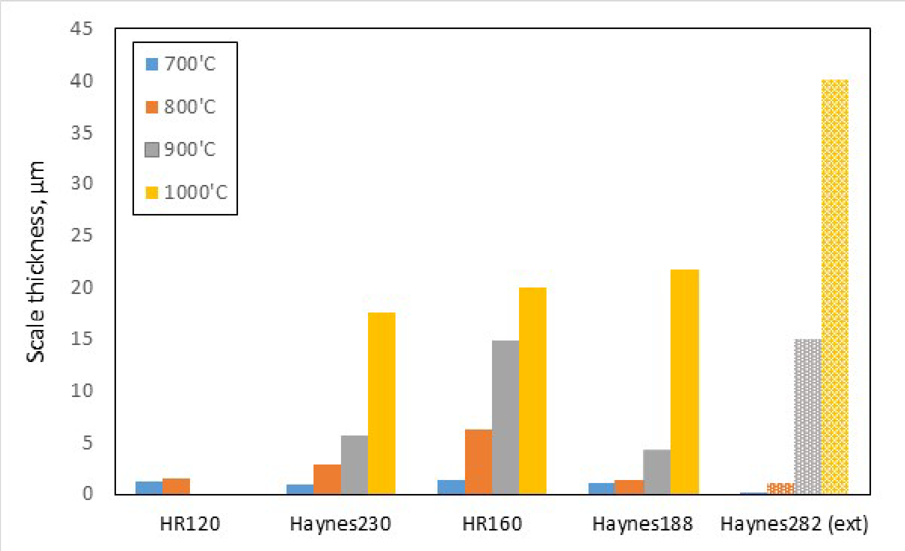


- Two-layered scales on the specimens reacted at 700-900°C, but only the darker oxide remains on the alloy after reaction at 1000°C.
- Intense scale breakage occurred at 1000°C as detailed by the SEM high magnification micrograph of a section of the internal surface of the tube that retained the chromia 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 Cr_2O_3 scale was supported by a semi-continuous SiO_2 layer.

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

- The alloys developed protective chromia-rich scales and at temperature > 800^{o}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^{o}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 SCO_2.
- The extent of corrosion due to exposure to s-CO_2 varied with temperature and presented different characteristics depending on alloy composition.
- Internal attack (subsurface degradation) in the temperature range 800-1000^{o}C appears greater than the metal loss due to oxide scale formation. The former being 50-75% of the total corrosion affected zone.

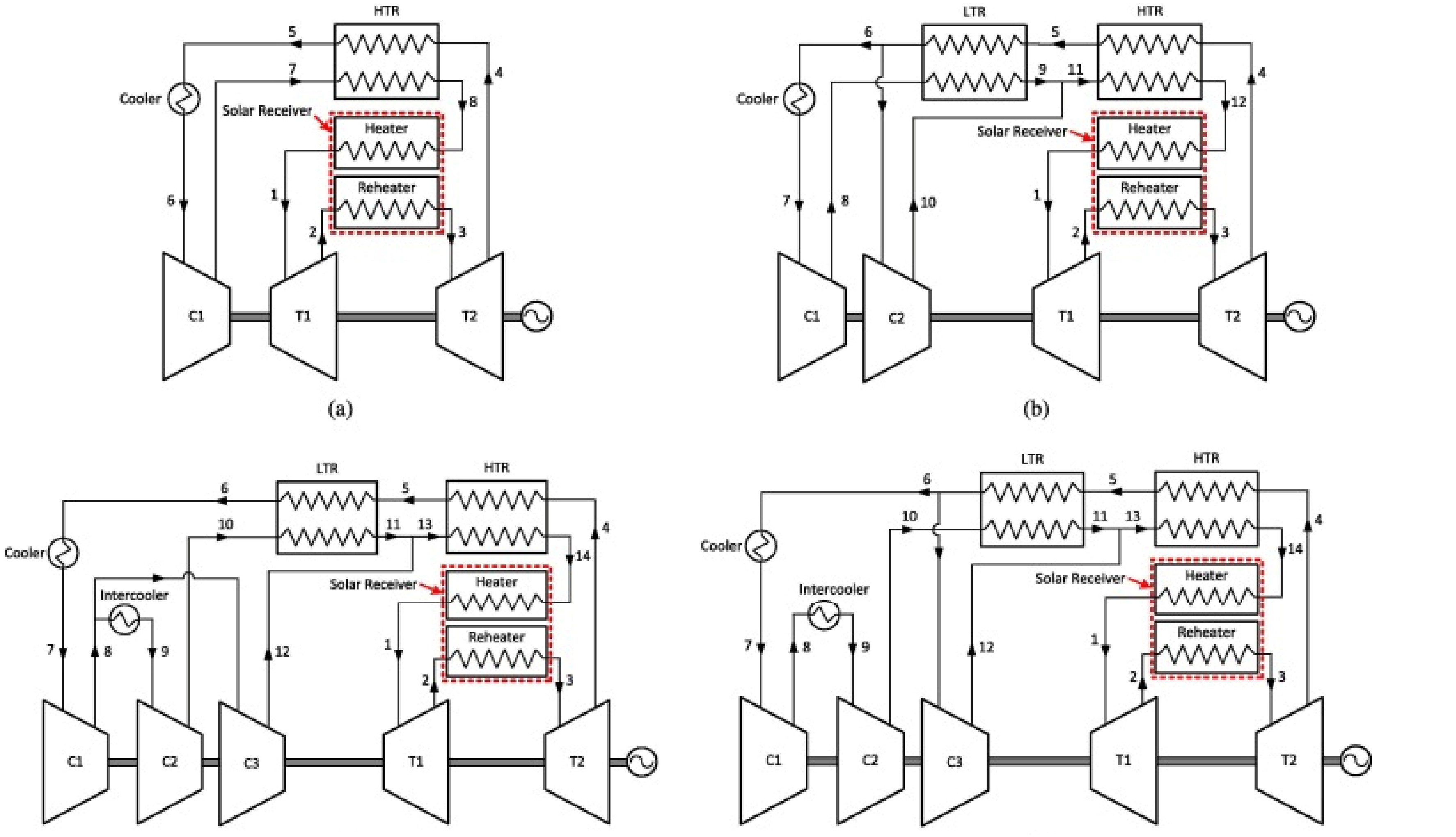
Next steps:

- 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.

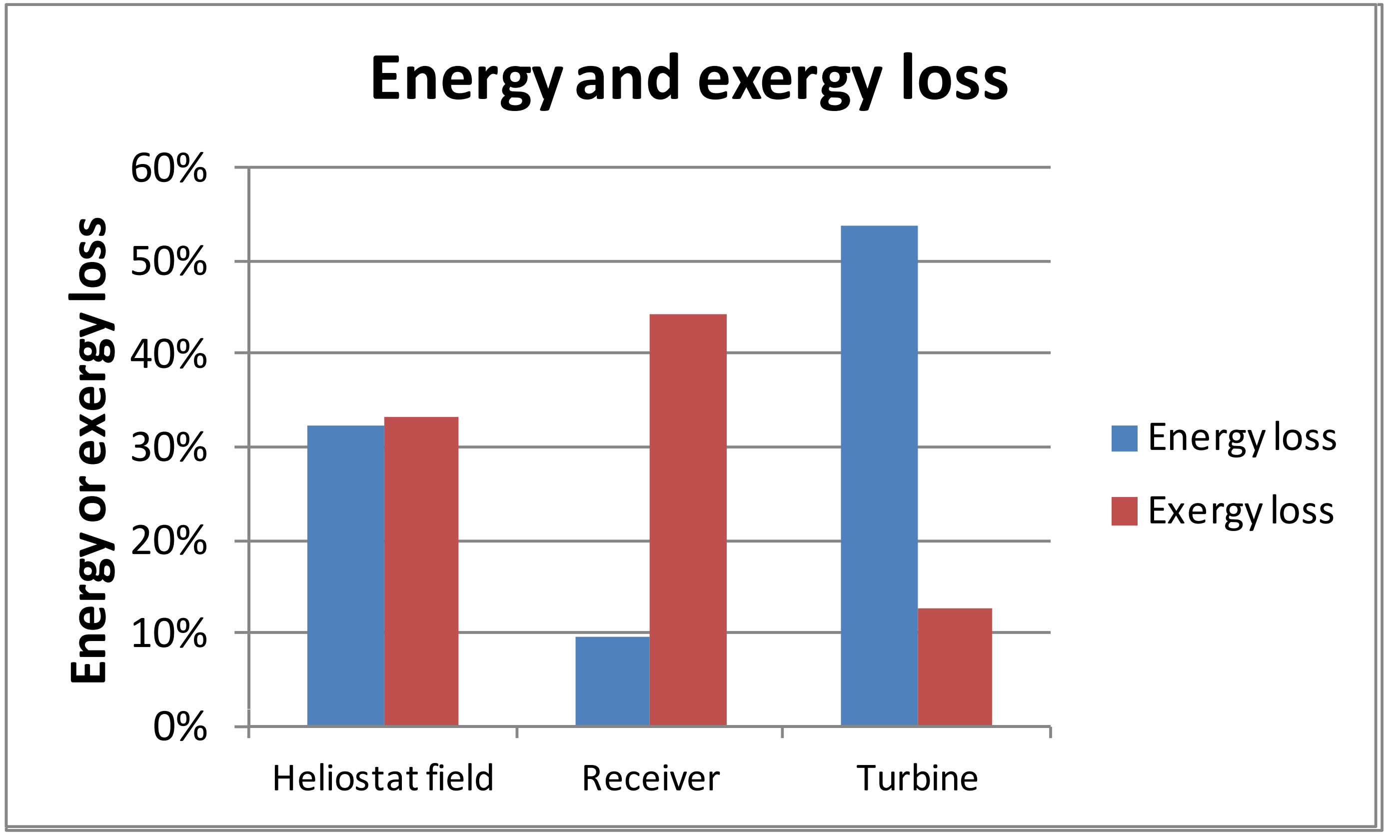
Exergy Model Development



(a) (b) (c) (d)

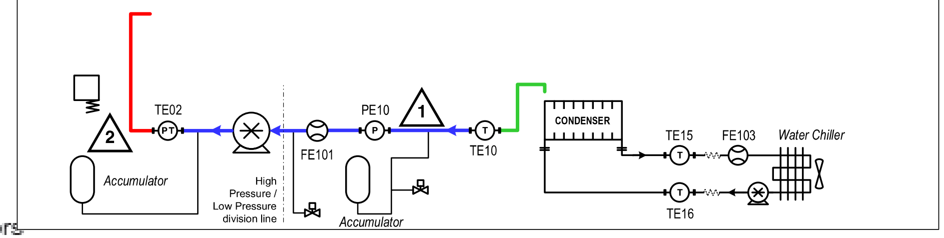
Applied Energy, Volume 148, 15 June 2015, Pages 348-365

Where can we make most thermodynamic impact?



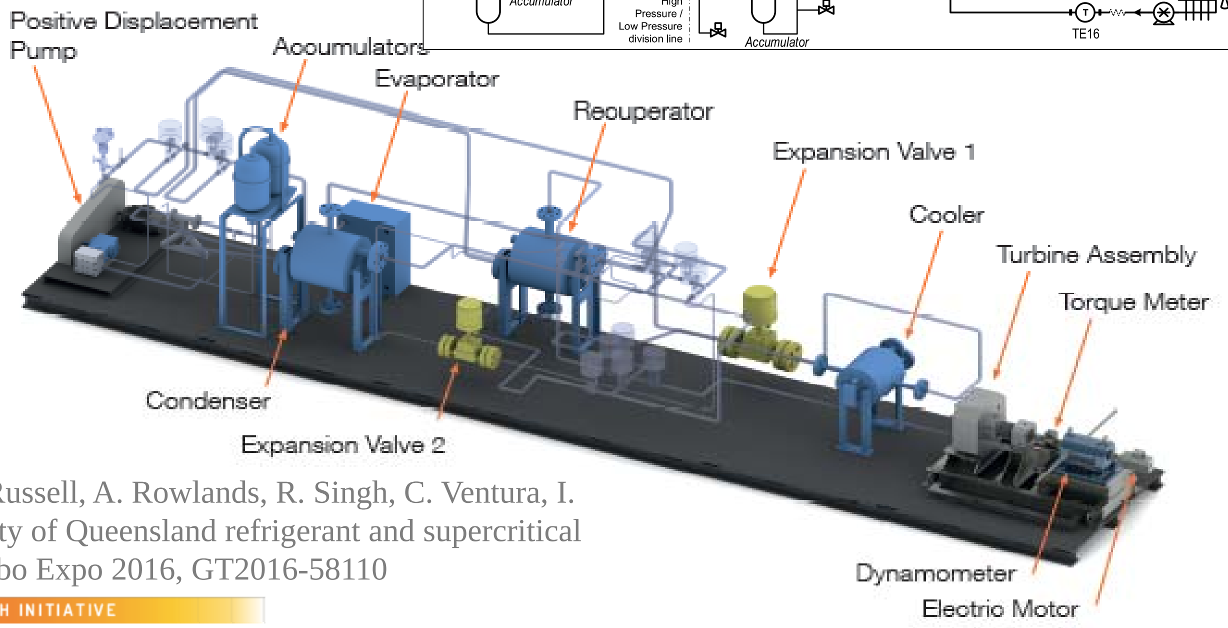
High Pressure Test Loop

- 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 : 250º 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

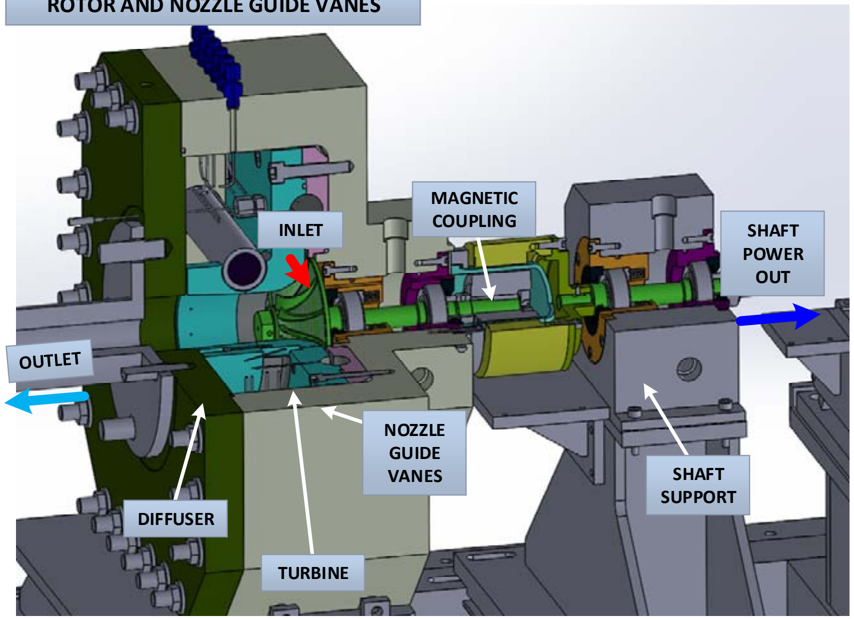
UQ 7kW R245fa turbine

- Stepping stone towards a radial sCO_2 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


ROTOR AND NOZZLE GUIDE VANES

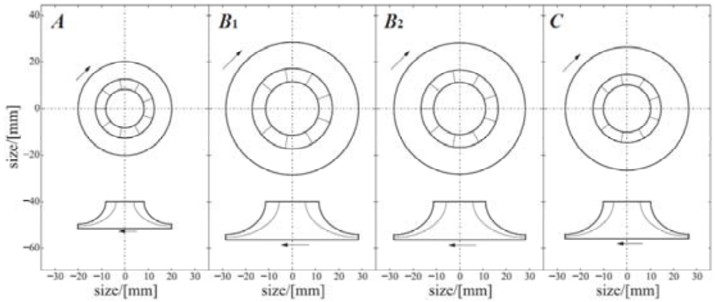
Speed: 32 000 RPM
Power: 7 kW
Temperature: 150º C
Pressure Ratio: 3.76

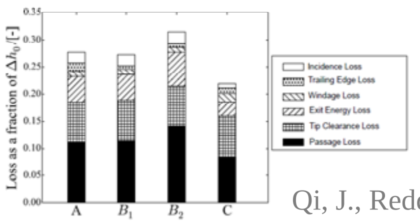


100kW sCO2 turbine

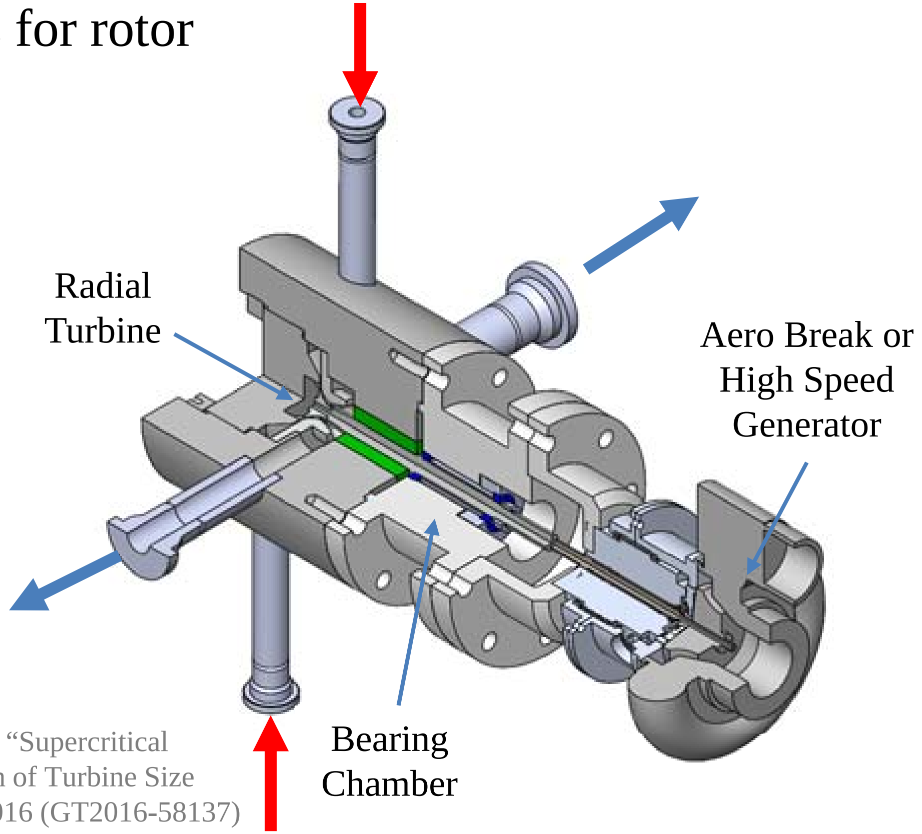
- Concept for family of turbines
  Power Range: 0.25 MW → 10 MW
- Scalable Rotor and Casing design
- Design selection based on in-house tools for rotor geometry, volutes, etc…
- Manufacture to commence in 2017

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

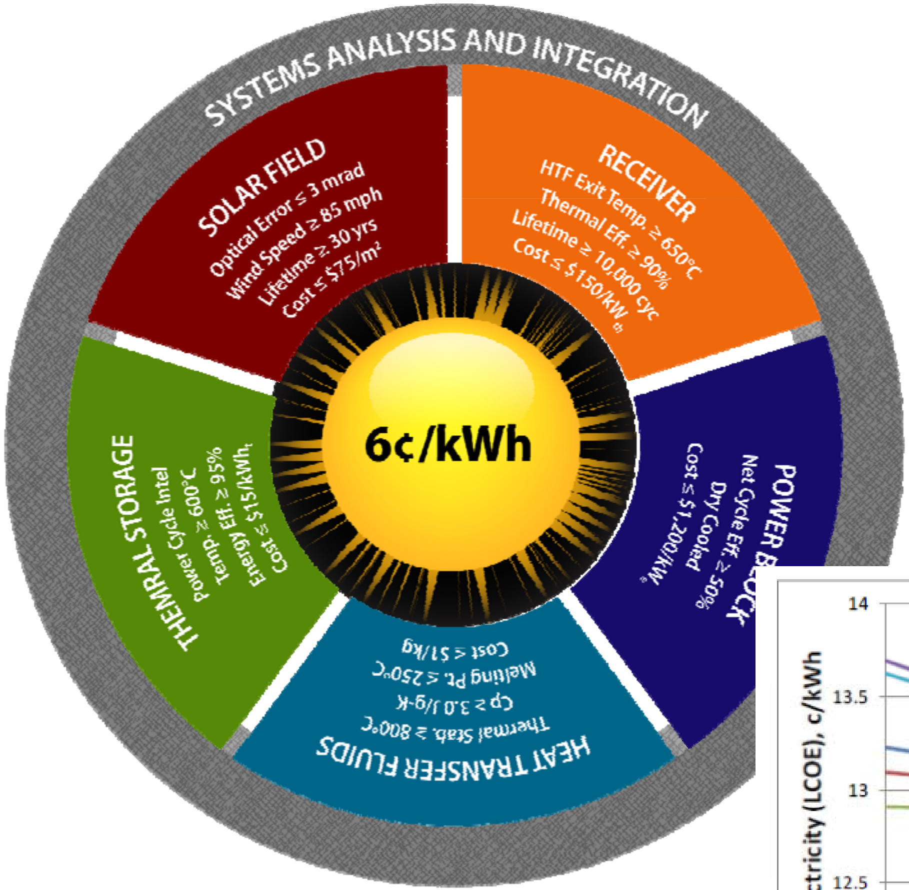


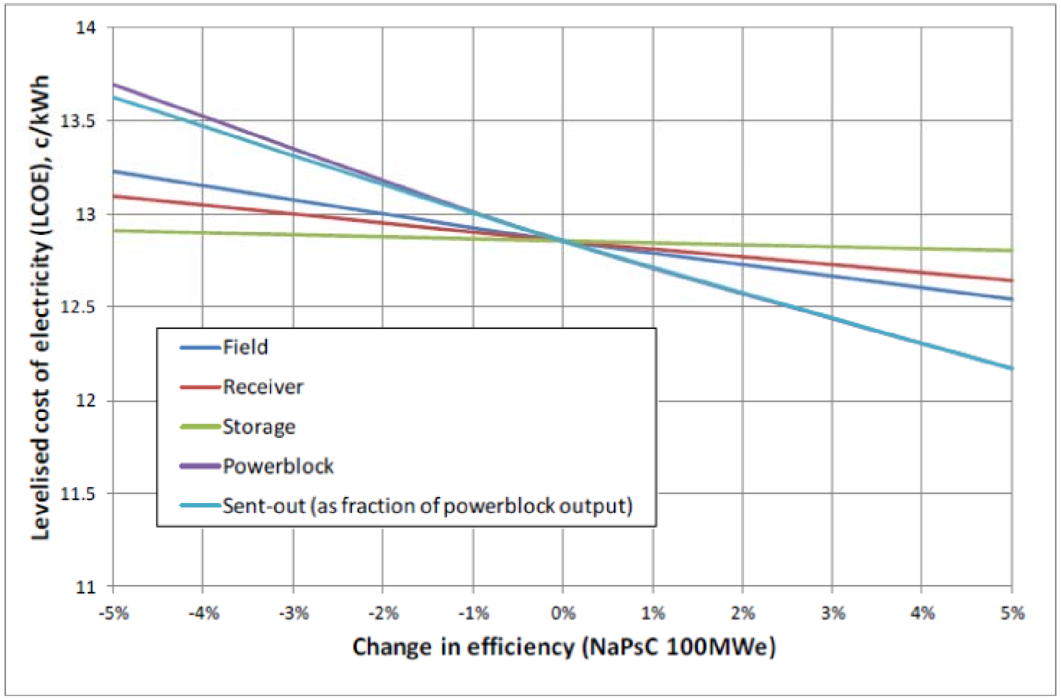


Qi, J., Reddell, T., Qin, K., Hooman, K., Jahn, I. 2016. "Supercritical CO2 Radial Turbine Design Performance as a Function of Turbine Size parameters". Proceedings of the ASME Turbo Expo 2016 (GT2016-58137)

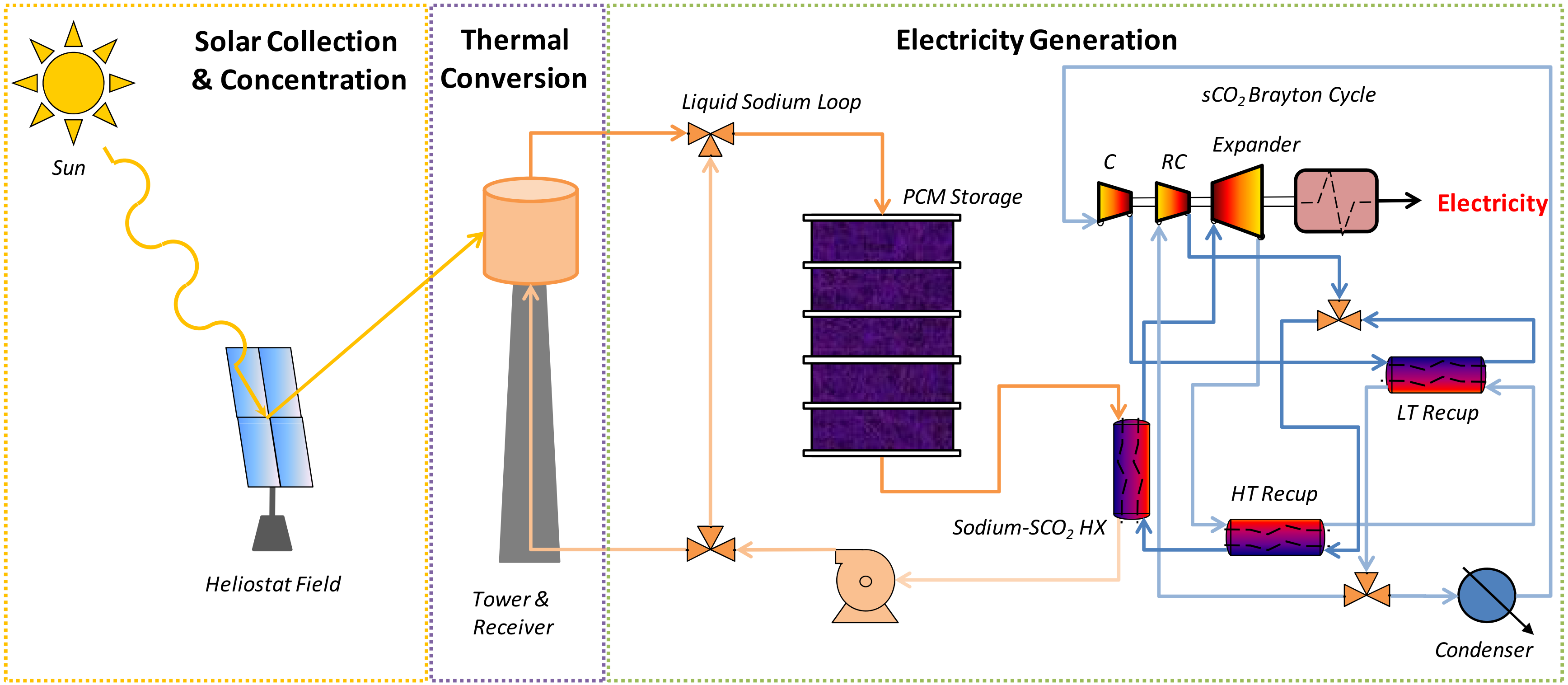


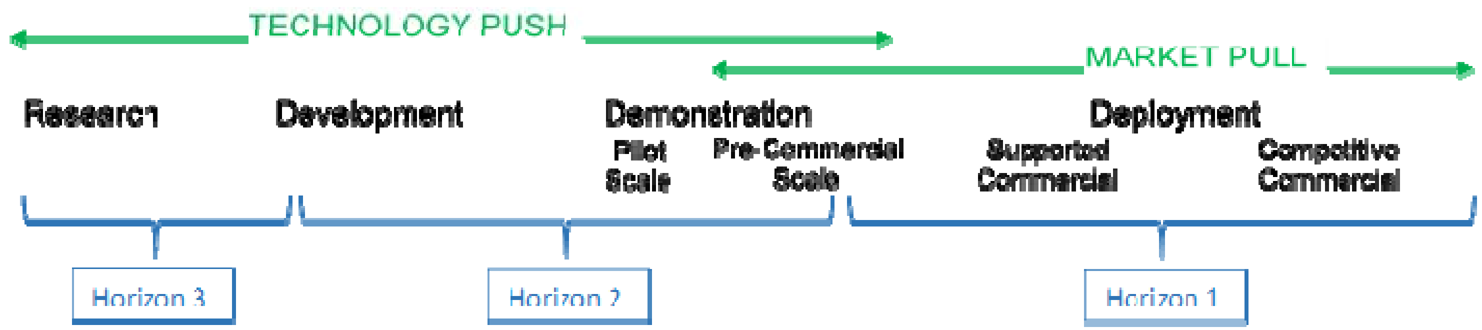
Component cost and performance targets





CSP-driven s-CO2 cycle - Advanced





Today

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 (≈100kW$_e$) med temp s-CO_2 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

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-CO_2 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-CO_2 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-CO_2 turbines
- Zero O&M heliostats

H3

- Fuels from thermally-driven atmospheric CO_2 reduction cycles
- Thermionics
- ??

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Thank you

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