ASTRI
AUSTRALIAN SOLAR THERMAL RESEARCH INITIATIVE

A systems approach to CST technologies

ASTRI – Australian Concentrating Solar Thermal Symposium and Workshop

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CST Vision for Australia

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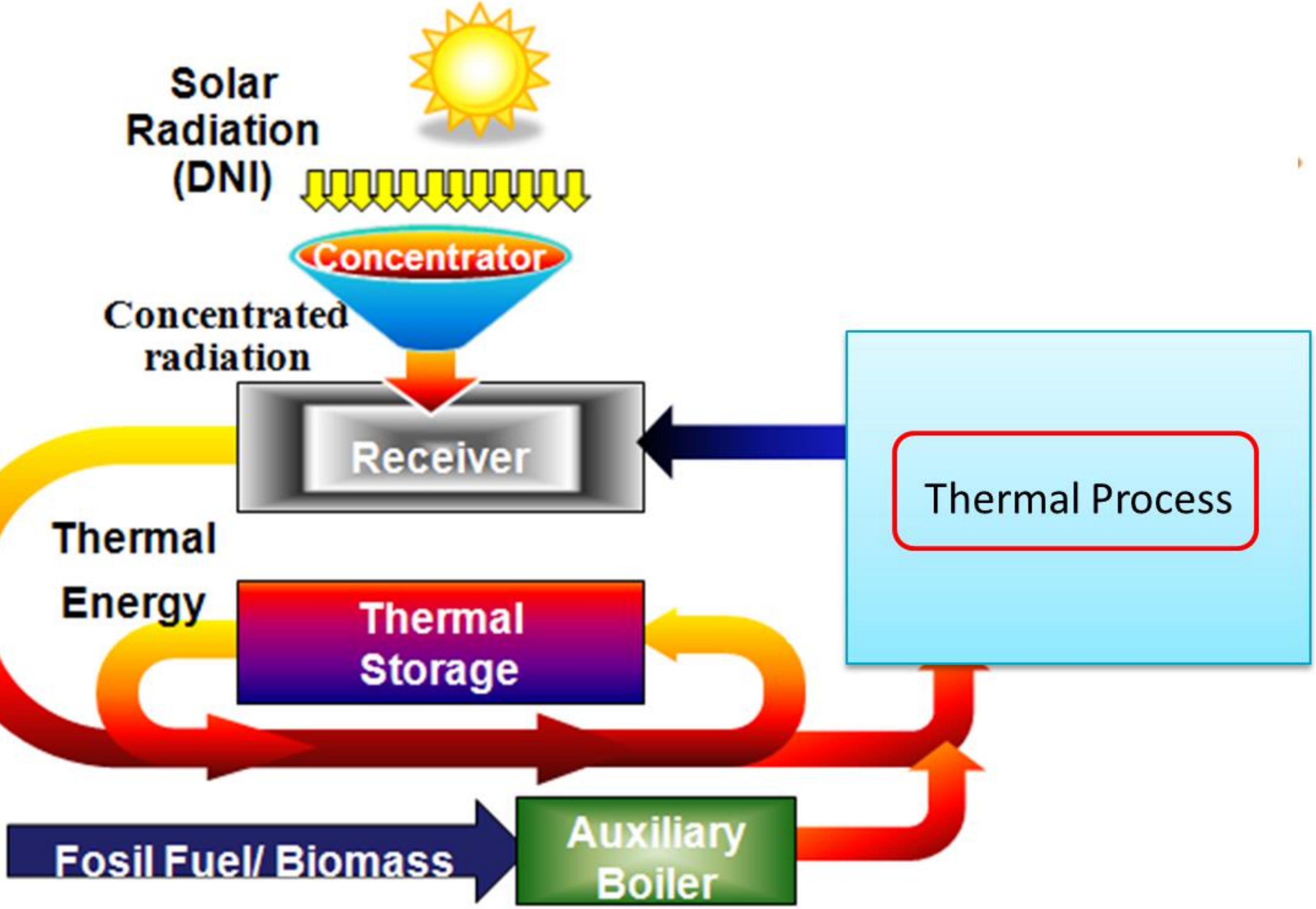
Solar thermal energy

Solar Energy → **Heat** → Useful Energy

Temperature of heat is critical

Hybridization and storage



- Heat process
- Electricity
- Solar fuels
- Solar desalination
- Solar detoxification
- Solar oil Recovery
- Solar mineralogy
- ……

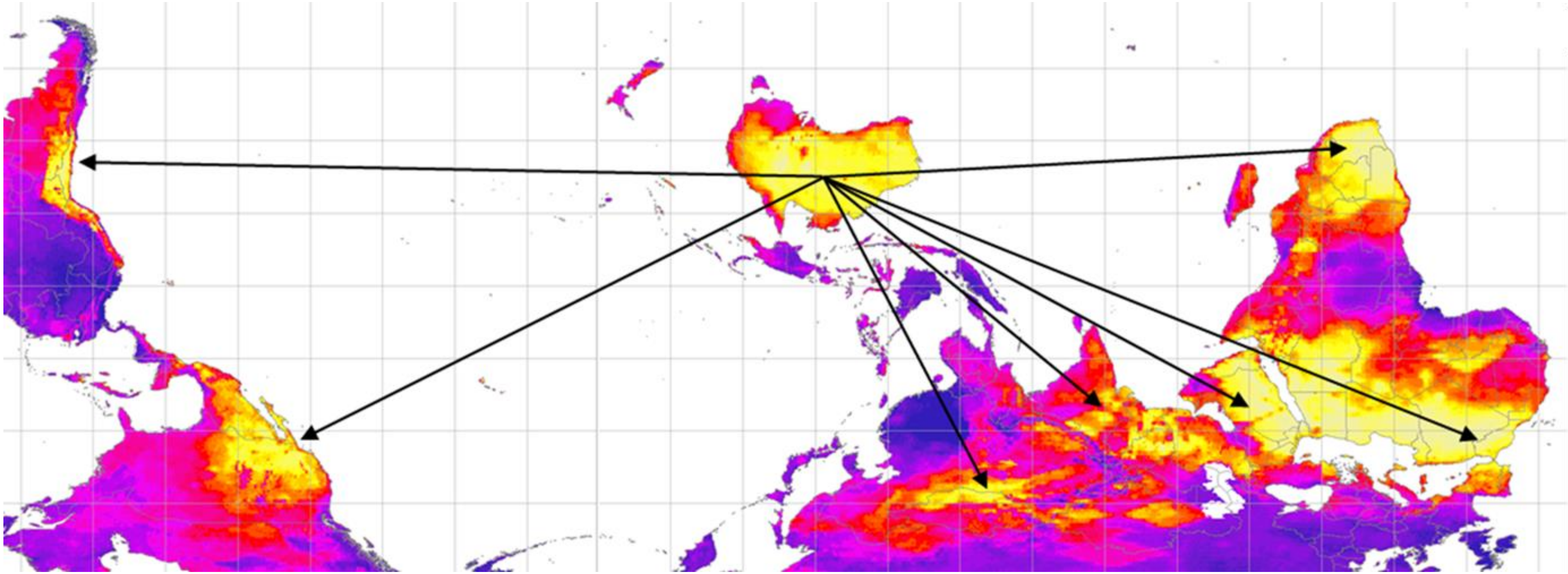
Value proposition of CST technologies

- CST provides a very large range of energy service options
  - Heating and cooling
  - Heat processes at high temperatures
  - Electricity
  - Solar fuels and other chemistry applications
- CST is easily hybridized and stored
  - If hybridized with biomass can provide a continuous 24/7 clean and renewable heat process or electricity production operation
  - If combined with a thermal storage system can provide the heat for the heat process application or for the deliver of electricity when is most needed or most economically profitable.
- When deployed with conventional power block
  - CST delivers dispatchable clean and renewable electricity and ancillary services to the grid

Value proposition of CST technologies

- CST utilises expertise already available in many countries
  - High potential for conversion or expansion of existing manufacturing capabilities in a country to serve the CST sector
  - Local content of CST projects
  - Positive impact on employment, tax revenues and GDP
- CST has all the attributes to become the backbone of the highly decarbonized energy system of the future
  - Electricity sector:
    - don’t need any conventional backup
    - roles as needed; from base-load to peaking plants
    - provide critical grid stability to increase penetration of non-dispatchable renewable technologies
  - Industrial and transport sectors:
    - provide process heat, fuel and solar chemistry solutions needed to highly decarbonize these sectors

Value proposition of CST technologies



Value proposition of CST technologies

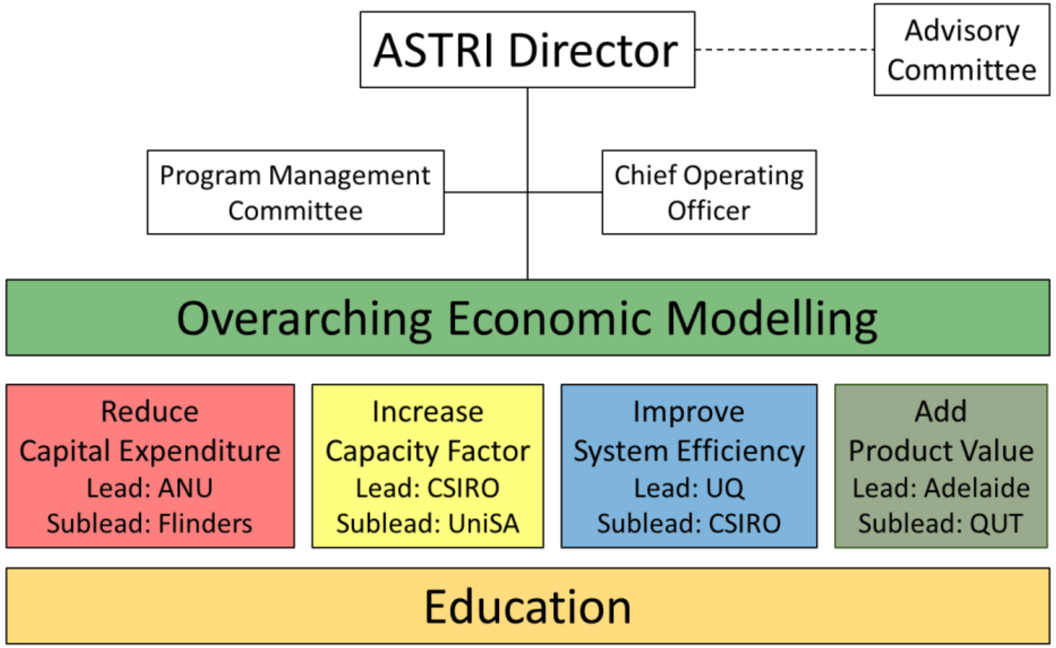
Goals:

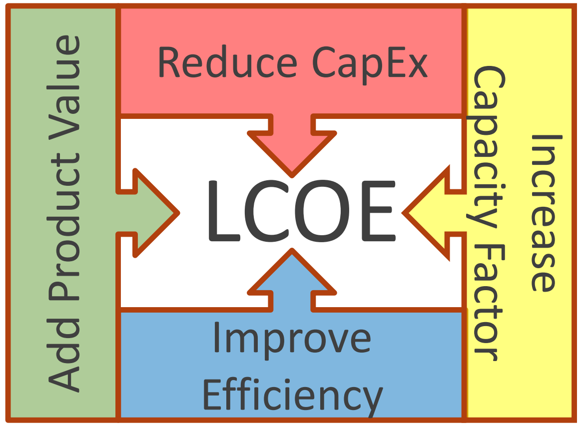
- Develop a competitive CST export industry and ecosystem
- Use CST electricity plants to progressively replace obsolete coal plants and advance in the decarbonisation of Australia electricity sector
- Use CST technologies to exploit market niches in Australia
  - Heating and cooling
  - Heat processes at high temperatures
  - Electricity
  - Solar fuels and other chemistry applications

ASTRI mandate

A technical goal – 12c/kWh by 2020

ASTRI is committed to demonstrating a pathway for reduction in LCOE of CST power plants, targeting 20c/kWh in Year 3 and 12c/kWh by 2020 whilst providing dispatchable firm supply.



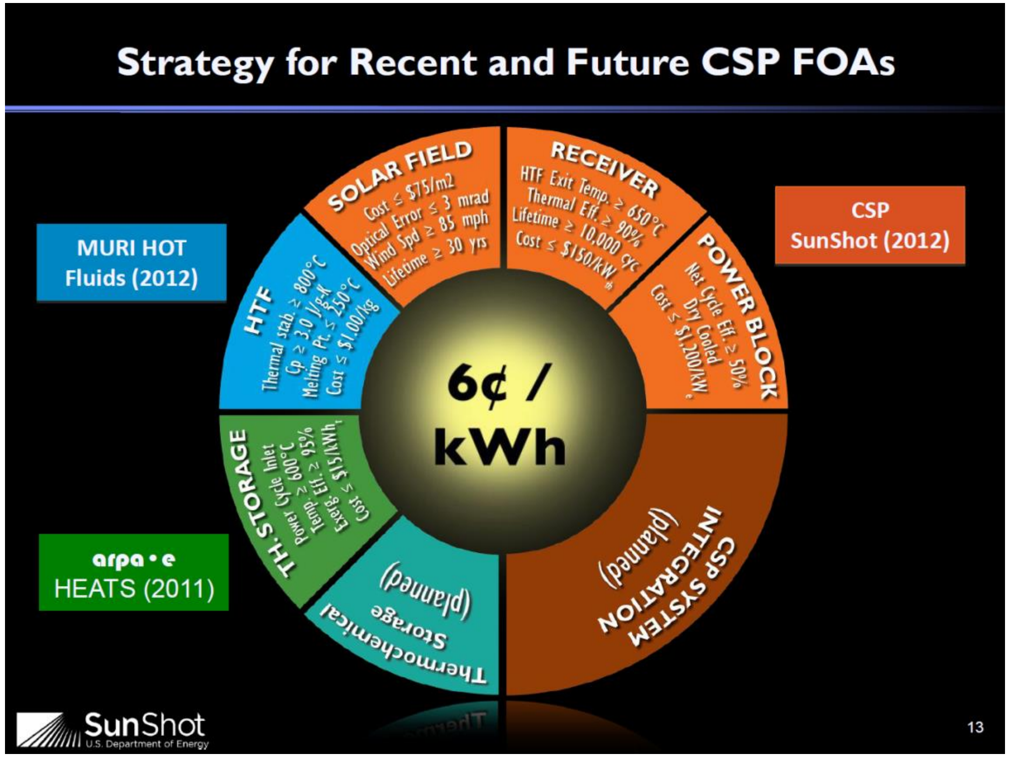


- Budget: $87m
  - ARENA $35m
  - Partners $46m
  - Industry $6m

- Program 8 years (2013-2020)
  - with critical review in Year 4 (2016)
- Overarching Economic Modelling
- Research Nodes
  - Reduce CapEx
  - Increase capacity factor
  - Improve efficiency
  - Add Product Value
- Education Program

A framework - USA Solar Energy Collaboration

- The ASTRI objectives link into the SunShot objectives through collaboration with:
  - initially
    - Sandia National Labs
    - NREL
    - Arizona State University
  - Other
    - US labs
    - Universities, and
    - Industry



Source: US DOE (2012) presented at USASEC workshop 8-Jun-2012, Austin, Texas

A set of partners

Australian National University

CSIRO

Flinders University

QUT

The University of Adelaide

The University of Queensland Australia

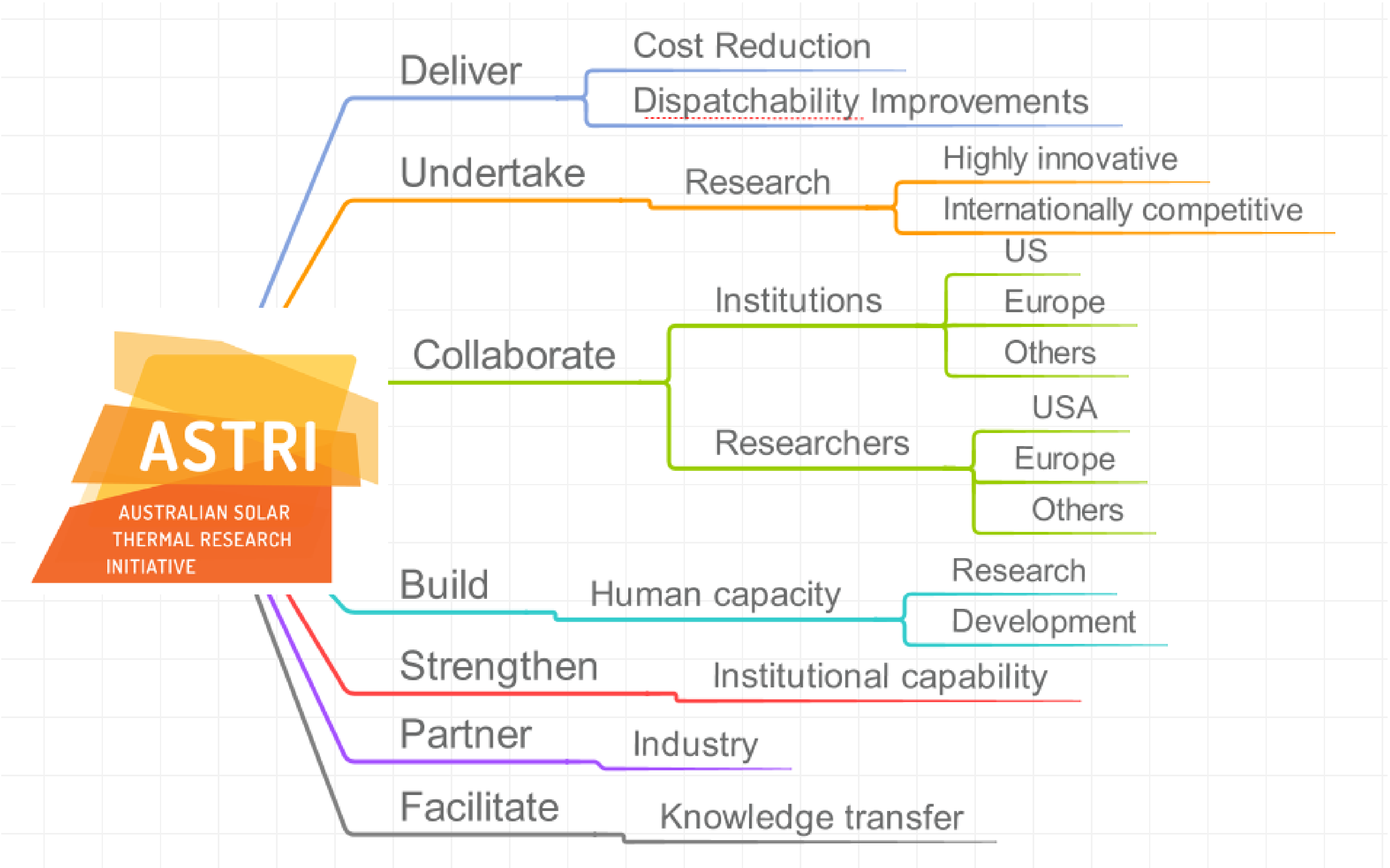
University of South Australia

Arizona State University

NREL
National Renewable Energy Laboratory

Sandia National Laboratories

A set of objectives



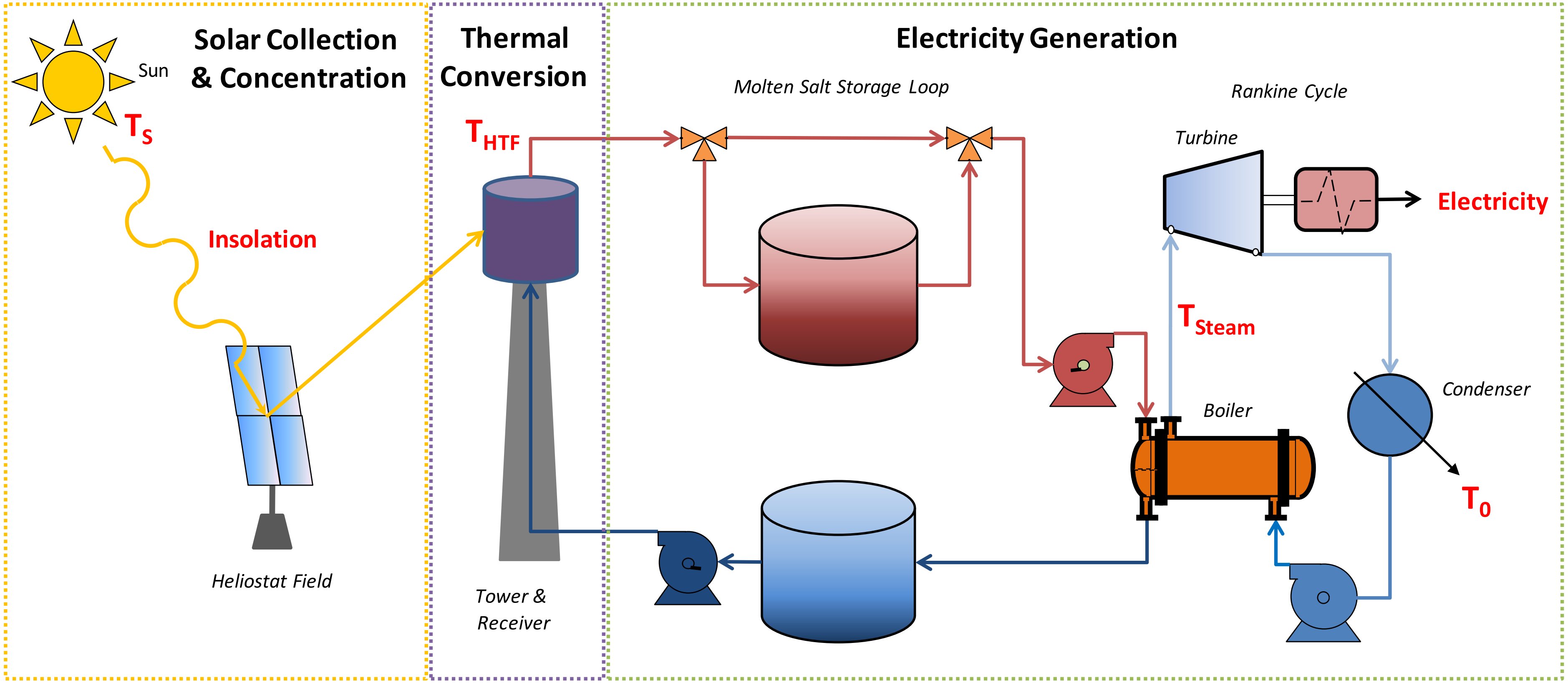
A set of Key Performance Indicators (KPIs)

		2013	2014	2015	2016	2017	2018	2019	2020	
KPI	**ASTRI Objective and KPI**	**Y1**	**Y2**	**Y3**	**Y4**	**Y5**	**Y6**	**Y7**	**Y8**	**Total**
	Research Quality									
1	Number of refereed journal publications	3	7	10	15	15	20	22	28	120
2	Percentage of joint refereed journal publications	0%	10%	15%	20%	22%	25%	28%	30%	
	US Collaboration									
3	Visits to/from US Collaborators	5	5	5	5	7	9	11	12	59
4	Number of new projects started with US institutions	0	1	3	5	4	4	4	4	25
	Human Capacity									
5	Accumulative number of new staff/postdocs/PhDs recruited	8	18	30	42	55	65	75	80	80
6	Accumulative number of post-graduate student completions [b]	0	0	0	4	12	20	28	44	44
	Collaboration involving research training									
7	Number of student/staff visits between partner institutions	20	20	20	20	20	20	20	20	160
	Industry Engagement									
8	Funding from external sources ($k)	$0	$200	$250	$300	$500	$800	$1,200	$2,000	$5,250
	Knowledge Transfer									
9	Number of conference presentations	3	5	7	10	12	15	18	22	92
	Financial									
10	Accumulative In-kind contributed ($k)	$2,249	$6,249	$10,613	$15,138	$19,432	$25,448	$31,184	$36,744	$36,744
	Technical[a]									
11	LCOE (c/kWh)	26.5	25	21.5	19.5	17.5	16	14	12	12
12	Overall annual efficiency (%)	13	14	15	16	17	17.5	18	18.5	18.5
13	% Reduction in CapEx	0	0	10	15	20	25	32	40	40
14	% Increase in capacity factor	0	0	10	15	20	23	26	30	30
15	O&M costs ($/kW-y)	80	80	75	70	65	60	55	50	50
	[a] The overarching economic modelling is required to produce these KPIs									

ASTRI projects

AUSTRALIAN SOLAR THERMAL RESEARCH INITIATIVE

We are working on…



- Heliostats
- Heliostat field configurations

- Receivers
  - Liquid metals
  - Particles

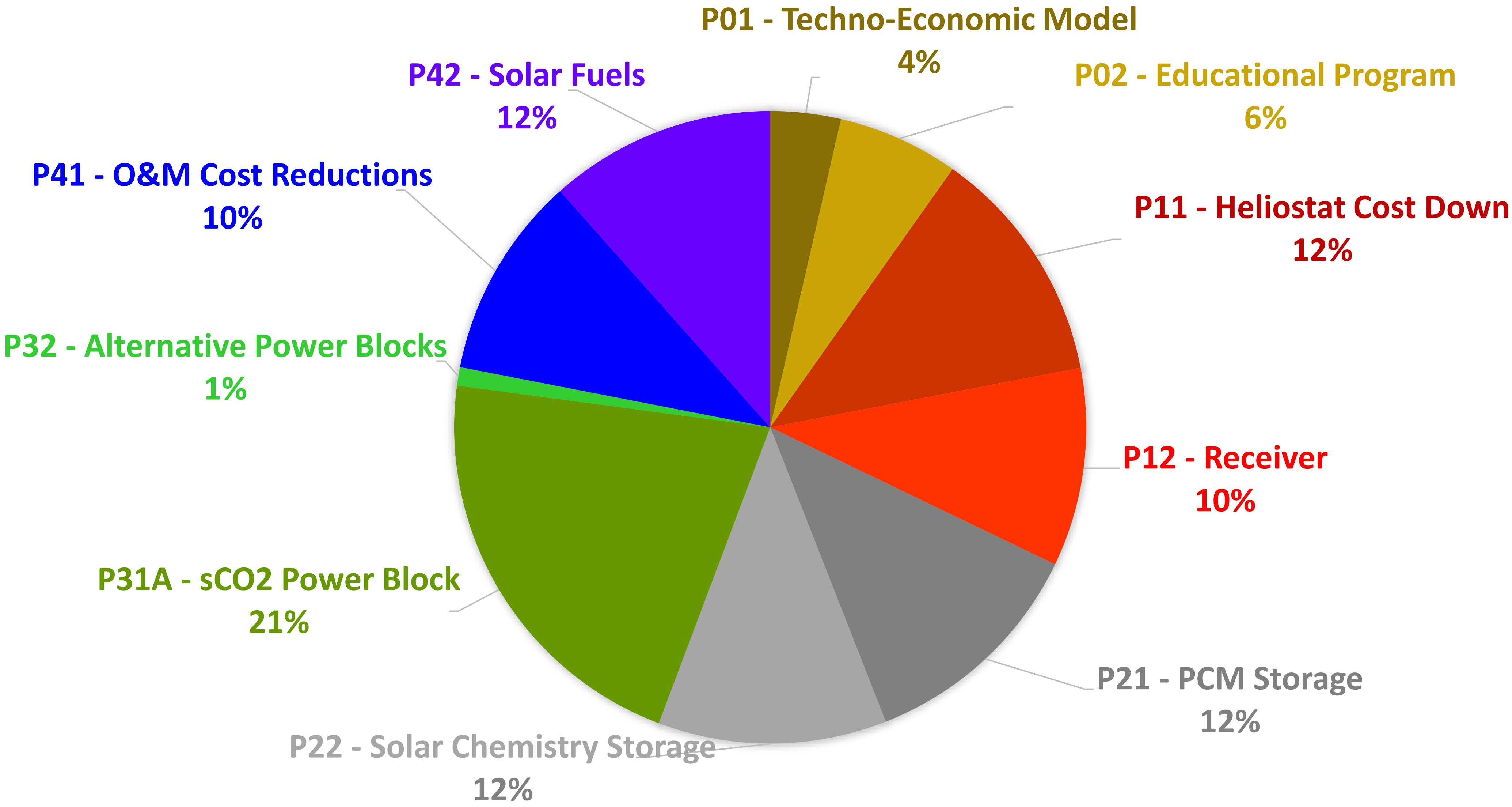
- Thermal Storage
  - PCM
  - Thermo-chemical
  - Others

- Power block
  - sCO2
  - Others

10 multi-institutions multi-disciplinary projects

ID	Nodes and Project Collaboration		CSIRO	ANU	UQ	UA	UniSA	QUT	Flinders
P01	**Overarching Economic Model**	**1**	**Lead**	**x**	**x**	**x**	**x**	**x**	**x**
	Node 1: Reduce capital expenditure (CapEx)		**x**	**Lead**	**x**	**x**	**x**	**x**	**Co-Lead**
P11	Heliostat field cost down implementation project	2	x	Lead		x	x	x	x
P12	Receiver performance project	3	x	Lead	x	x			x
	Node 2: Increase capacity factor		**Lead**	**x**		**x**	**Co-Lead**	**x**	
P21	High-temperature storage project	4	Lead	x		x	x		
P22	Reliable low-cost PCM thermal storage project	5	x				Lead	x	
	Node 3: Improve efficiency		**Co-Lead**		**Lead**			**x**	
P31	Supercritical CO2 system - power block project	6	x		Lead			x	
P32	Alternative power blocks project	7	Lead		x			x	
	Node 4: Add product value		**x**	**x**	**x**	**Lead**	**x**	**Co-lead**	**x**
P41	Cost-effective O&M project	8	x	x	x			Lead	x
P42	Solar fuels project	9	x	x		Lead	x		x
P02	**Education Program**	**10**	**x**	**x**	**x**	**Lead**	**x**	**x**	**x**

10 multi-institutions multi-disciplinary projects



System approach

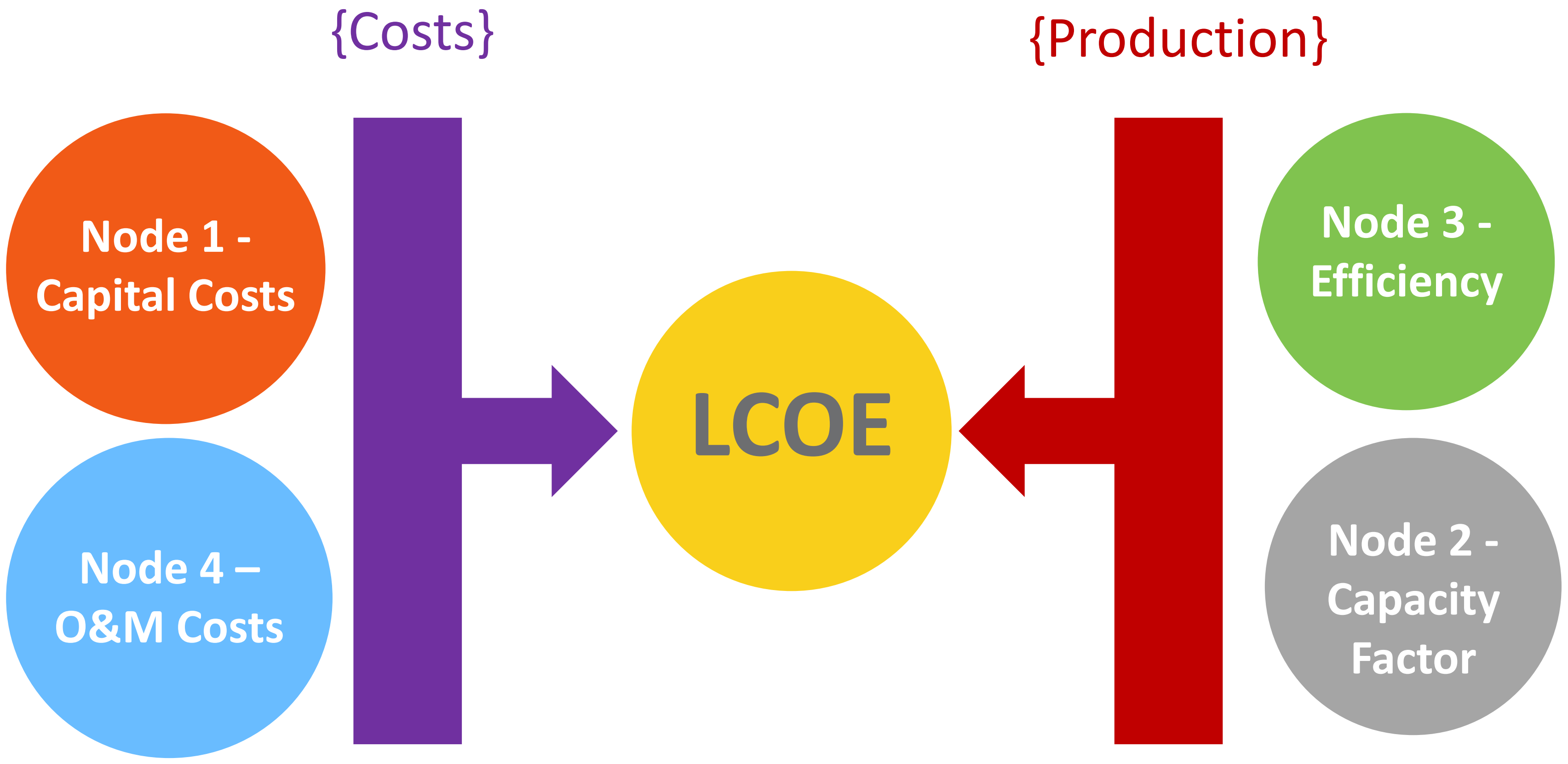
Ensuring that our research is relevant

1. All ASTRI projects must contribute to at least an ASTRI CST system configuration.
2. The goals of all ASTRI projects are specified in terms of realistic ranges of cost and performance targets/expectations, which are regularly updated.
3. A sophisticated techno-economic model of the ASTRI CST system configurations is fed with cost and performance information from the ASTRI projects.
4. The techno-economic model model delivers the probability function of the LCOE for all system configuration and provides information about the impact of each project in LCOE reductions.

Ensuring that our research is relevant

5. Based upon the results of the techno-economic modelling, decisions are made with regard to changing the scope of a project or terminating it.
6. We do not only research how to improve CST system components but how to develop a large portfolio of ASTRI CST system configurations with the potential to reach the target LCOE.
7. The larger the ASTRI CST system configurations portfolio and the larger the contribution of a project to different configurations within the portfolio, the higher the probability of the project delivering substantial impact for Australia.

Levelised Cost of Electricity model



The LCOE model requires input from all ASTRI Nodes.

Levelised Cost Of Electricity (LCOE)

$$LCOE = \frac{\text{All CapEx} + \text{All OpEx}}{\text{Total Generation}} \quad \text{over the entire plant life}$$

Or in a format to represent the contributions of all ASTRI Nodes:

$$LCOE = \frac{\sum_{t=1}^{n} \frac{C_t + M_t + F_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{E_t \times CF_t \times \eta_t}{(1+r)^t}}$$

Where:

- C=Capital cost
- M=Operating and maintenance cost
- F=Fuel cost (if applicable)
- E=Energy input (kWh)
- CF= Capacity factor (fraction)
- η=Plant efficiency (fraction)

All for each individual year t of the project, and

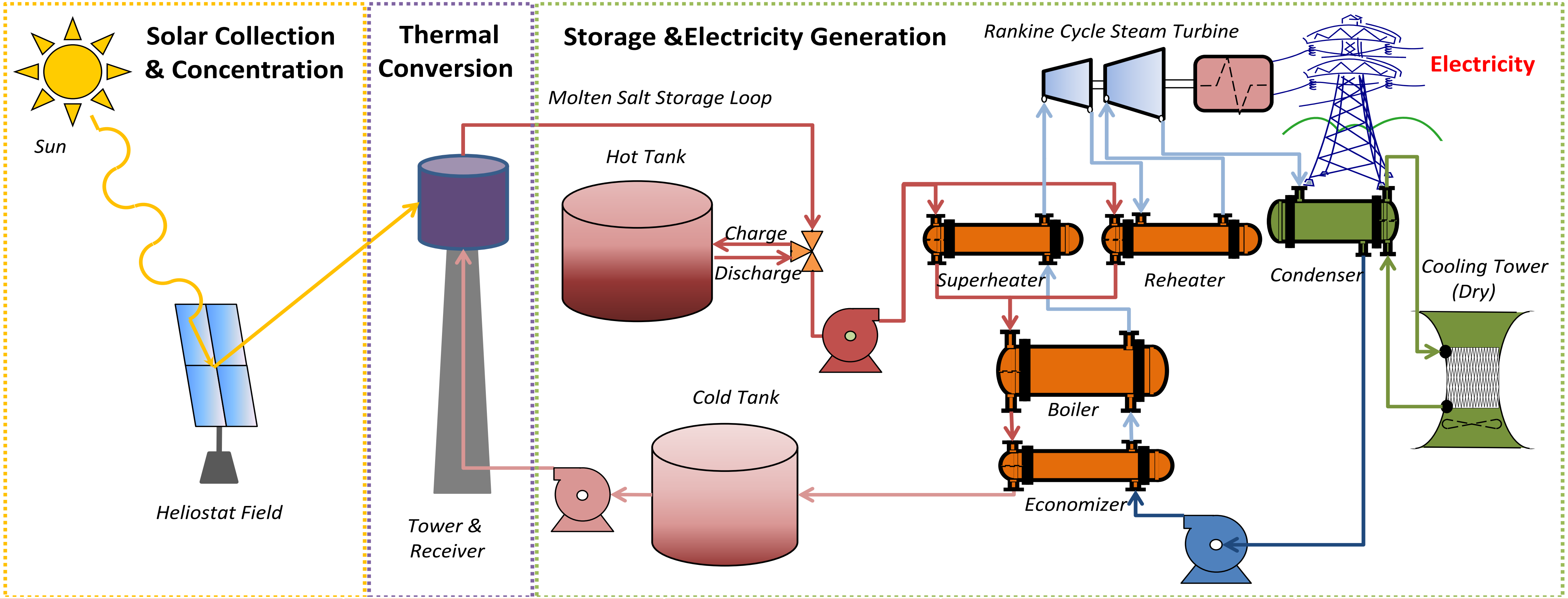
- n=Project life (years)
- r=Discount rate factor (may also vary)

ASTRI solar tower reference plant

Reference system

Tower system using conventional molten salt with a steam Rankine power block: 100MWe(net) with 4 hours of storage

System performance and cost maintained by P01 to reflect current commercial values expected at an Australian site

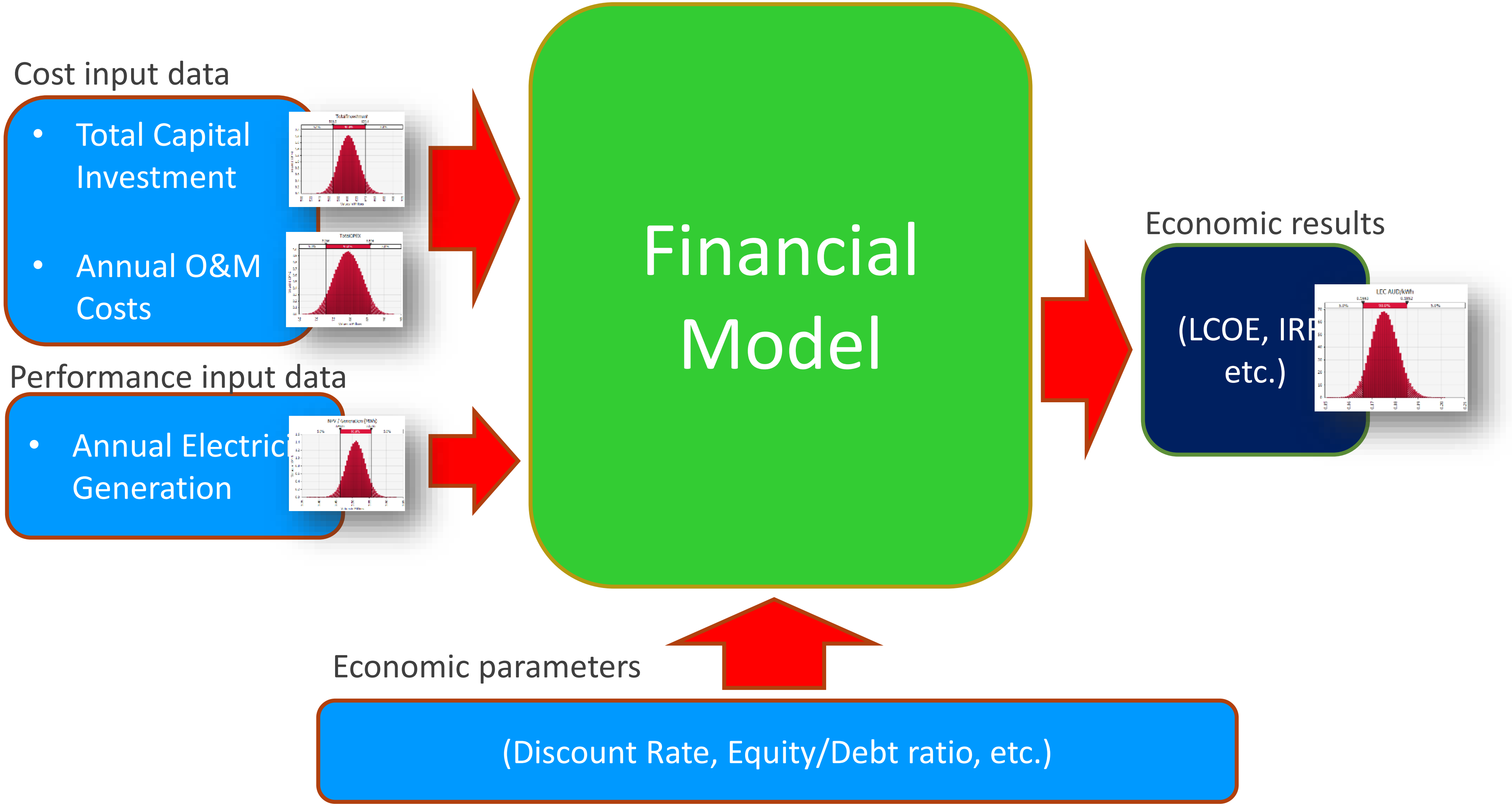


Efficiency	56.5 %	88.2 %	99.3 %	37.7 %	13.3 - 16.7 (14.8) %
Cost	$142-238 (180)/m^2	$130-285 (180)/kWt	$16-85 (37)/kWh	$800-1670 (1350)/kWe	**14.5-20.1 (17.3)c/kWh**

Modelling of uncertainty and variability

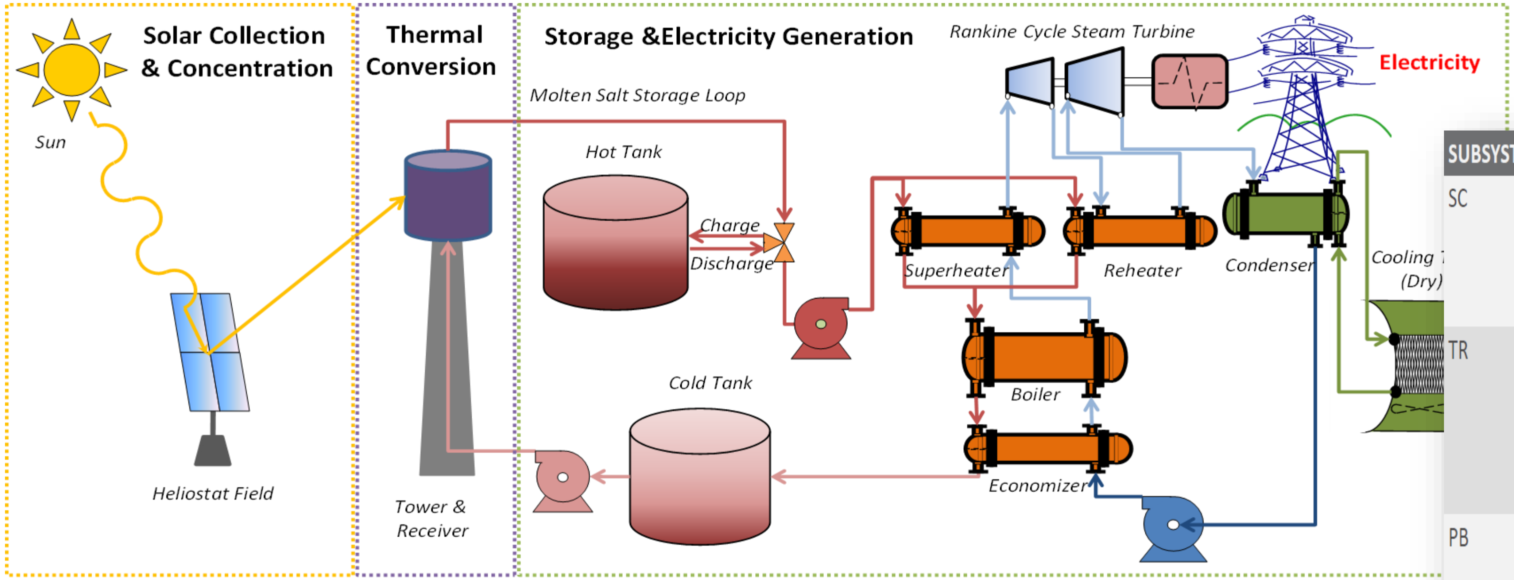
- When carrying out an economic feasibility analysis of a Concentrating Solar Thermal (CST) plant you have both uncertainty and variability associated to your input data.
- A natural way of modelling both is to associate a probability distribution to your input values.
- Uncertainty is a measure of your lack of information and can be decrease by increasing the amount and quality of the information.
- Variability, however, is an intrinsic property of commodity-type costs, e.g., molten salt, and natural phenomena, e.g., Direct Normal Irradiance (DNI).

Stochastic techno-economic feasibility analysis



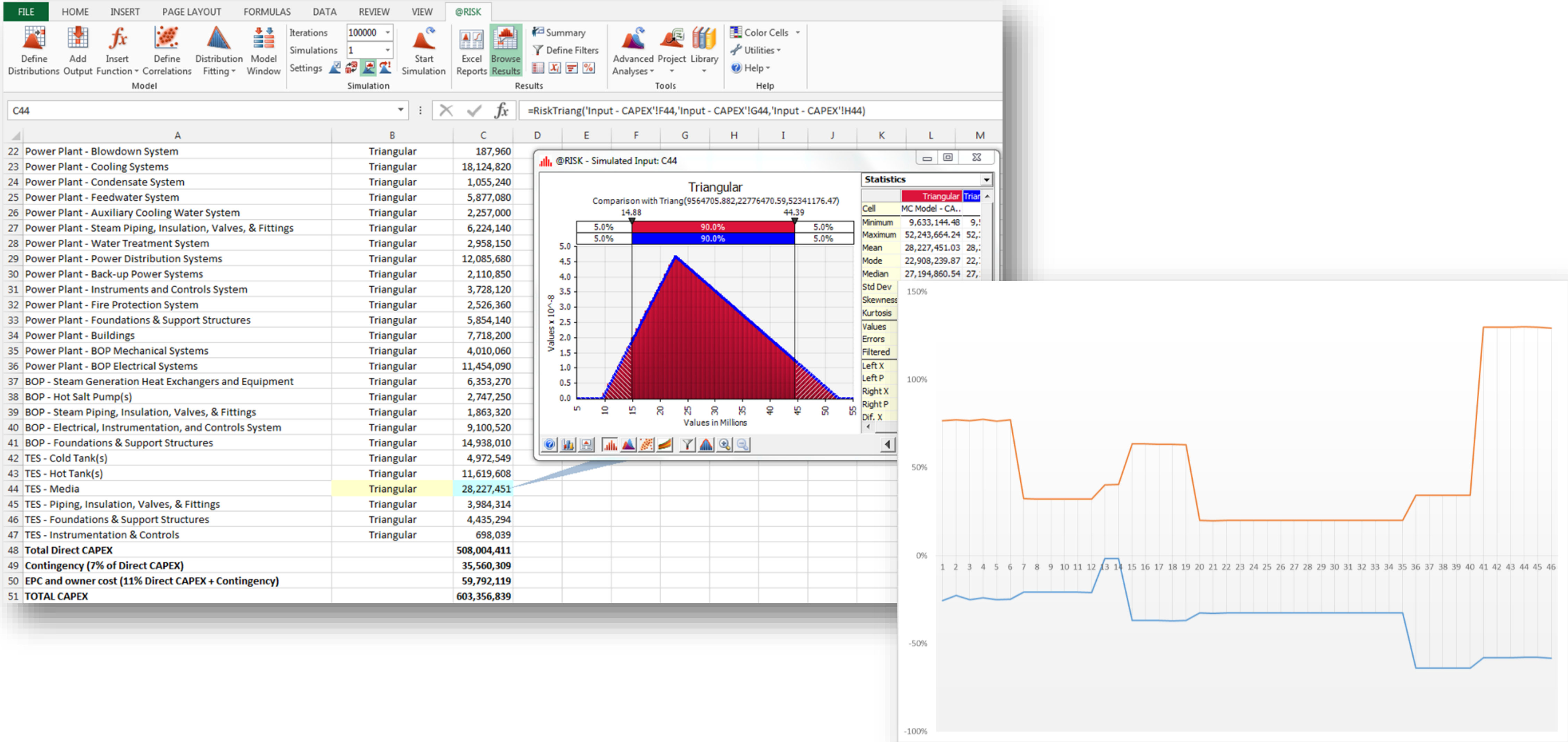
ASTRI solar tower reference plant

The ASTRI solar tower reference plant is a typical two tank molten salt solar tower with a net capacity of 100 MWe and 4 hours of thermal storage, located in Alice Springs, Australia.



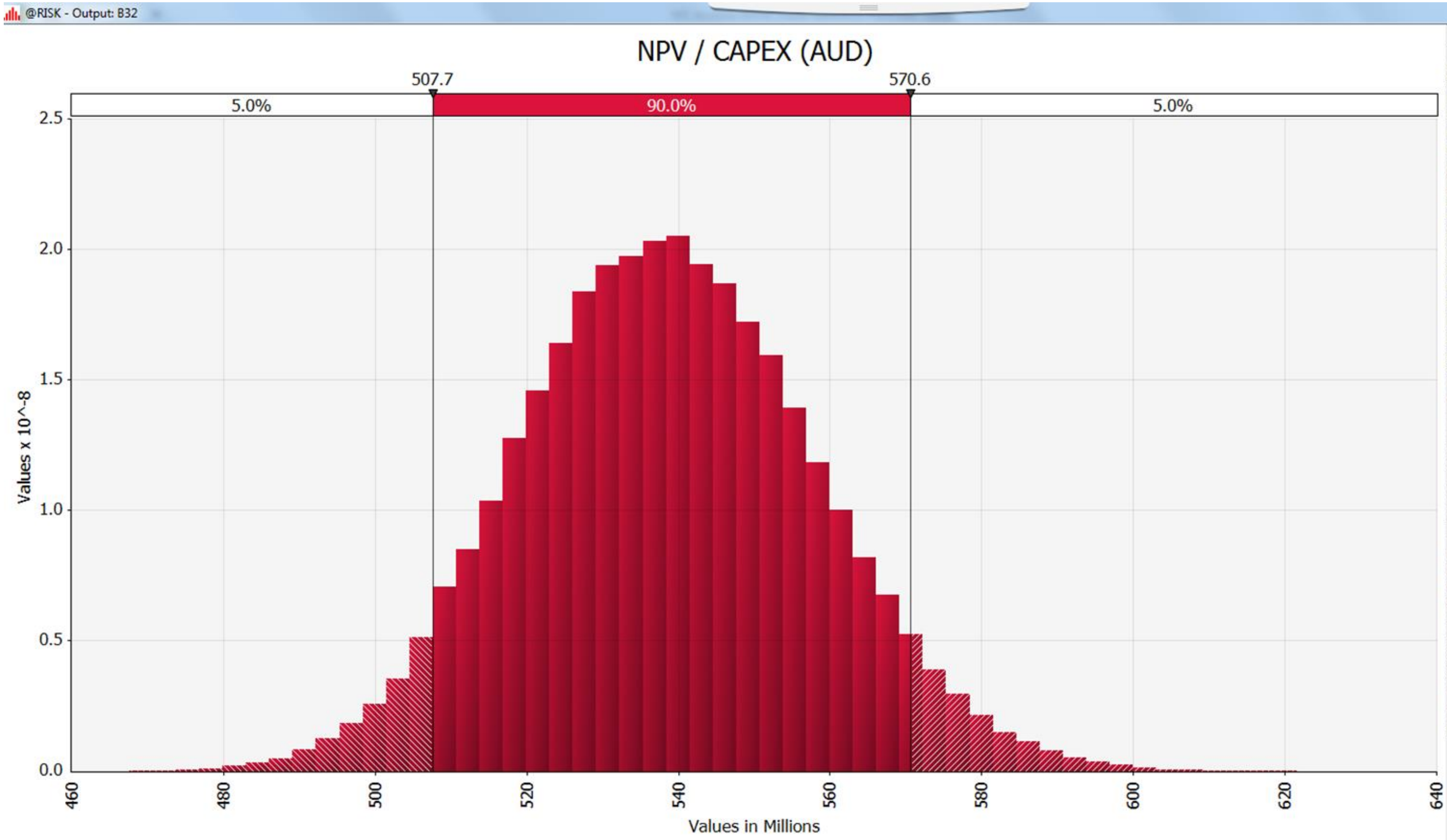
SUBSYSTEM	ITEM	VALUE
SC	• Heliostat size • Number of heliostats • Mirror reflectance and soiling • Solar multiple	• 12.2 m x 12.2 m • 6377 • 0.9 • 1.8
TR	• Tower height • Receiver type • Receiver height • Receiver diameter • Receiver design thermal power	• 183.33 m • External • 18.67 m • 15 m • 529.412 MWt
PB	• Design turbine gross output • Nameplate capacity • Rated cycle conversion efficiency • Design thermal power • Design heat transfer fluid inlet temperature • Design heat transfer fluid outlet temperature • Condenser type • Storage type • Full load hours of storage	• 111 MWe • 100 MWe • 0.3774 • 294.118 MWt • 574 °C • 290 °C • Air cooled • Two tank molten salt system • 4 hours

CAPEX uncertainty and variability



	A	B	C
22	Power Plant - Blowdown System	Triangular	187,960
23	Power Plant - Cooling Systems	Triangular	18,124,820
24	Power Plant - Condensate System	Triangular	1,055,240
25	Power Plant - Feedwater System	Triangular	5,877,080
26	Power Plant - Auxiliary Cooling Water System	Triangular	2,257,000
27	Power Plant - Steam Piping, Insulation, Valves, & Fittings	Triangular	6,224,140
28	Power Plant - Water Treatment System	Triangular	2,958,150
29	Power Plant - Power Distribution Systems	Triangular	12,085,680
30	Power Plant - Back-up Power Systems	Triangular	2,110,850
31	Power Plant - Instruments and Controls System	Triangular	3,728,120
32	Power Plant - Fire Protection System	Triangular	2,526,360
33	Power Plant - Foundations & Support Structures	Triangular	5,854,140
34	Power Plant - Buildings	Triangular	7,718,200
35	Power Plant - BOP Mechanical Systems	Triangular	4,010,060
36	Power Plant - BOP Electrical Systems	Triangular	11,454,090
37	BOP - Steam Generation Heat Exchangers and Equipment	Triangular	6,353,270
38	BOP - Hot Salt Pump(s)	Triangular	2,747,250
39	BOP - Steam Piping, Insulation, Valves, & Fittings	Triangular	1,863,320
40	BOP - Electrical, Instrumentation, and Controls System	Triangular	9,100,520
41	BOP - Foundations & Support Structures	Triangular	14,938,010
42	TES - Cold Tank(s)	Triangular	4,972,549
43	TES - Hot Tank(s)	Triangular	11,619,608
44	TES - Media	Triangular	28,227,451
45	TES - Piping, Insulation, Valves, & Fittings	Triangular	3,984,314
46	TES - Foundations & Support Structures	Triangular	4,435,294
47	TES - Instrumentation & Controls	Triangular	698,039
48	**Total Direct CAPEX**		**508,004,411**
49	**Contingency (7% of Direct CAPEX)**		**35,560,309**
50	**EPC and owner cost (11% Direct CAPEX + Contingency)**		**59,792,119**
51	**TOTAL CAPEX**		**603,356,839**

CAPEX uncertainty and variability

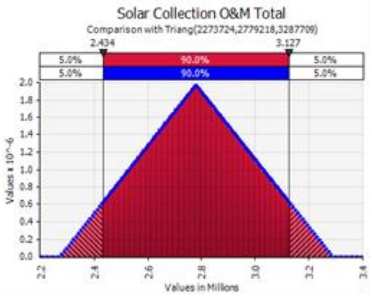


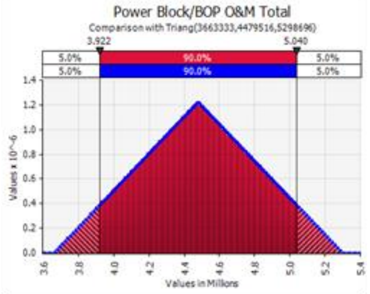
Statistics

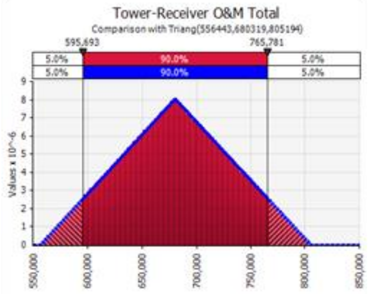
	NPV / CAPEX (AUD)
Cell	MC Model - LCOE!B32
Minimum	467,593,334.33
Maximum	621,524,478.97
Mean	538,544,797.67
Mode	535,524,982.32
Median	538,230,533.77
Std Dev	19,204,726.42
Skewness	0.0962
Kurtosis	2.9182
Values	100000
Errors	0
Filtered	0
Left X	507,678,648.91
Left P	5.0%
Right X	570,575,292.36
Right P	95.0%
Dif. X	62,896,643.46
Dif. P	90.0%
1%	495,601,649.47
5%	507,678,648.91
10%	514,048,007.31
15%	518,533,025.49
20%	522,133,626.35
25%	525,268,860.44
30%	528,063,391.82
35%	530,724,835.47
40%	533,271,293.58
45%	535,763,734.38
50%	538,230,533.77
55%	540,672,109.71
60%	543,154,531.82
65%	545,840,223.13
70%	548,557,711.97
75%	551,539,976.38
80%	554,728,678.35
85%	558,609,554.69
90%	563,457,280.01
95%	570,575,292.36
99%	584,522,555.08

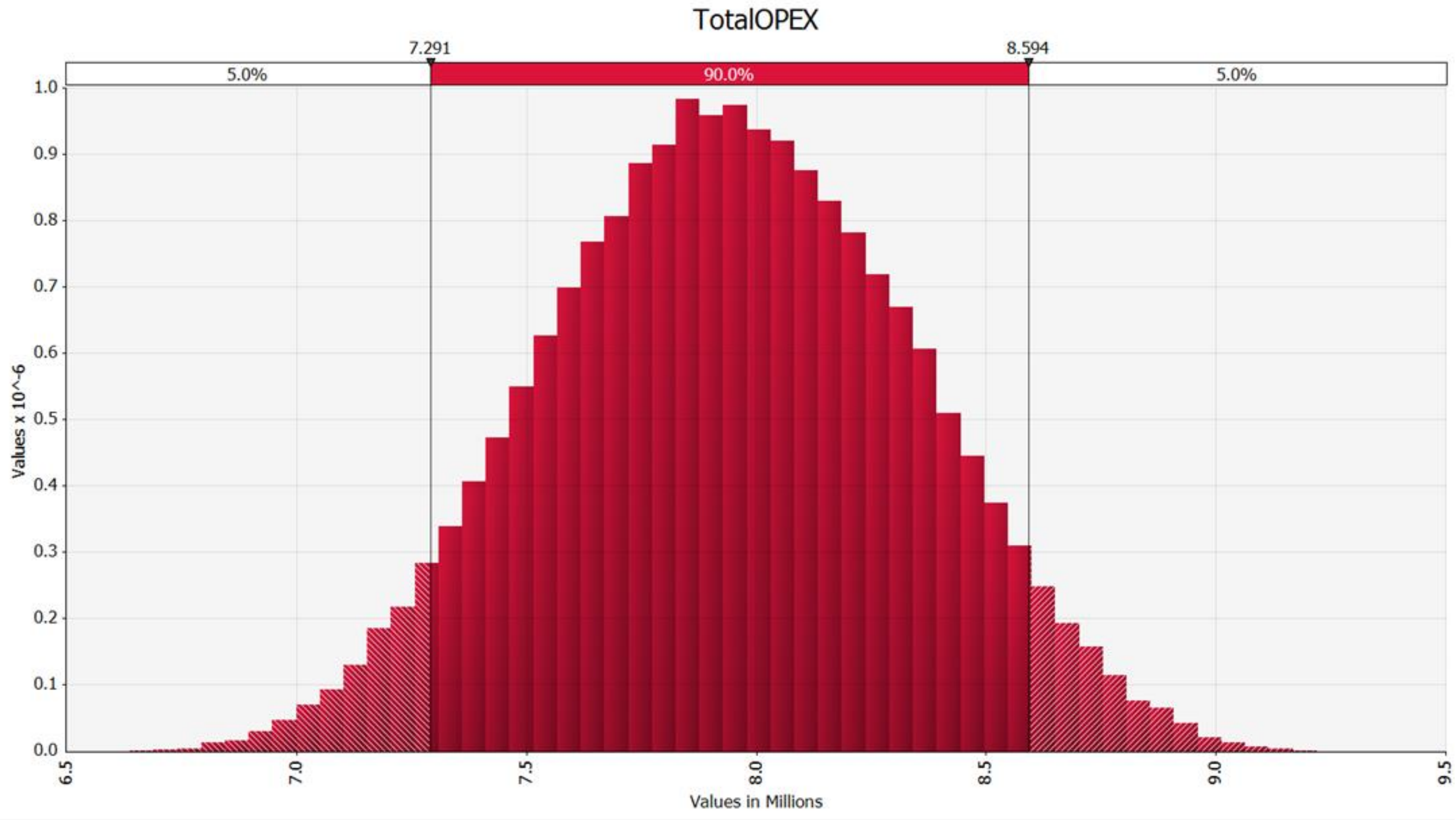
OPEX uncertainty and variability

Concept	Minimum (AUD/Year)	Likely (AUD/Year)	Maximum (AUD/Year)	Distribution
Solar Collection O&M Total	2,273,724	2,779,218	3,287,709	Triangular
Tower-Receiver O&M Total	556,443	680,319	805,194	Triangular
Power Block/BOP O&M Total	3,663,333	4,479,516	5,298,696	Triangular

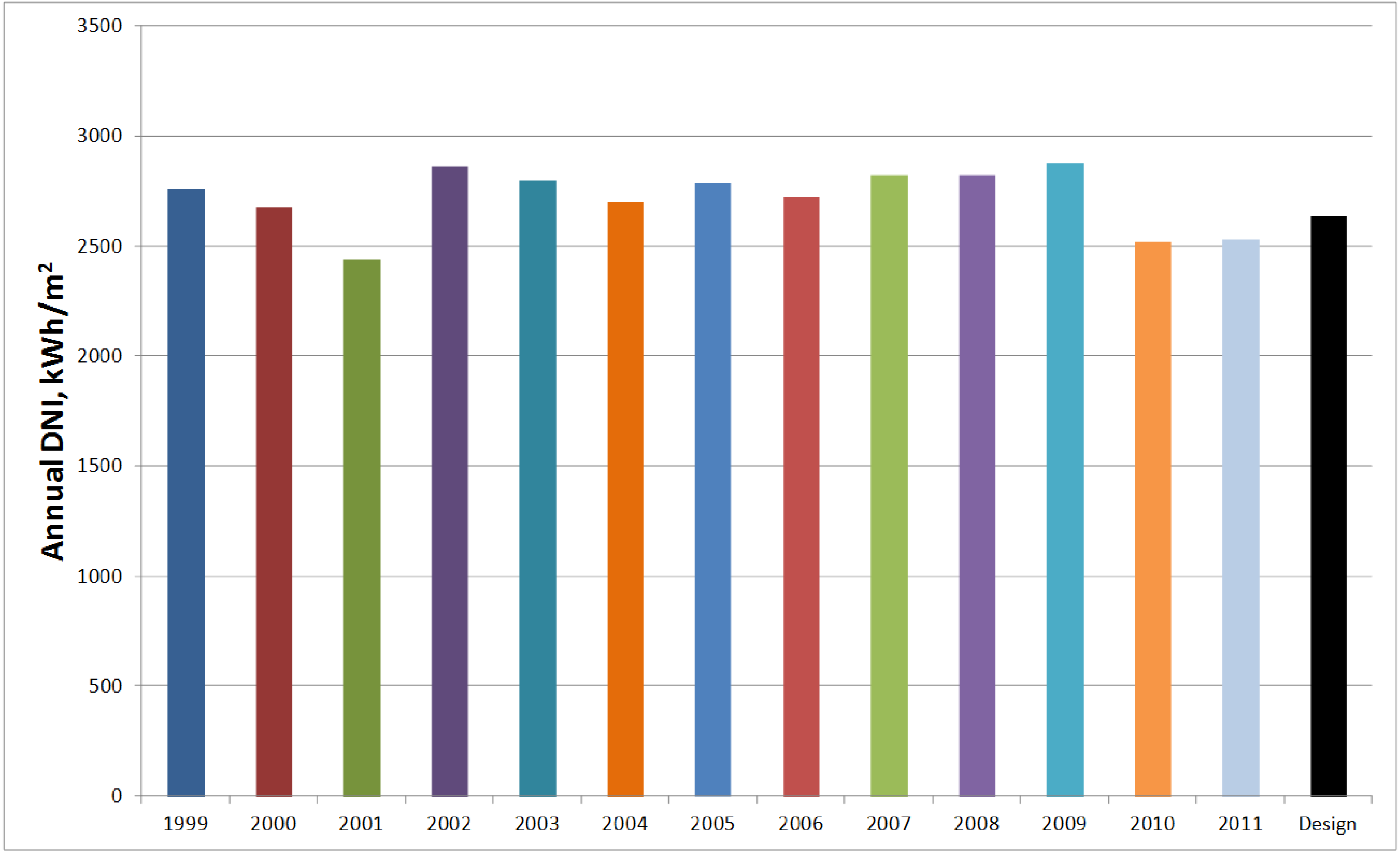




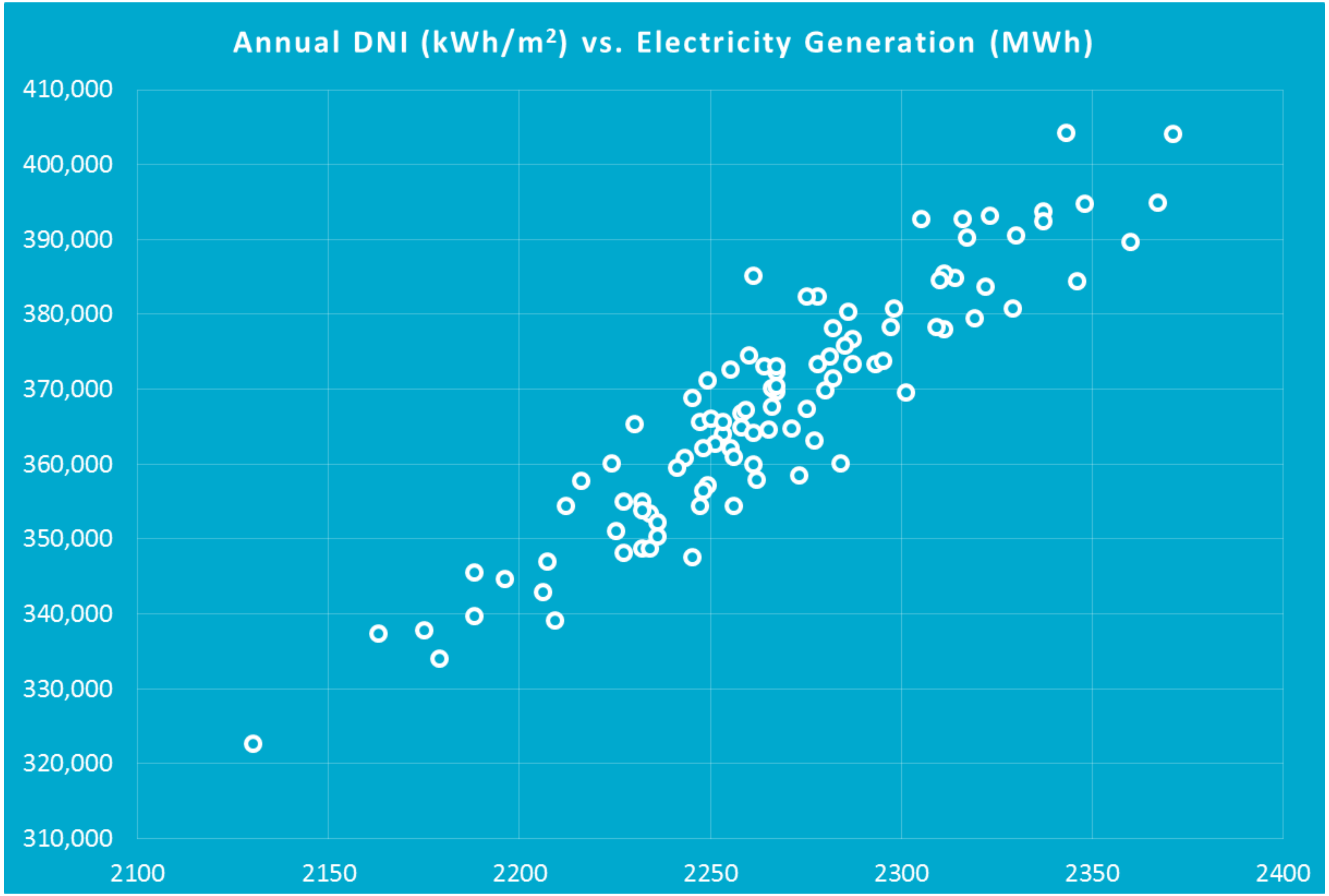




High-quality measured years for Alice Spring



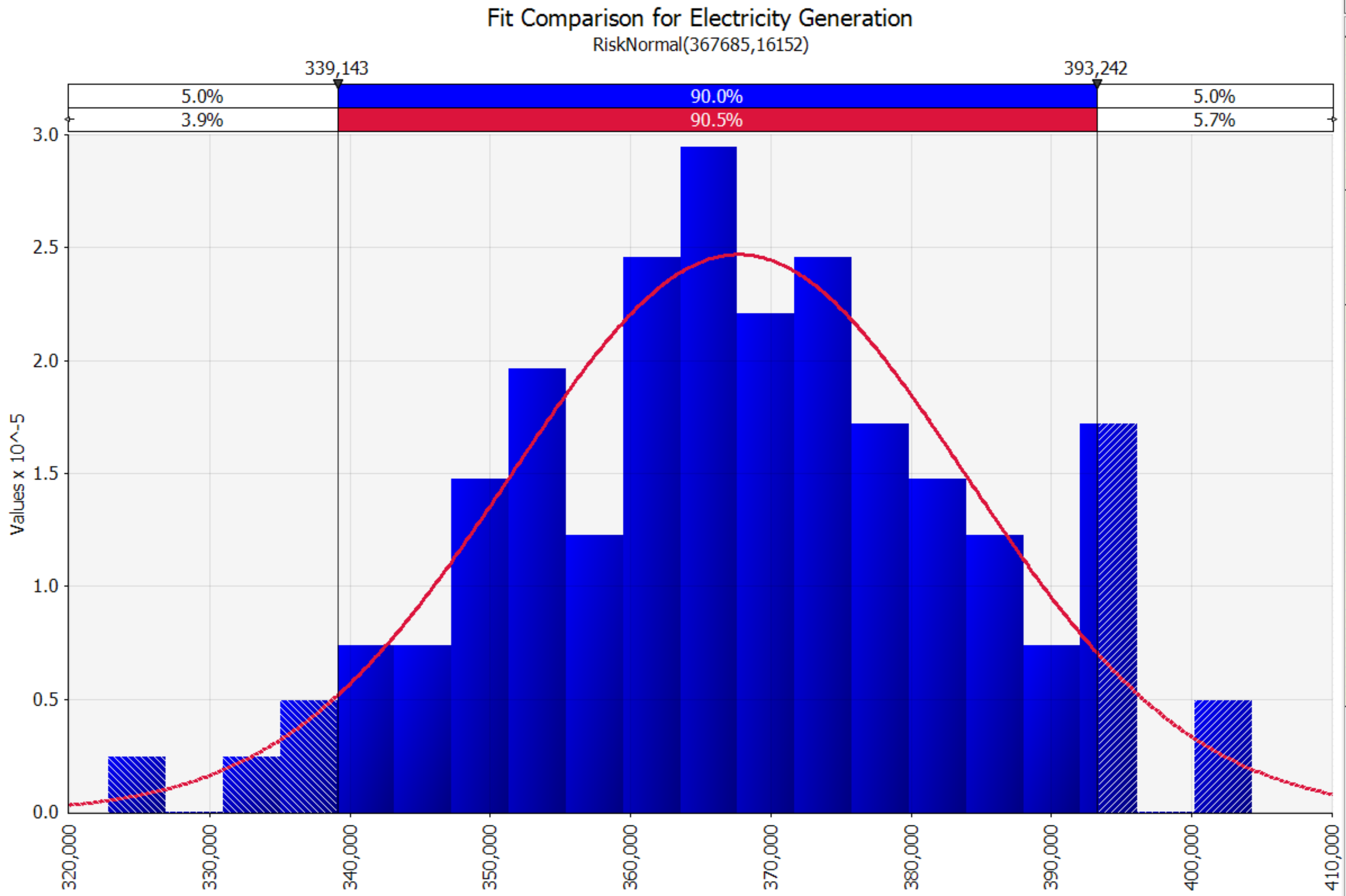
Electricity generation variability



Electricity generation variability

Fit Ranking

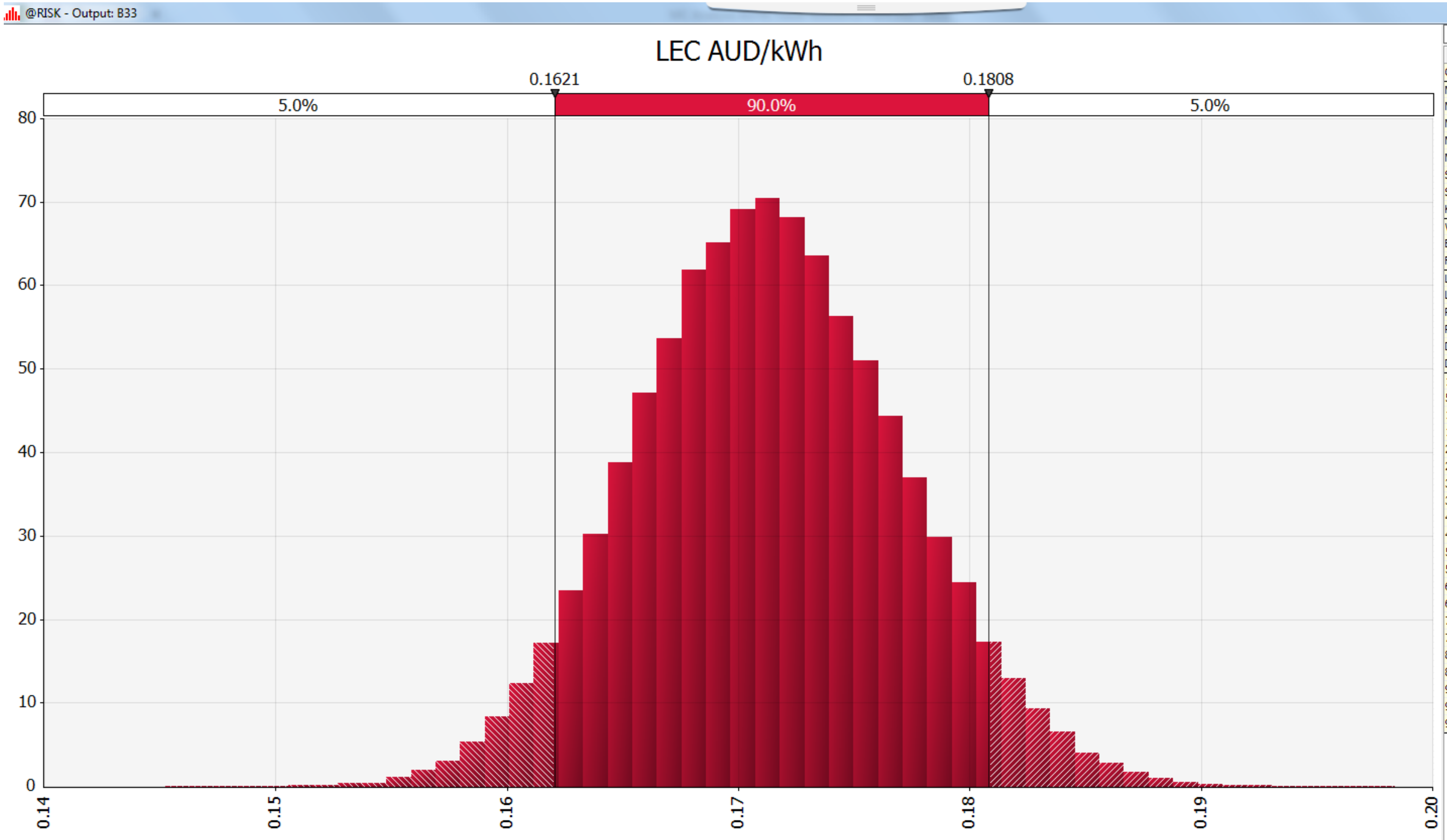
	Fit	AIC
☑	Normal	2224.8803
☐	Weibull	2226.7935
☐	Logistic	2227.5706
☐	BetaGeneral	2228.6505
☐	Triang	2229.8403
☐	Laplace	2235.0701
☐	ExtValueMin	2236.0620
☐	ExtValue	2242.2484
☐	Uniform	2269.7587
☐	Expon	2348.4223
☐	Pareto	2357.6225
☐	Levy	2444.1795
☐	*Gamma*	*N/A*
☐	*InvGauss*	*N/A*
☐	*LogLogistic*	*N/A*
☐	*Lognorm*	*N/A*
☐	*Pearson5*	*N/A*
☐	*Pearson6*	*N/A*



Statistics

	Input	Normal
Minimum	322,817.00	−∞
Maximum	404,302.00	+∞
Mean	367,685.58	367,685.00
Mode	≈373,316.33	367,685.00
Median	367,349.00	367,685.00
Std Dev	16,152.73	16,152.00
Skewness	-0.0809	0.0000
Kurtosis	2.8451	3.0000
Left X	339,143	339,143
Left P	5.0%	3.9%
Right X	393,242	393,242
Right P	95.0%	94.3%
Dif. X	54,099.00	54,099.00
Dif. P	90.0%	90.5%
1%	322,817.00	330,109.83
5%	339,143.00	341,117.32
10%	347,014.00	346,985.38
15%	351,123.00	350,944.53
20%	354,499.00	354,091.13
25%	356,615.00	356,790.64
30%	359,998.00	359,214.88
35%	361,124.00	361,461.30
40%	364,179.00	363,592.94
45%	365,389.00	365,655.32
50%	367,349.00	367,685.00
55%	369,990.00	369,714.68
60%	372,482.00	371,777.06
65%	373,372.00	373,908.70
70%	374,638.00	376,155.12
75%	378,404.00	378,579.36
80%	380,827.00	381,278.87
85%	384,896.00	384,425.47
90%	390,356.00	388,384.62
95%	393,242.00	394,252.68
99%	404,183.00	405,260.17

LCOE probability distribution

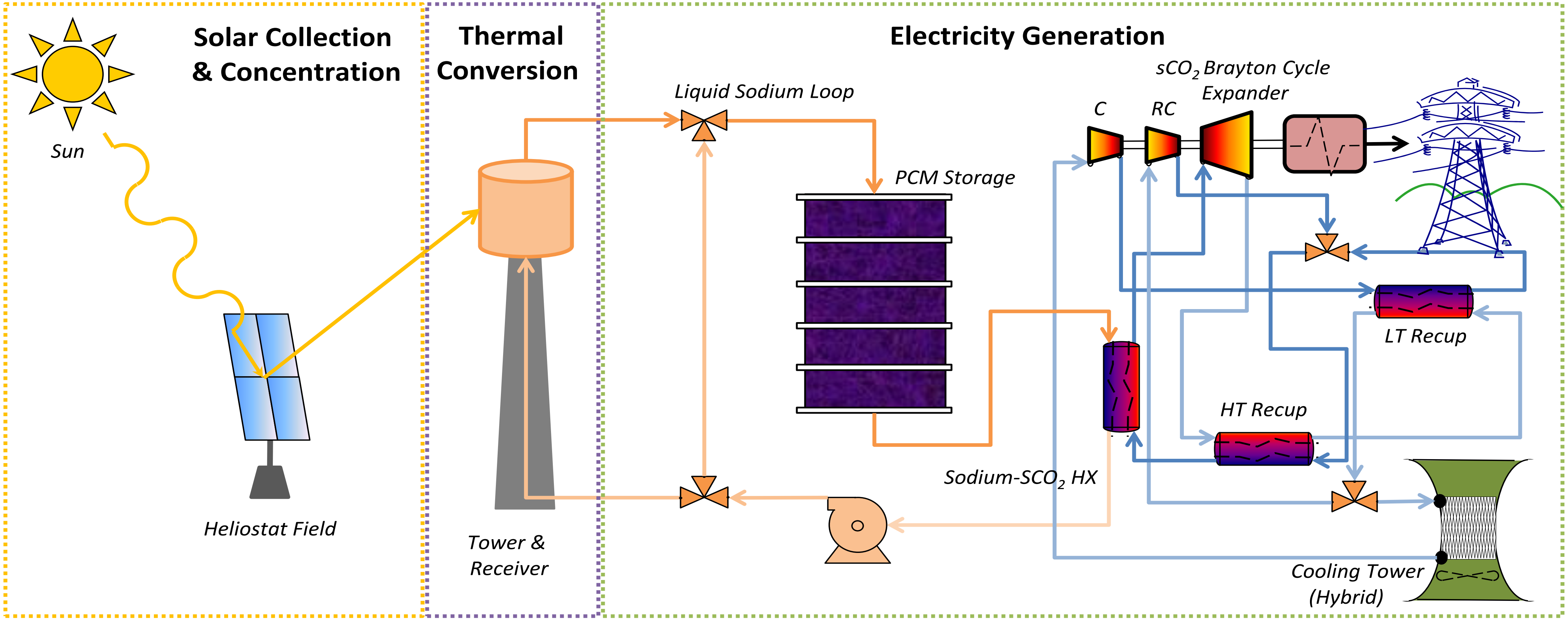


Statistics	LEC AUD/kWh
Cell	MC Model - LCOE!B33
Minimum	0.145227
Maximum	0.198370
Mean	0.171305
Mode	0.169973
Median	0.171207
Std Dev	0.005699
Skewness	0.0878
Kurtosis	2.9245
Values	100000
Errors	0
Filtered	0
Left X	0.1621
Left P	5.0%
Right X	0.1808
Right P	95.0%
Dif. X	0.018765
Dif. P	90.0%
1%	0.158562
5%	0.162068
10%	0.164033
15%	0.165387
20%	0.166455
25%	0.167397
30%	0.168222
35%	0.169019
40%	0.169769
45%	0.170487
50%	0.171207
55%	0.171913
60%	0.172652
65%	0.173403
70%	0.174250
75%	0.175137
80%	0.176138
85%	0.177282
90%	0.178734
95%	0.180834
99%	0.184775

ASTRI configurations

NaPsC system

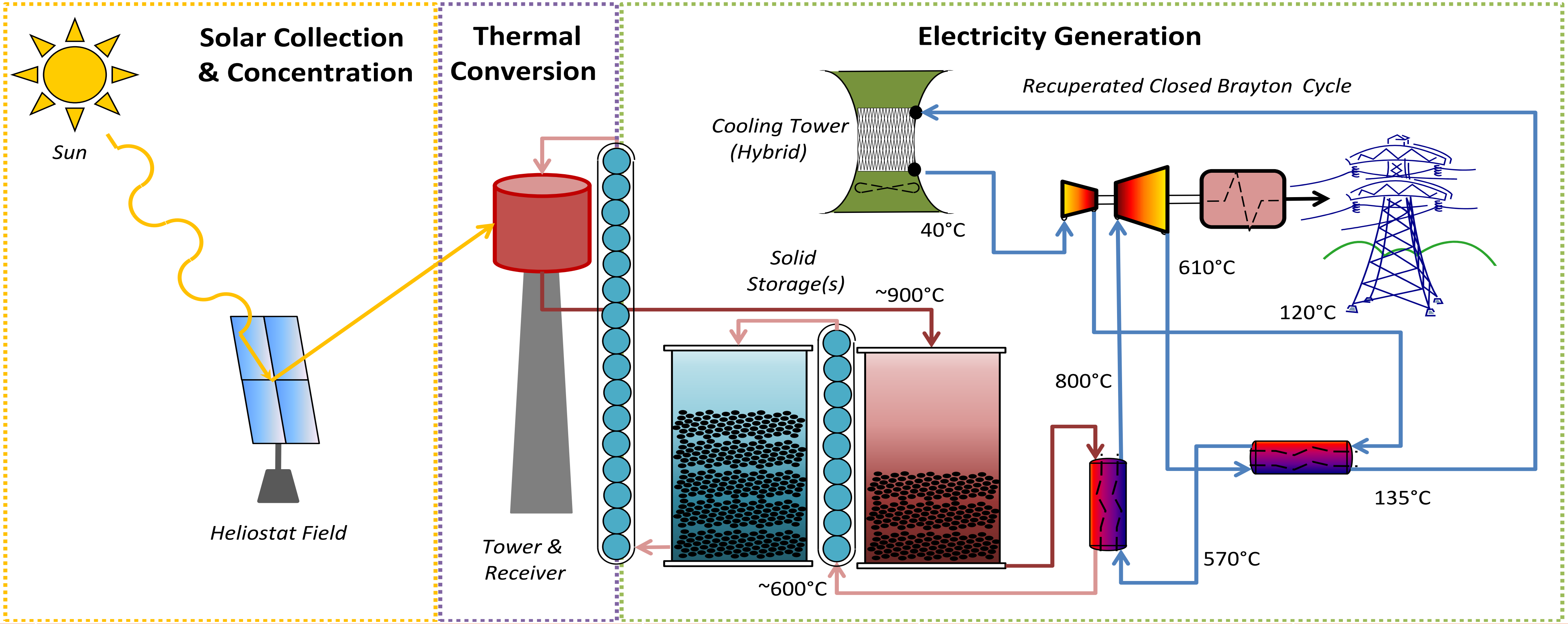
Tower system using sodium receiver, PCM storage and sCO_2 power block: 22.5 or 90MWe(net) with 6 hours of storage



Efficiency	57 – 59 %	83 – 86 %	93 – 96 %	47 – 49 %	18.3 – 19.8 (19.1) %
Cost	\$95-160 (120)/m²	\$130-285 (180)/kWt	\$13-69 (30)/kWht	\$855-1781 (1440)/kWe	**9.4–14.7 (11.9)c/kWh**

ParICC system

Tower system using particle receiver, solid storage and closed Brayton power block: 70-100MWe(net) with 6 hours of storage

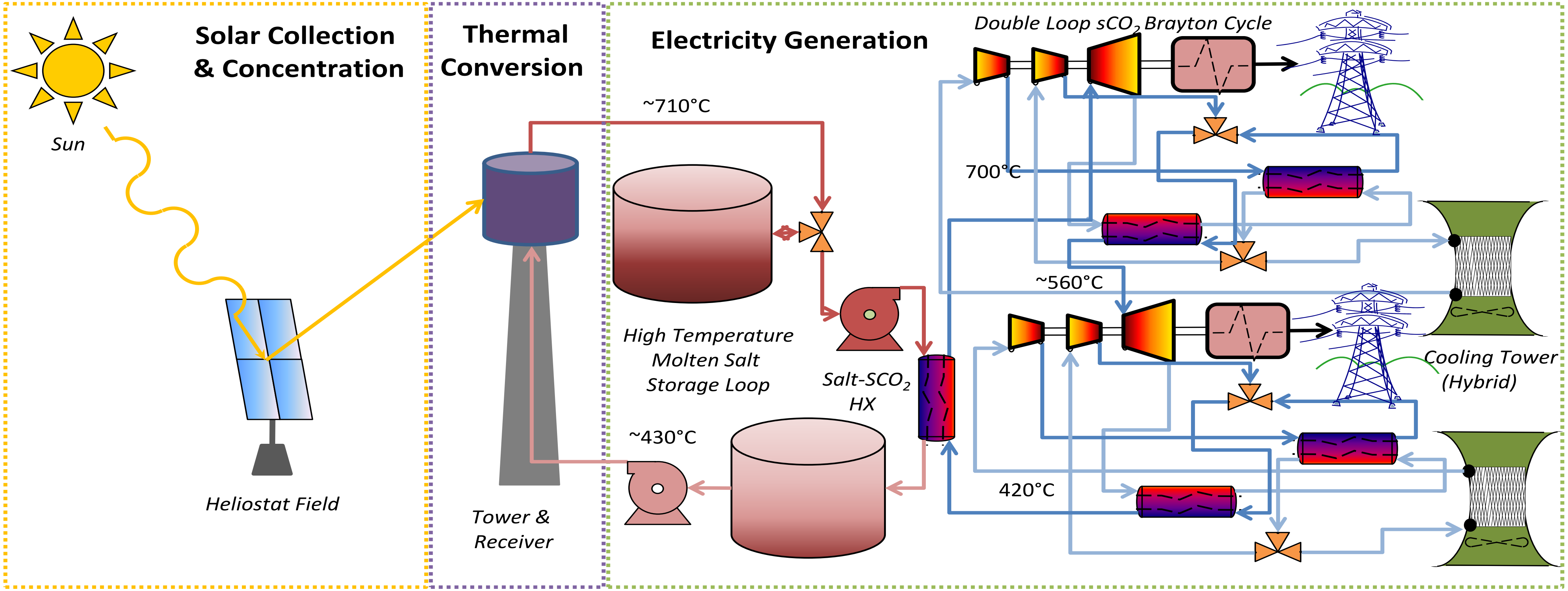


Efficiency	57 – 59 %	79 – 81 %	83 – 86 %	48 – 50 %	16.7 – 18.7 (16.4) %
Cost	$95-160 (120)/m^2	$100-220 (140)/kWt	$8-46 (20)/kWht	$1067-2227 (1800)/kWe	**9.3-16.0 (12.2)c/kWh**

HiTCas system

Tower system using novel molten salt receiver and storage with cascading power block: 40.5MWe(net) with 6 hours of storage

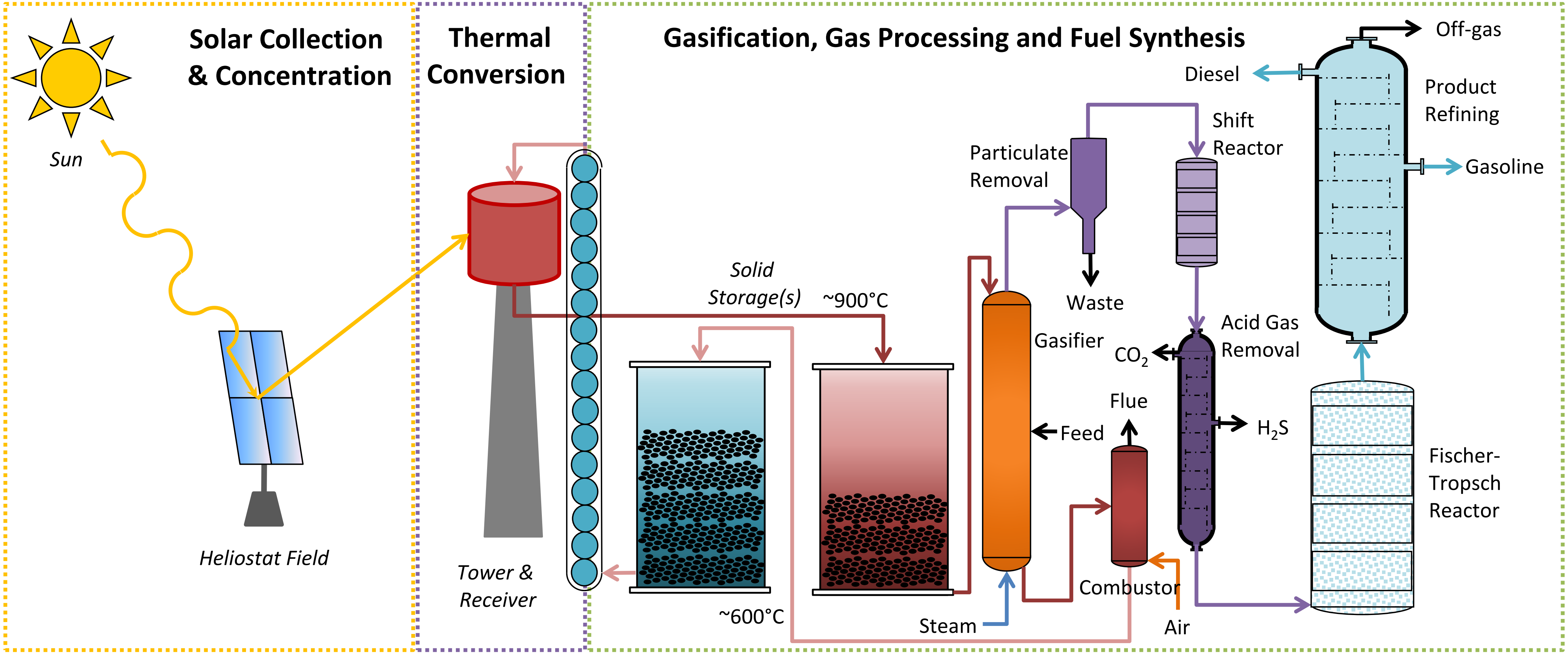
Bottoming cycle choice could be either a second stage of sCO2 (P31A) or an alternative power block (P32)



Efficiency	57 – 59 %	88 – 91 %	96 – 99 %	48 – 49 %	19.4-22.0 (20.6) %
Cost	$95-160 (120)/m^2	$129-284 (180)/kWt	$16-85 (37)/kWht	$1090-2275 (1839)/kWe	**9.2-17.1 (13.1)c/kWh**

SolarFuels system

Tower system using high temperature particle receiver and storage for hybrid gasification and fuel synthesis



Accomplishments and impact

AUSTRALIAN SOLAR THERMAL RESEARCH INITIATIVE

Accomplishments and impact

In addition to demonstrating full achievement, and more, of all the KPIs as scheduled, during the time elapsed since ASTRI started on 1 November 2012, the research program has also achieved the following:

- A significant increase in **participation** of the Australian research community in CST. This is shown in the participation of Australian researchers in international conferences, in the participation of Australian research institutions in international CST research projects and programs, in the quality of the CST proposals submitted to ARENA and other funding bodies, and in the increased numbers of doctoral students and post-doctoral fellows engaged in CST research. It has 125 researchers working in the program with 41 post-graduate students, 18 postdoctoral fellows.
- A dramatic increase in the **capabilities** and know-how in the field of CST technologies of the Australian universities that are part of ASTRI. This is shown in the increased quality of their contributions to the research program, which reflect a continuous advance in their understanding of the problems and advantages associated to CST technologies.

Accomplishments and impact (cont.)

- The agreement among ASTRI partners on a **clear strategy** to achieve the fundamental technological challenge of ASTRI – to substantially improve the cost competitiveness of CST technologies for electricity production and for the production of synthetic fuels. This strategy is based upon the concept of ASTRI CST configurations, which are solar power plant configurations with the potential to achieve the technical target of ASTRI in terms of the LCOE of the electricity produced by the power plant or in terms of the LCOE of the synthetic fuels produced.
- The exploration of new exciting **disruptive** CST technologies with the potential to make a big difference and to position Australia at the forefront of CST technologies worldwide. As a strategic research initiative, ASTRI has supported research on innovative concepts to deliver relevant research outputs that produce a suite of commercialisable outcomes.

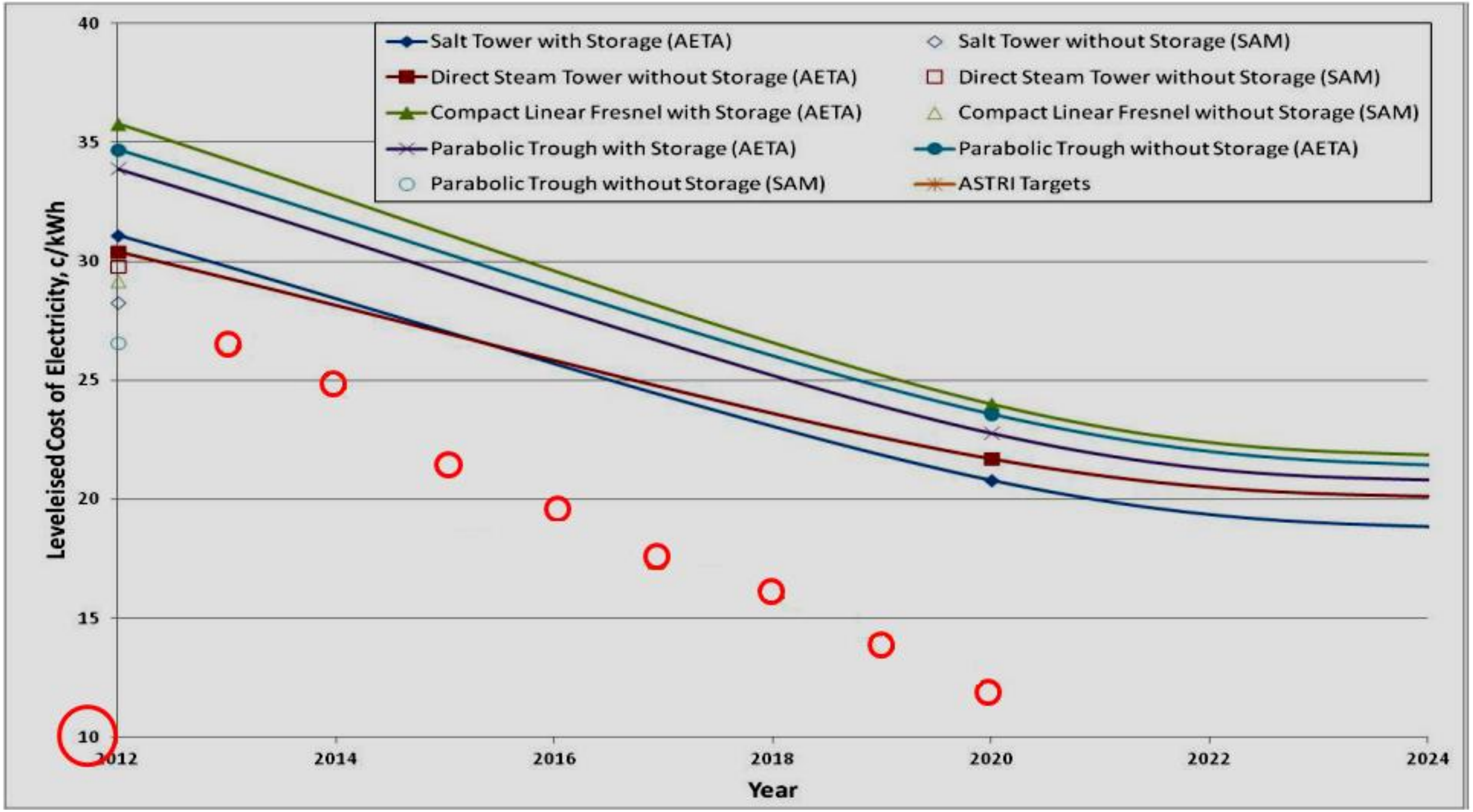
Accomplishments and impact (cont.)

- The gradual emergence of ASTRI as the **reference forum** where industry, researchers, and policy makers discuss about what opportunities CST can offer to Australia and how to seize these opportunities. This is shown in the increased relevance and developing profile of public aspects of the Annual ASTRI Workshop, the participation of ASTRI representatives in government and industry events, the increase engagement with industry in Australia, and the role that ASTRI is playing in formulating an overall CST strategy for Australia.
- **Direct engagement with industry** and government has resulted in a range of contributions to ASTRI projects. ASTRI has valuable in-kind support from RATCH-Australia for the mirror cleaning part of the operation and maintenance (O&M) project.
- Funds from the Queensland Government have helped in the **development of research infrastructure** for the hybrid cooling tower to be used in the supercritical carbon dioxide (sCO2) project. The total value of support from these funding partners has been $527,000.

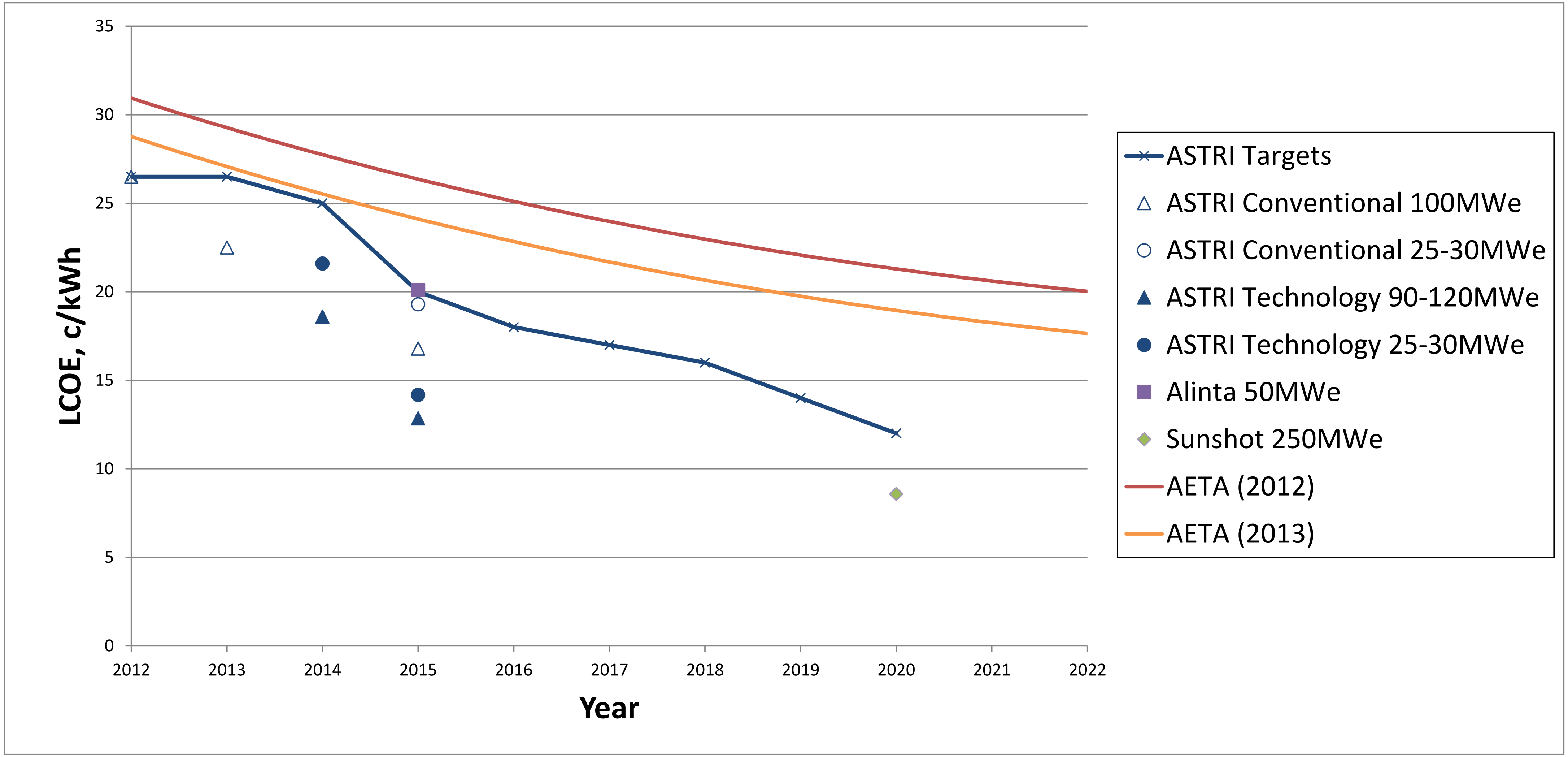
The way forward

ASTRI
AUSTRALIAN SOLAR THERMAL RESEARCH INITIATIVE

ASTRI main rationale



ASTRI targets and assessments



Changes in the ASTRI reference plant costs

- ASTRI regular reviews of the international CSP industry and evaluates the likely LCOE for a 100MWe plant with 4 hours of storage plant in Australia. This assessment has reduced from an LCOE 26.5c/kWh (2012) to ~16.8c/kWh (current).
- Subsequent changes to LCOE estimates have resulted from:
  - Shifting from Parabolic Trough to Central Tower technology, reducing LCOE to ~23.0c/kWh
  - Optimisation of the plant specifications and heliostat cost reduction from \$220/m^2 to \$180/m^2, reducing the LCOE to ~17.3c/kWh.
  - Improved solar field optimisation design, reducing LCOE to ~17.0c/kWh
  - Adopting Australian labour staffing structures, reducing LCOE to ~16.8c/kWh
- Future changes that seem likely to reduce LCOE in conventional systems are: continued heliostat improvement and field design, the use of more efficient steam turbine cycles in larger systems, changes to storage systems and increased automation in O&M.

For the next four years of ASTRI we should…

- Define more ambitious technical targets.
- Advance the TRL of all ASTRI technologies.
- Continue de-risking all ASTRI technologies.
- Increase the emphasis in CST applications other than electricity.

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CSIRO

Australian National University

The University of Queensland Australia

The University of Adelaide

University of South Australia

QUT

Flinders University

Thank you

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