Economics of Solar Thermal Power in India:

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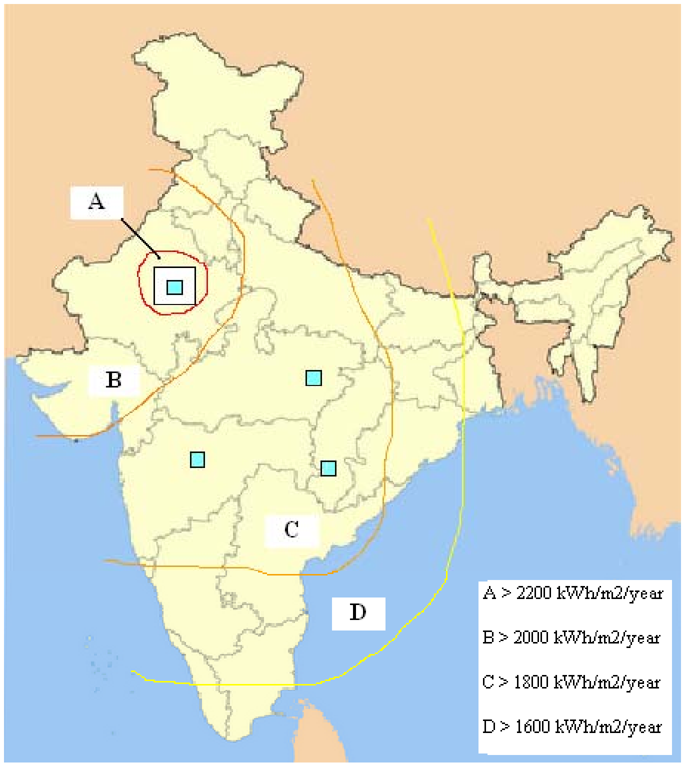
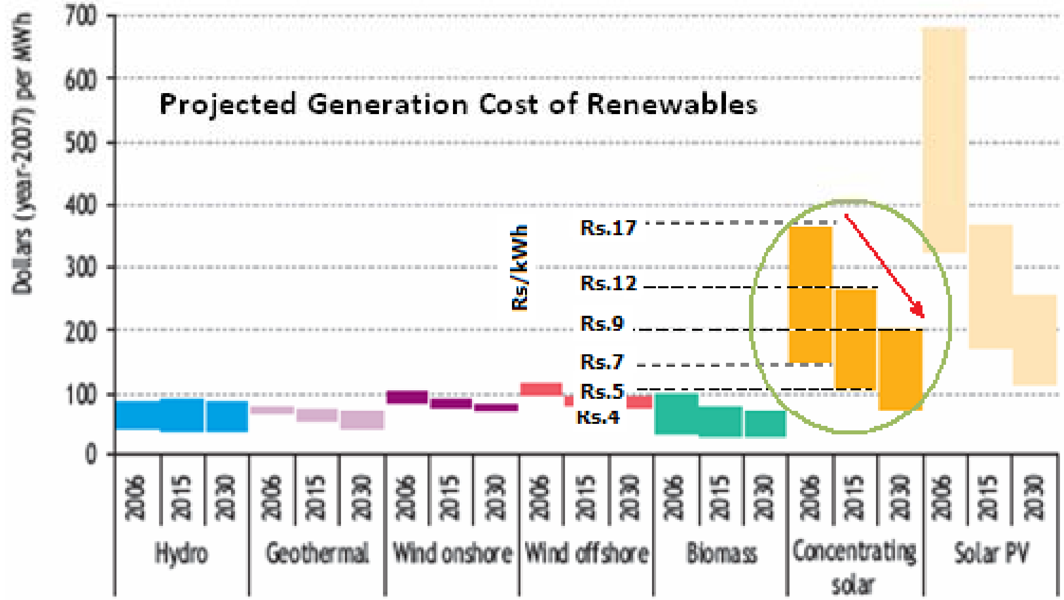
Challenges



Solar Insolation and area required

□= 2500 sq.km

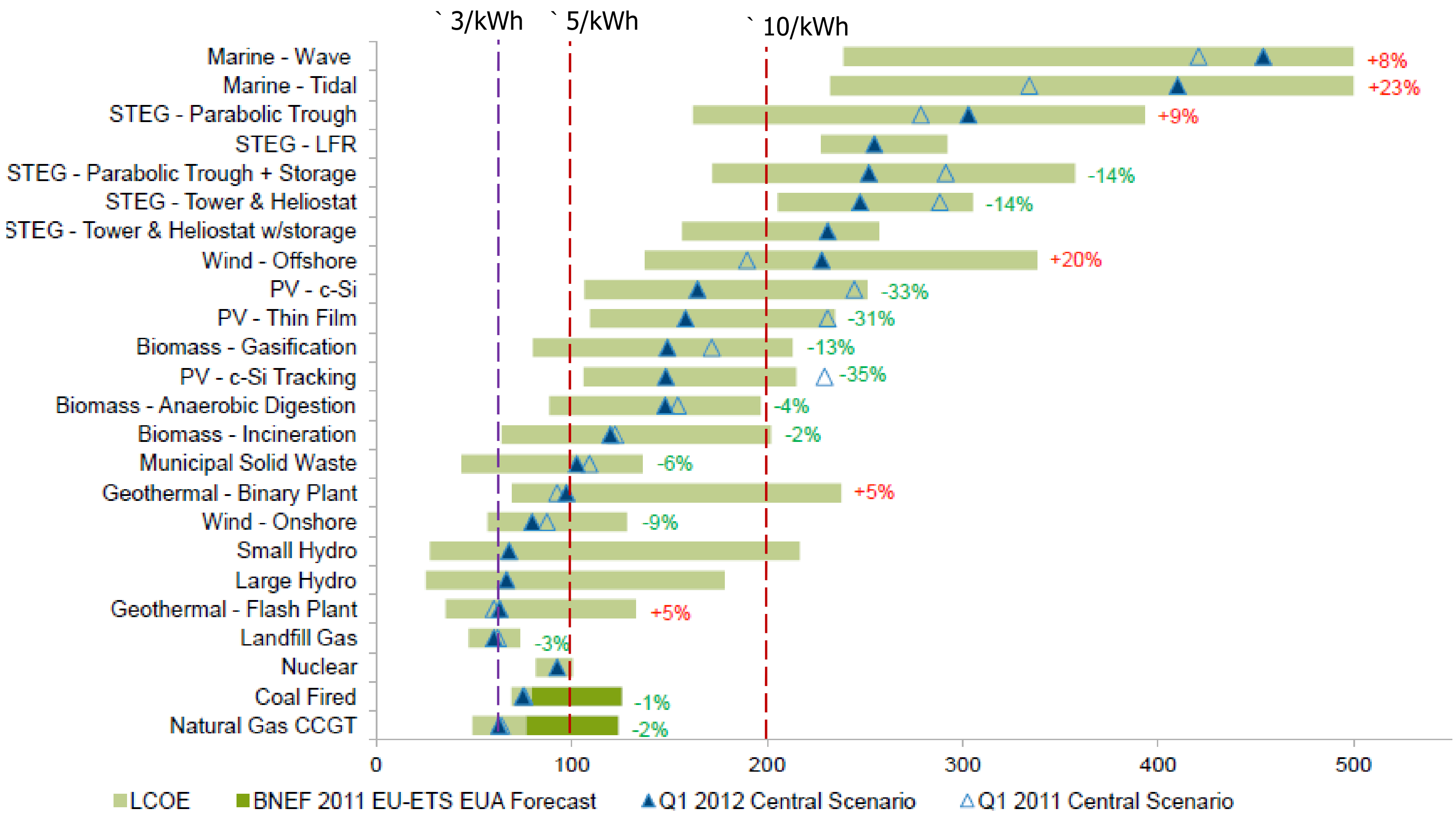
■= 625 sq.km



Source: World Energy Outlook – 2008, International Energy Agency

1. Limited experience in CSP in the country
2. Need for cost reduction
3. Need for indigenous technology, system development
4. Need for demonstration, public domain information

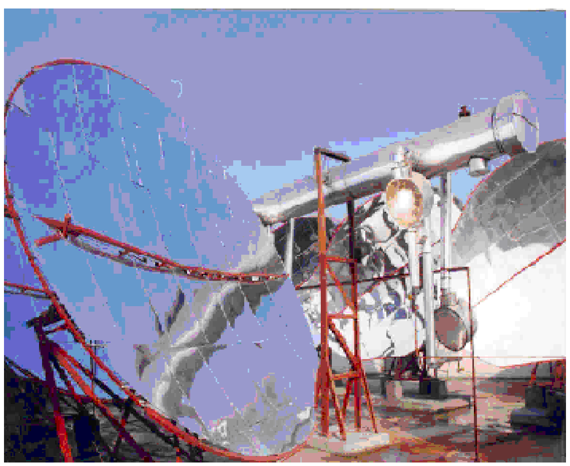
Estimated cost of Energy



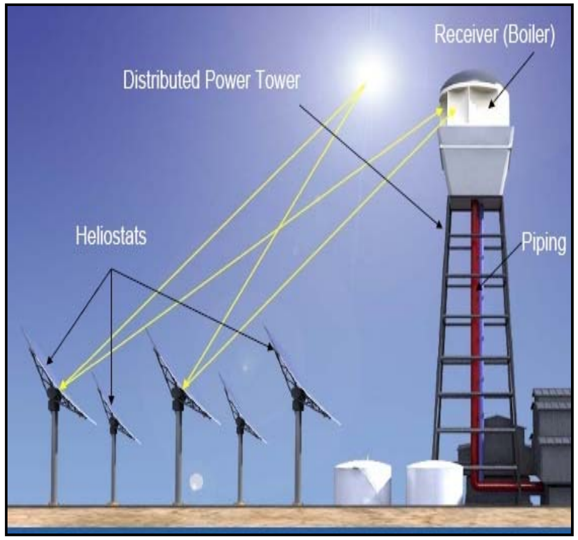
Source: Bloomberg New Energy Finance estimates

Solar Concentrators

Parabolic Trough



Scheffler paraboloid dish



Heliostat

CLFR Technology

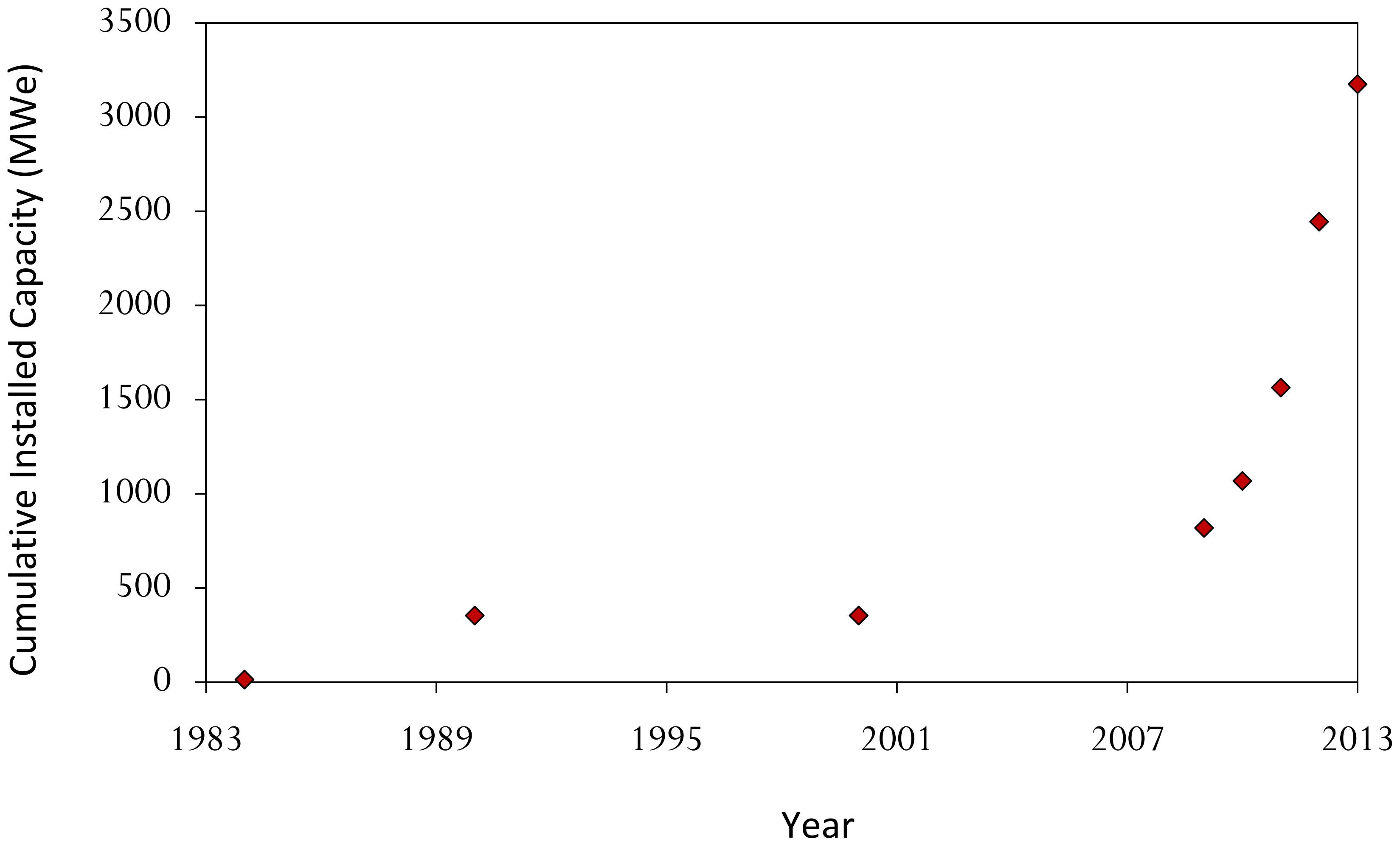
Arun Technology

Solar Thermal Technologies

	Companies	**Operating temp.**	**Efficiency, η**	**Remarks**
Parabolic Trough	Abener, Thermax, KIE Solatherm	350-400℃	Peak 14-20% 11-16% Annual	Commercial
Linear Fresnel Reflector	KG Design, Areva	220-250℃	Peak 18% Annual 13%	Lower cost
Dish	Gadhia Solar, Clique, WRST, Birla Terra Joule, ATE	200 - 700℃	Peak 30% Annual 12-25%	Solar heating cooking
Heliostats Solar Tower	E-Solar (ACME) 2.5 MW at Bikaner Sunborne	450-565℃	23-25% 7-20%	

Worldwide operational CSP plants based on PTC technology

(Source: http://www.nrel.gov/csp/solarpaces/by_status.cfm)



Worldwide operational CSP plants based on PTC technology

- **Most commercially applied technology with more than 3100 MWe installed capacity (Operational)**
- **Turbine inlet pressure range: 40 bar to 100 bar**
- **Solar Field Outlet Temperature Range: 300°C to 550°C**
- **Godawari Green Energy - Solar thermal power plant**
  - Turbine Capacity (Gross): 50.0 MW
  - PPA/Tariff Rate: 12.2 Rs per kWh
  - PPA/Tariff Period: 25 years

Worldwide operational CSP plants based on SPT technology

(Source: http://www.nrel.gov/csp/solarpaces/by_status.cfm)

Capacity (MW)	Name	Country	Aperture Area (m^2)	Tower Height (m)	HTF	Solar Field Outlet Temp. (°C)	Storage (hrs)	Turbine Inlet Pressure (bar)
11	PS10	Spain	75000	115	Water	300	1	45
20	PS20	Spain	150000	165	Water	300	1	45
19.9	Gemasolar	Spain	318000	140	Molten Salt	565	15	-
5	Sierra Sun Tower	USA	27670	55	Water	440	0	-
1.5	Julich Solar Tower	Germany	18000	60	Air	680	1.5	-
2.5	ACME	India	16279	46	Water	-	0	60
1	Dahan Power Plant	China	10000	118	Water	400	1	-
3	Lake Cargelligo	Australia	6080	-	Water	500	Yes	50

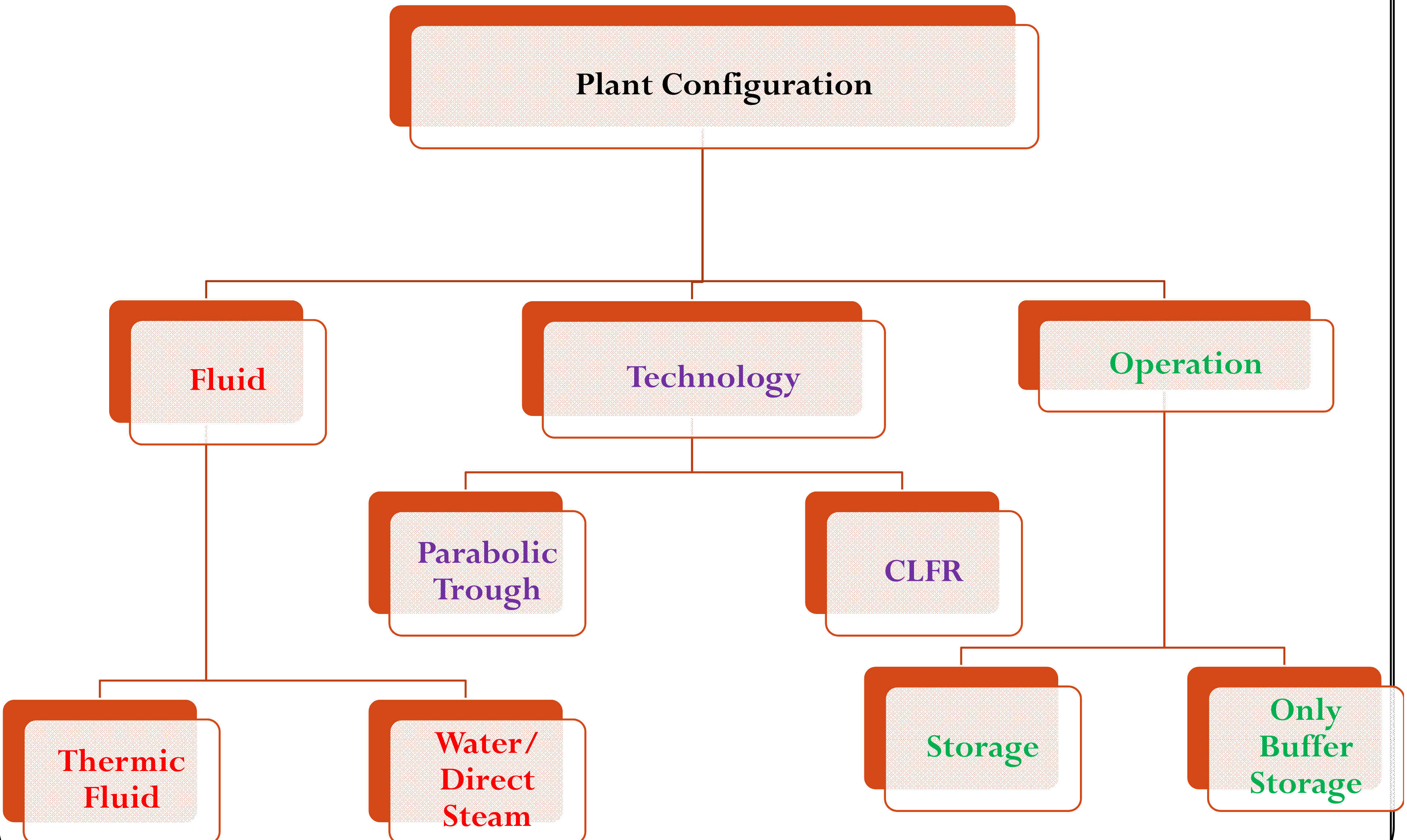
Worldwide operational CSP plants based on LFR technology

(Source: http://www.nrel.gov/csp/solarpaces/by_status.cfm)

Capacity (MW)	Name	Developer/ EPC	Country	Aperture Area (m^2)	Storage (hrs)	Turbine Inlet Pressure (bar)	Solar Field Outlet Temp. (°C)
0.25	Augustin Fresnel	Solar Euromed	France	4000	0.25	100	300
9	Liddell Power Station	Novatec Solar	Australia	18490	-	55	270
5	Kimberlina	Areva	USA	26000	-	40	-
1.4	Puerto Errado 1	Novatec Solar	Spain	18662	yes	55	270
30	Puerto Errado 2	Novatec Solar	Spain	302000	0.5	55	270

- **100 MWe CSP plant of Reliance Power about to commissioned**
- **Project cost: $336 million** (Source: www.csp-world.com)

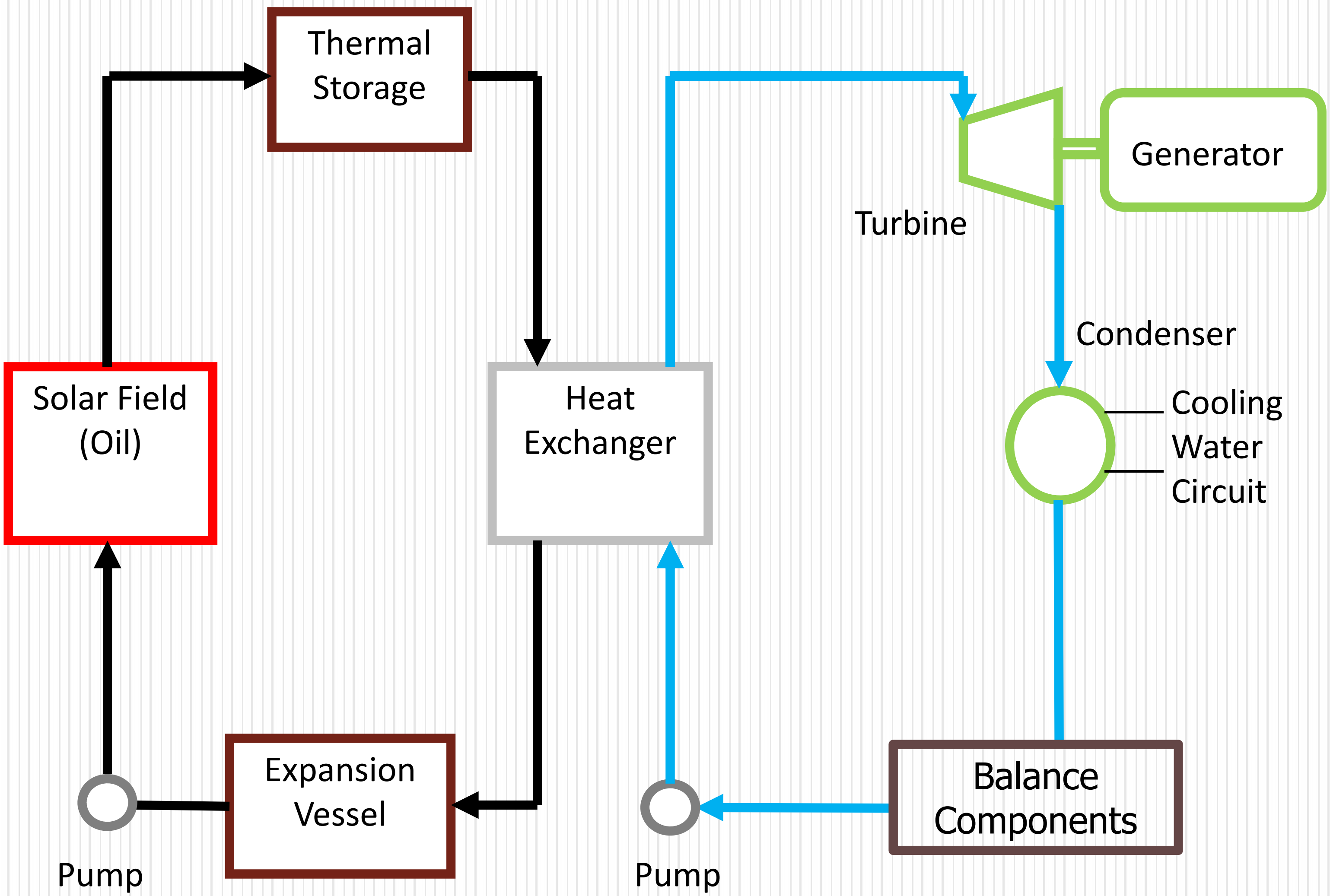
Configuration



Annualised Life Cycle Cost

- Annualised Life Cycle Costs (ALCC) - annual cost of owning and operating equipment
- $ALCC = C_0\ CRF(d,n) + AC_f + AC_{O\&M}$
- $CRF(d,n) = [d(1+d)^n]/[(1+d)^n - 1]$
- discount rate d, Life n years, C_0 Capital Cost, AC_f, $AC_{O\&M}$, annual cost - fuel and O&M CRF – Capital recovery factor
- Cost of Generated Energy = ALCC/ Annual net generation

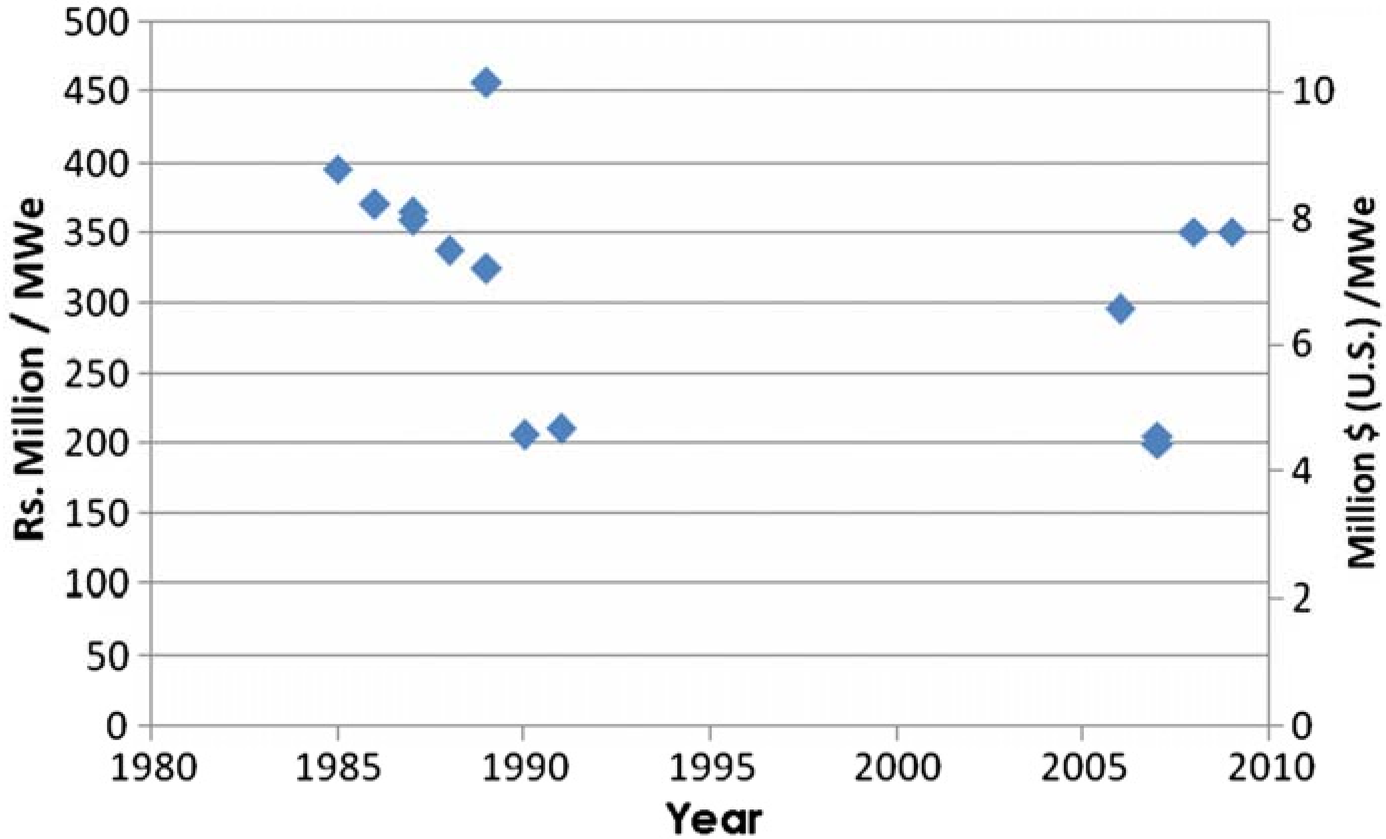
Schematic of Solar Thermal Power Plant



Assumptions – Cost Analysis

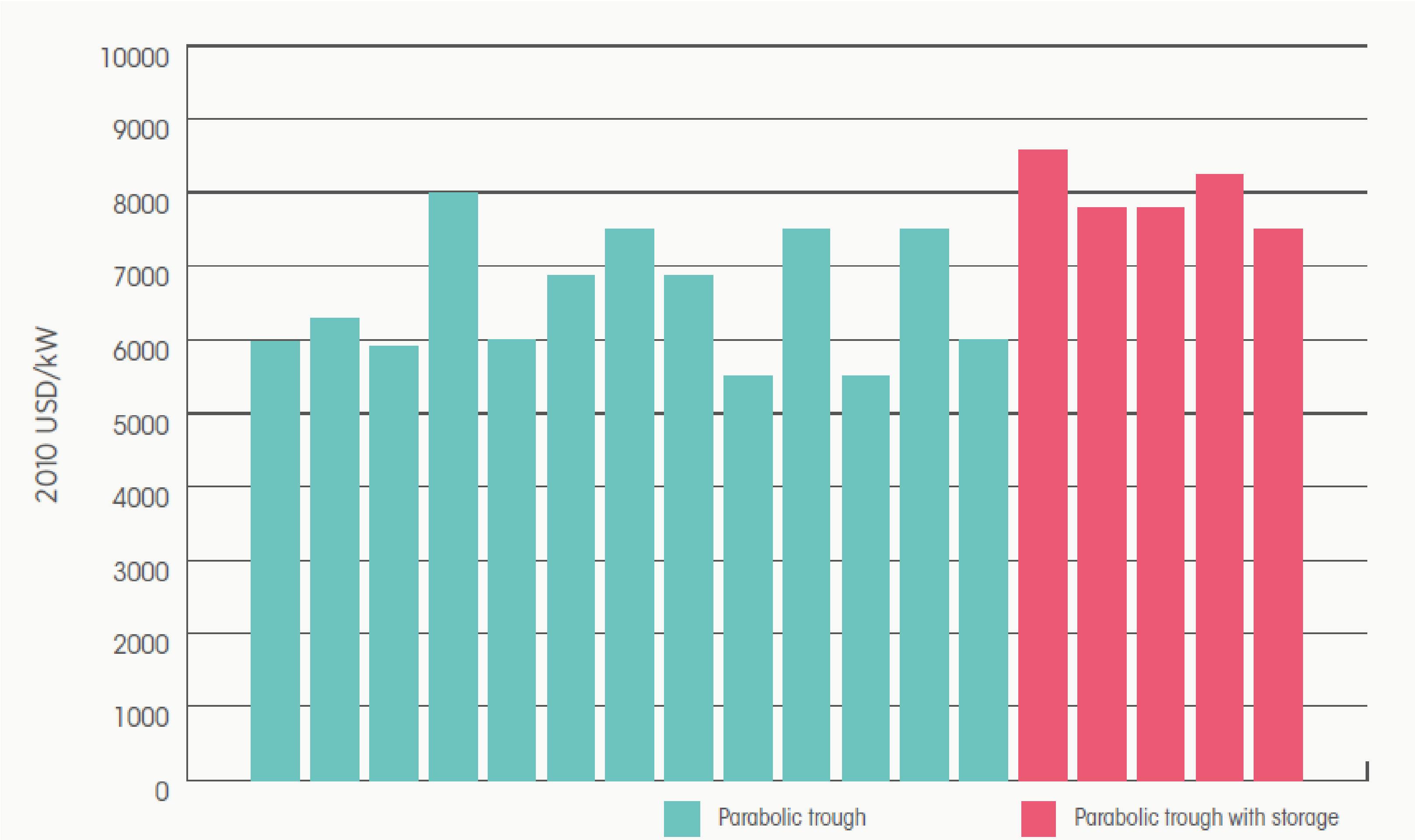
Equipment	Cost (Rs.)	Per Unit	Remarks
HX	10 Million	MWe	
PT cost	15000	m^2	
CLFR cost	10000	m^2	
HTF_{cost}	150	kg	
Mirrors	0.5	%	Annual Replacement
HTF	1	%	Annual Replacement
Receivers	2	%	Annual Replacement
O&M	3	%	Of Equipment

Trend in CSP Plant Cost



Source: Krishnamurthy, P., Mishra, S., and Banerjee, R., Energy Policy, 2012

PTC Power Plant Capital Cost

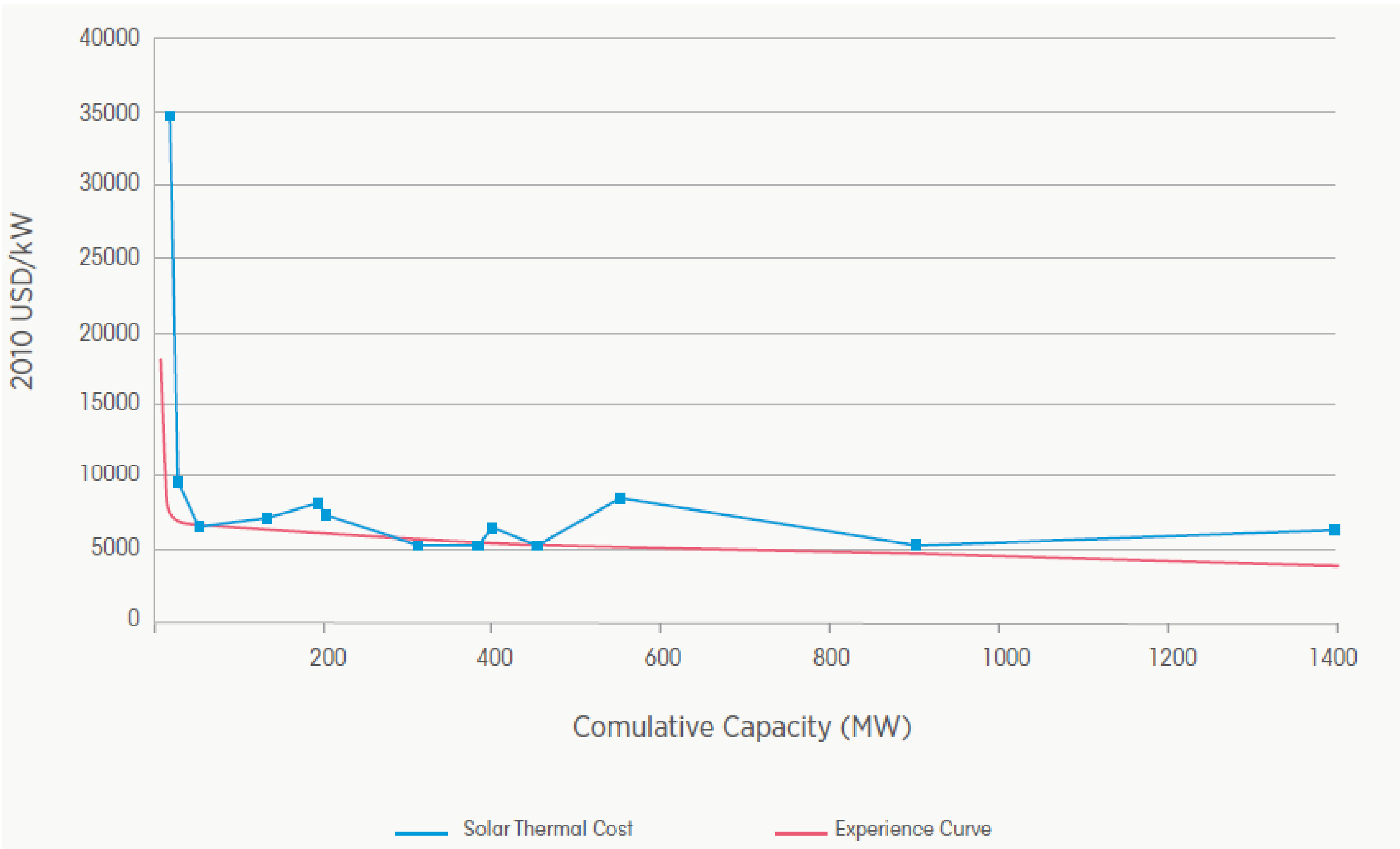


Source: IRENA, 2012

PTC versus trough – O& M cost

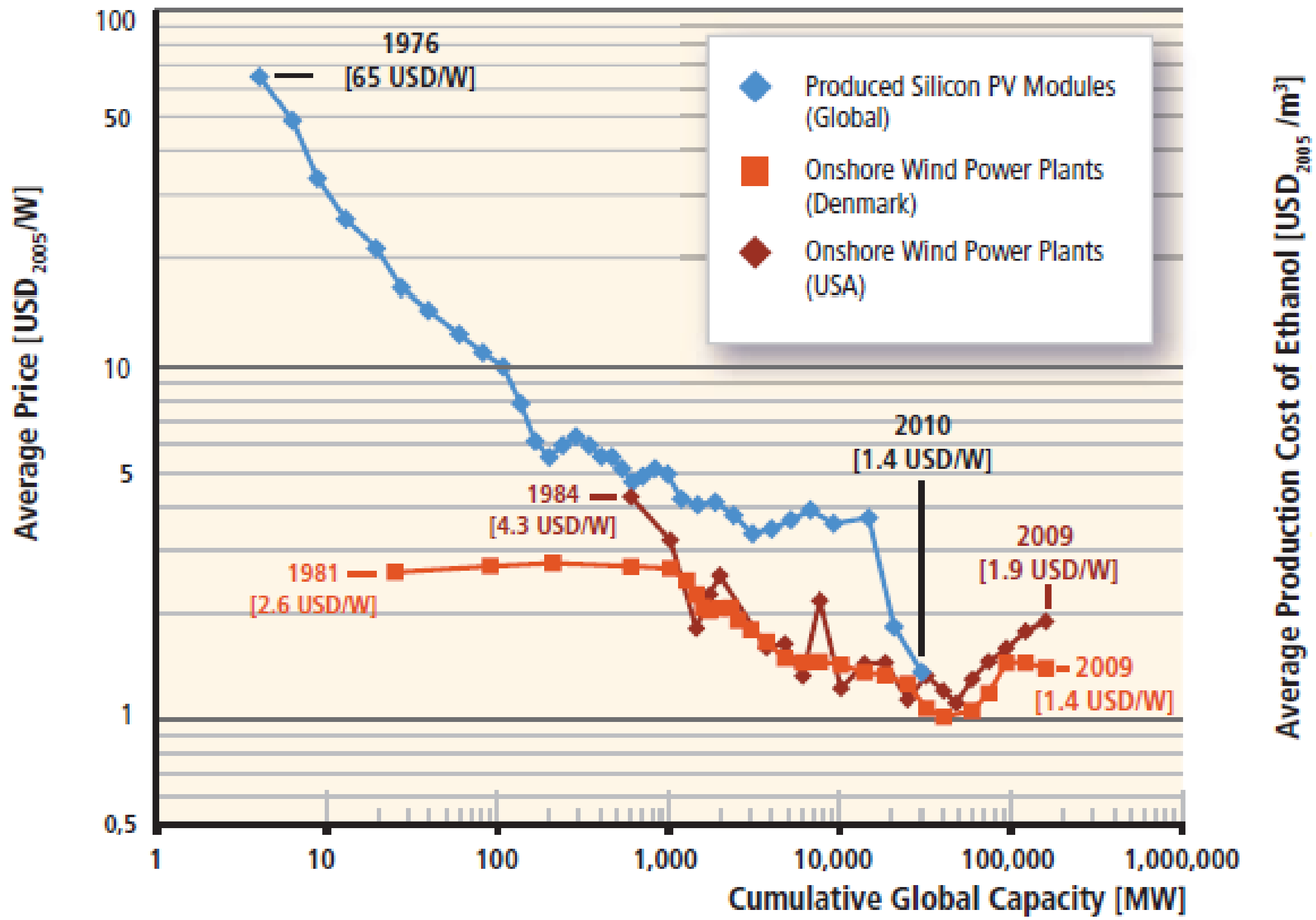
Source: IRENA, 2013

Learning Curve - CSP



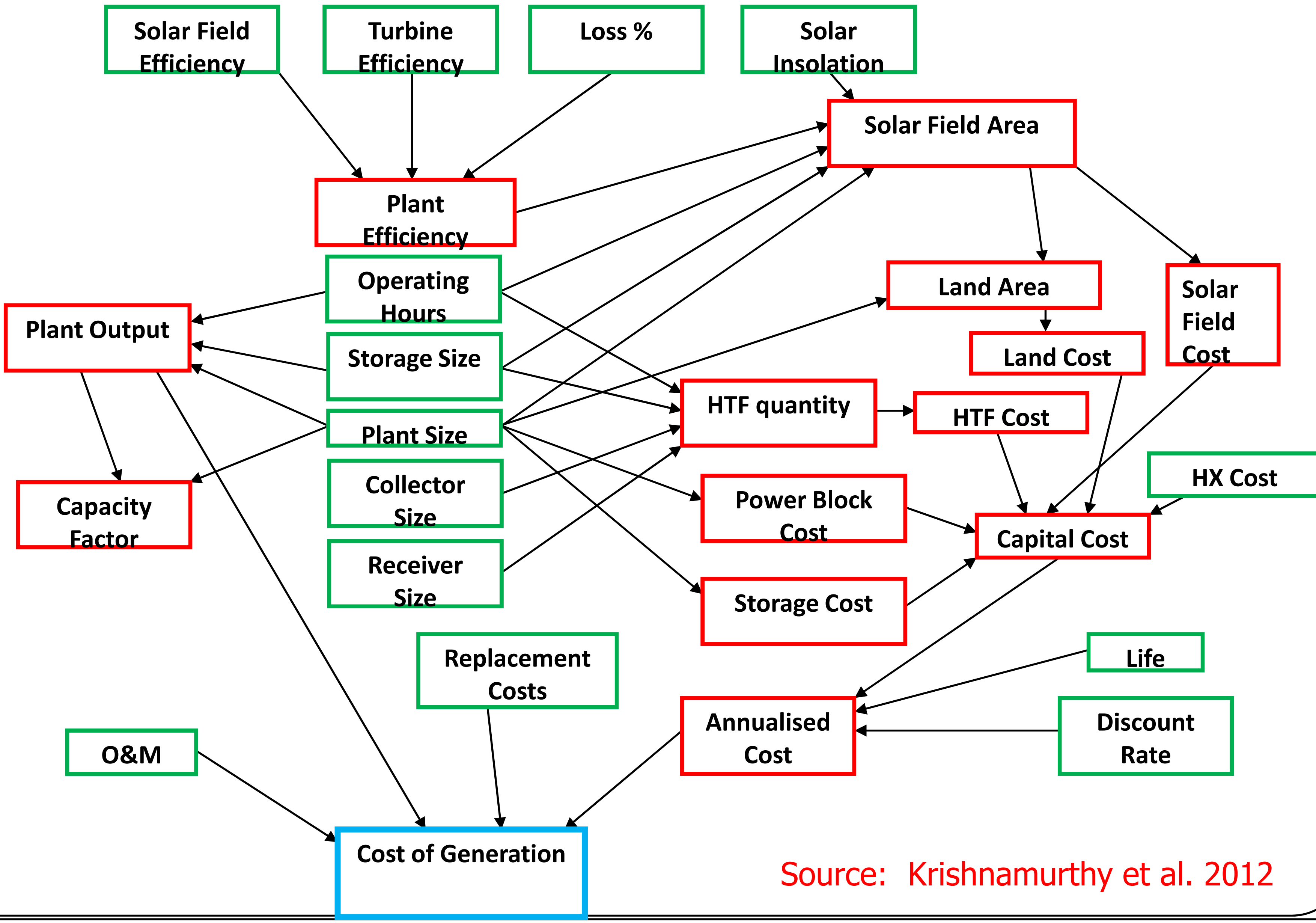
Source: IRENA, 2012

Learning Curve for Renewables

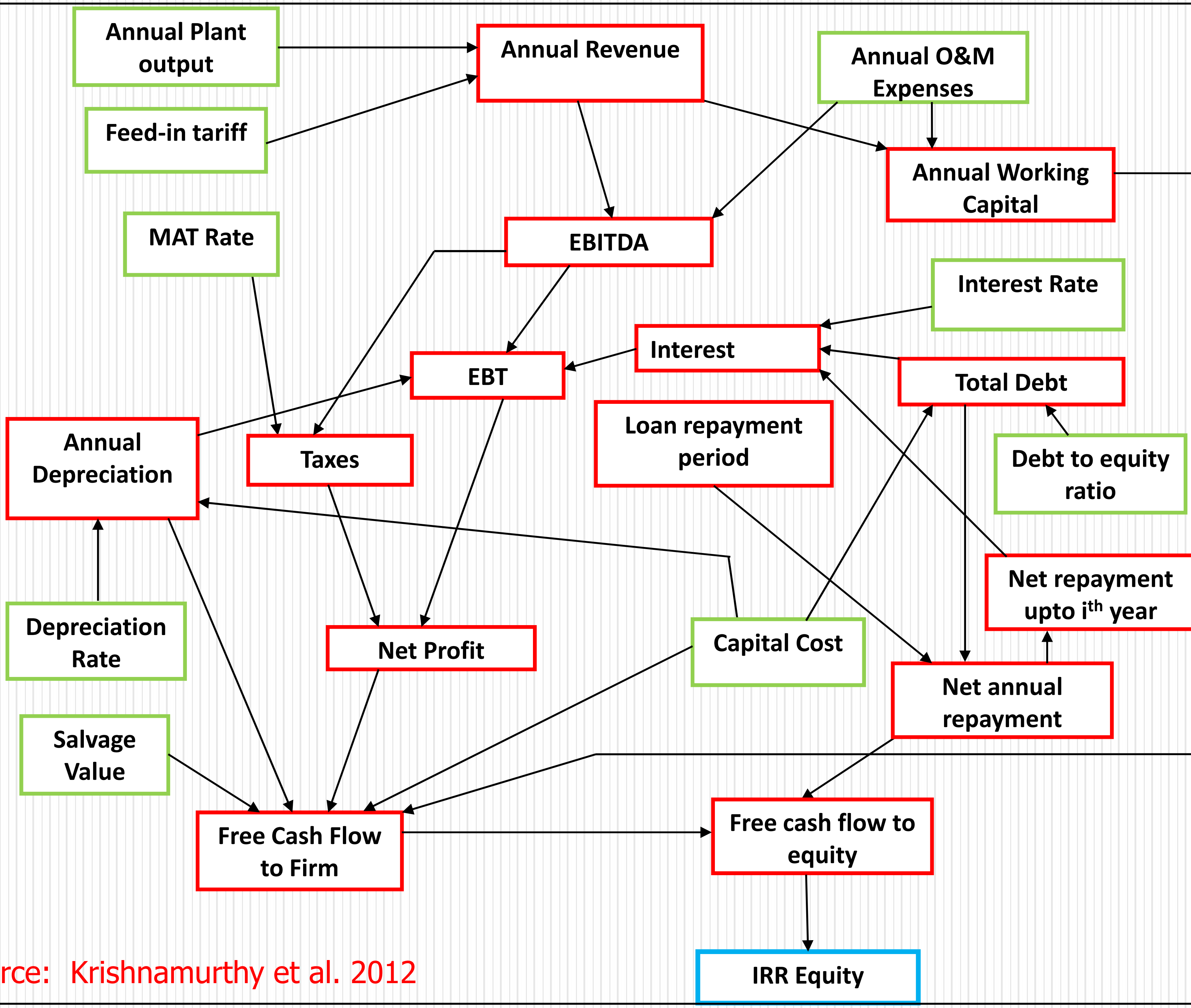


Source: IPCC, 2012

Methodology - Cost Analysis



Source: Krishnamurthy et al. 2012



Source: Krishnamurthy et al. 2012

Capital cost Break-up PTC plant

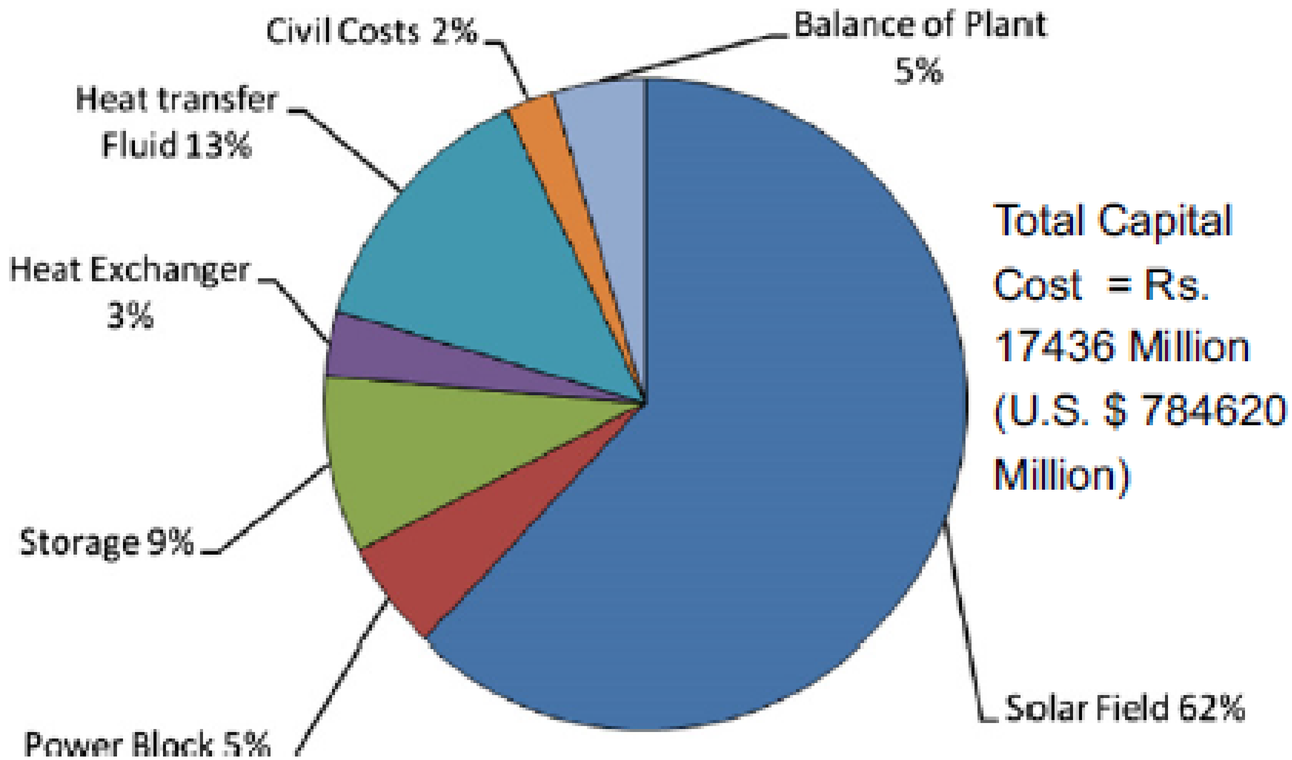
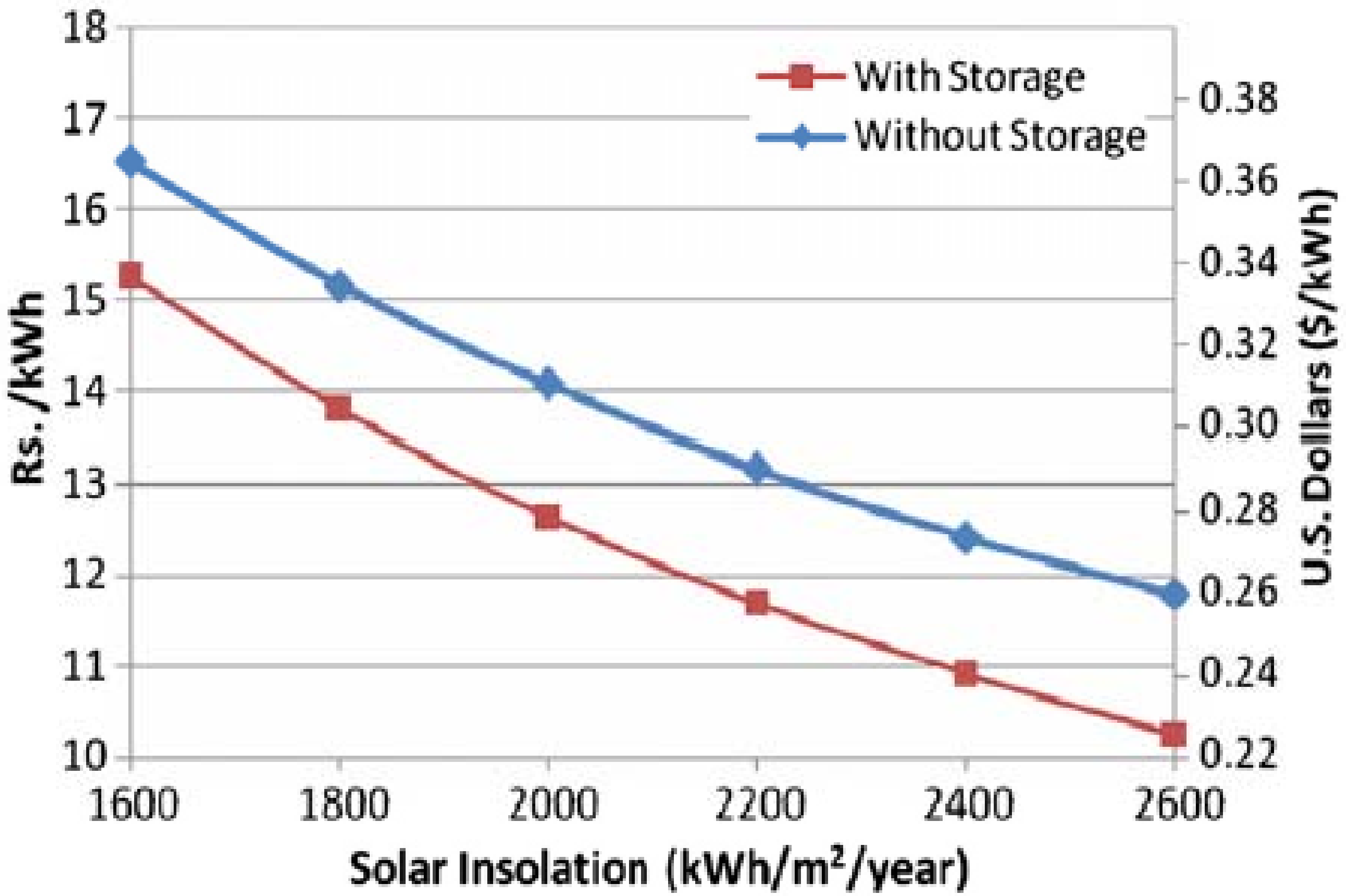


Fig. 7. Capital cost breakup for base case.

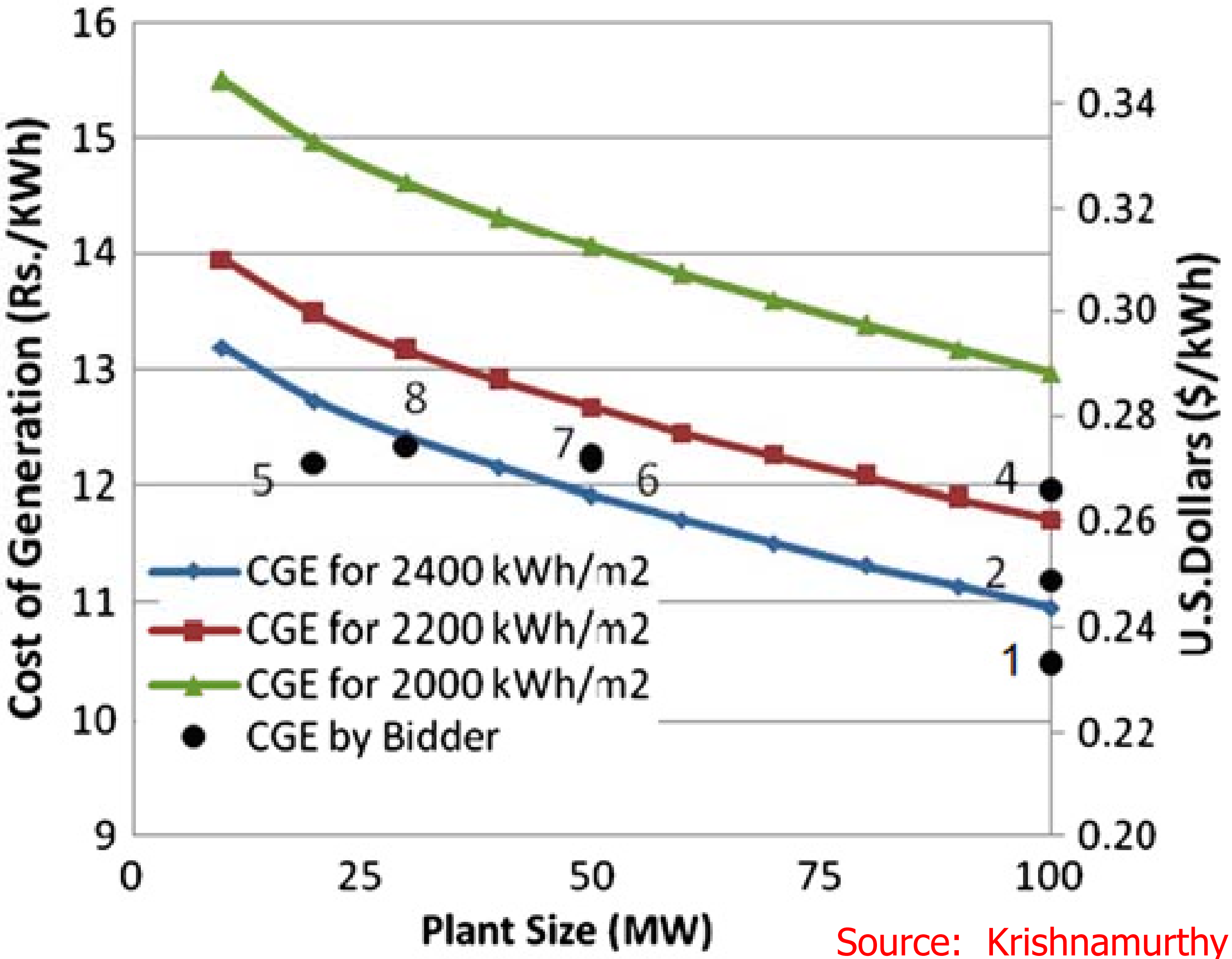
Source: Krishnamurthy et al. 2012

PTC- with and without storage



Source: Krishnamurthy et al. 2012

Effect of Plant Size



Source: Krishnamurthy et al. 2012

Summary of Results

			Plant Size (MWe)								
			10			**50**			**100**		
Solar Insolation ($kWh/m^2/year$)	**2000**	**Rs.**	12.24	15.50	17.26	10.31	13.04	14.52	10.25	12.97	14.44
		USc	26.6	33.7	37.5	22.4	28.3	31.5	22.3	28.2	31.4
	2200	**Rs.**	11.53	14.60	16.26	9.66	12.22	13.61	9.55	12.08	13.45
		USc	25.0	31.7	35.3	21.0	26.5	29.5	20.7	26.2	29.2
	2400	**Rs.**	10.94	13.85	15.43	9.12	11.54	12.85	8.96	11.33	12.62
		USc	23.7	30.1	33.5	19.8	25.1	27.9	19.5	24.6	27.4
			6	**10**	**12**	**6**	**10**	**12**	**6**	**10**	**12**
			Discount Rate (%)								

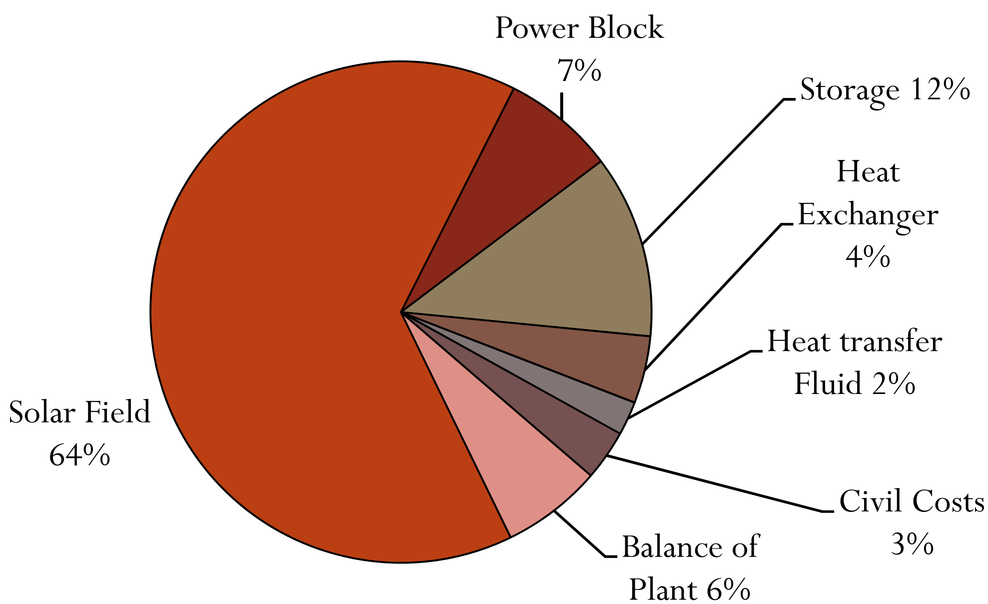
Source: Krishnamurthy, P., Mishra, S., and Banerjee, R., Energy Policy, 2012

Base Case

- 50 MWe Solar Thermal
- 7.5 Hour Thermal Storage
- Oil Loop
- Design Solar Insolation = 650 W/m^2
- Location - New Delhi
- PT and CLFR comparison

Results – PT vs CLFR

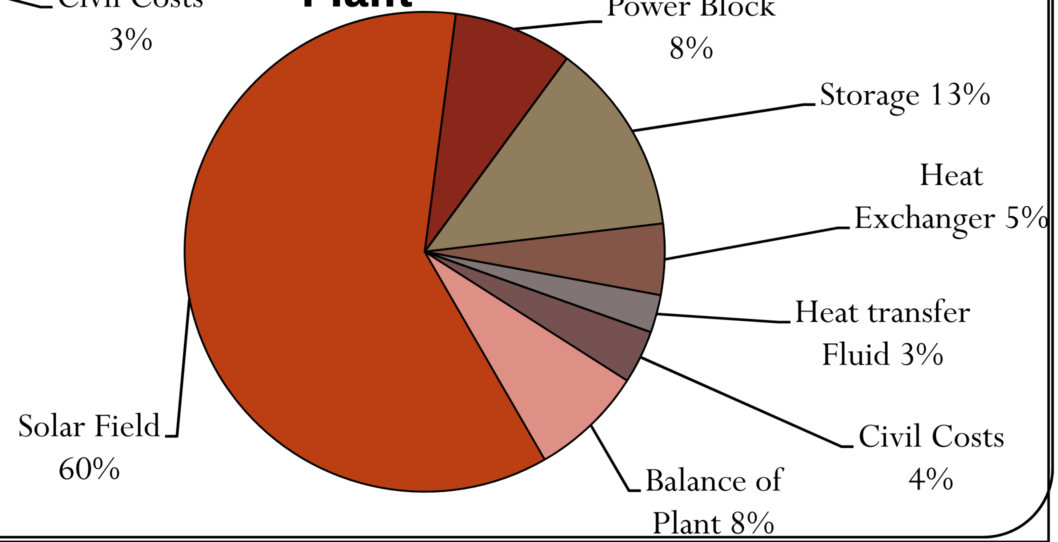
Cost Breakup – PT Power Plant



Capital Cost = Rs. 1045 Crores
Capital Cost = Rs. 209 Million / MWe
CGE = 9.69 Rs/kWh
IRR = 20%
Capacity Factor = 0.35

Capital Cost = Rs. 1164 Crores
Capital Cost = Rs. 233 Million / MWe
CGE = 10.54 Rs/kWh
IRR = 17%
Capacity Factor = 0.36

Cost Breakup – CLFR Power Plant

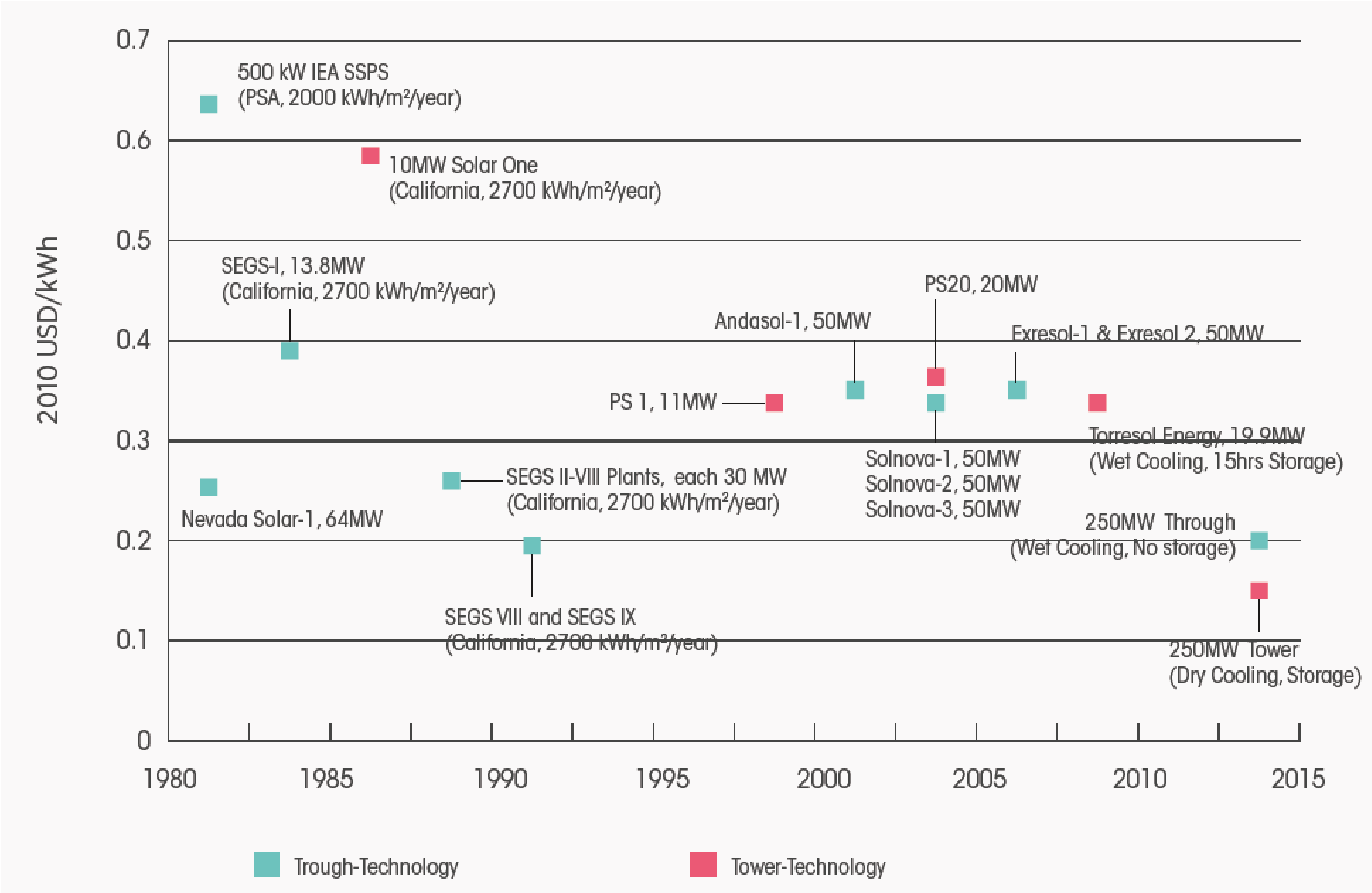


Comparison of Renewable Projects

TECHNOLOGY	CAPITAL EXPENSES (RS. '10 MILLION/MW)	OPERATING EXPENSES (RS / KWH)	TARIFF (RS./ KWH)	TYPICAL INITIAL DEBT LEVELS (% OF TOTAL CAPITAL)	EQUITY INTERNAL RATE OF RETURN (%)	COST OF DOMESTIC DEBT (%)	DEBT-EQUITY SPREAD (%)
Solar PV	7-10	0.60	7.5- 12.5	70-75%	12-15%	12 -14%	0-3%
Solar CSP	12	0.90	11-15	70-75%	14-20%	12 -14%	2-8%
Biomass Power	5.5	1.00 (excl. biomass cost)	5	60-70%	20-25%	13 -14%	7-12%
Wind	6	0.45	3.7 -5	70-75%	15-18%	11 -12%	4-7%
Small Hydro	5.5	0.60	2.2-2.6	70-75%	17-20%	11 -12%	6-9%

Source: Nelson et al, **2012**

Estimated LCOE for existing and proposed Parabolic Trough and Solar Tower CSP Plants

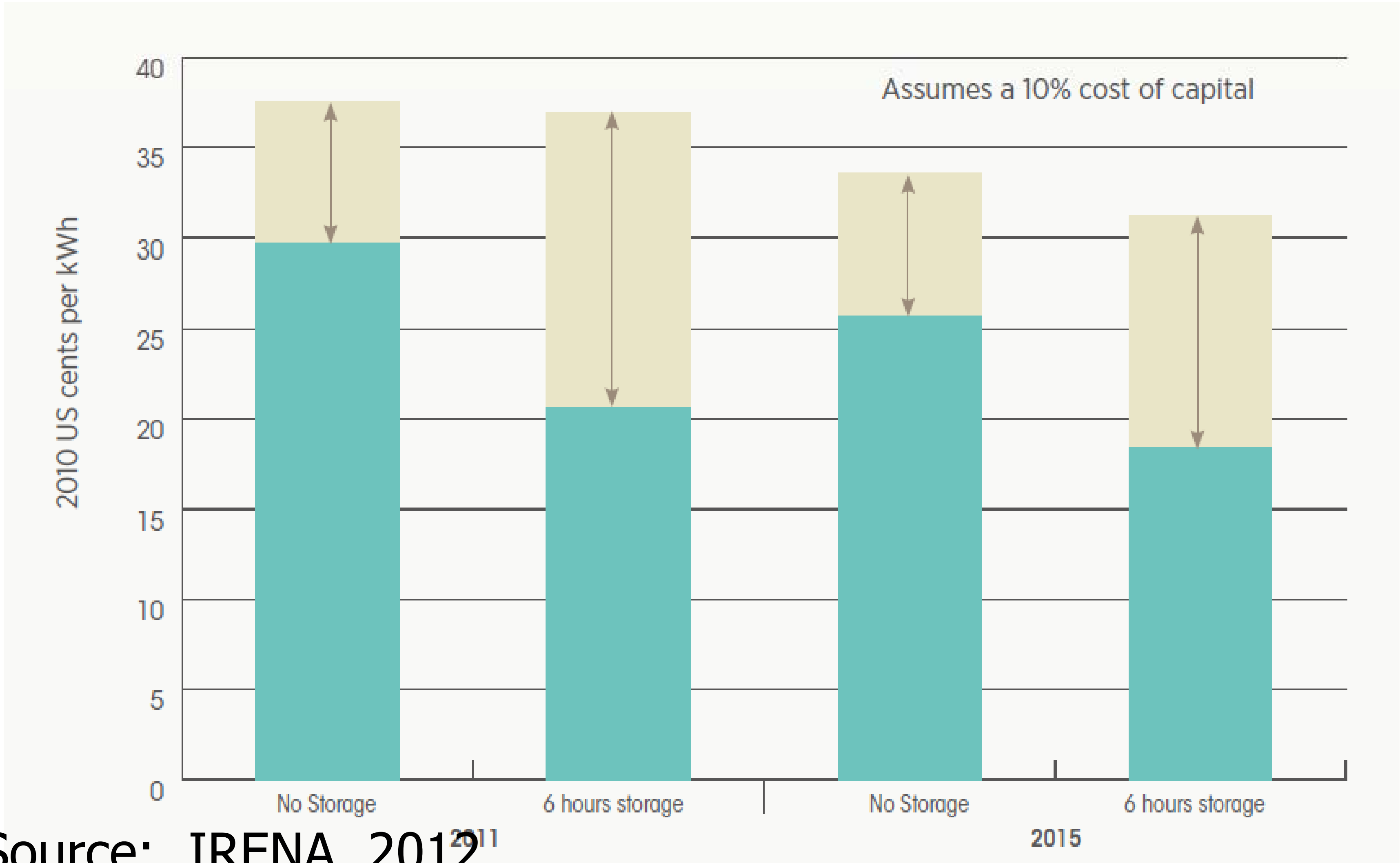


Source: IRENA, 2012

Returns on Debt and Equity

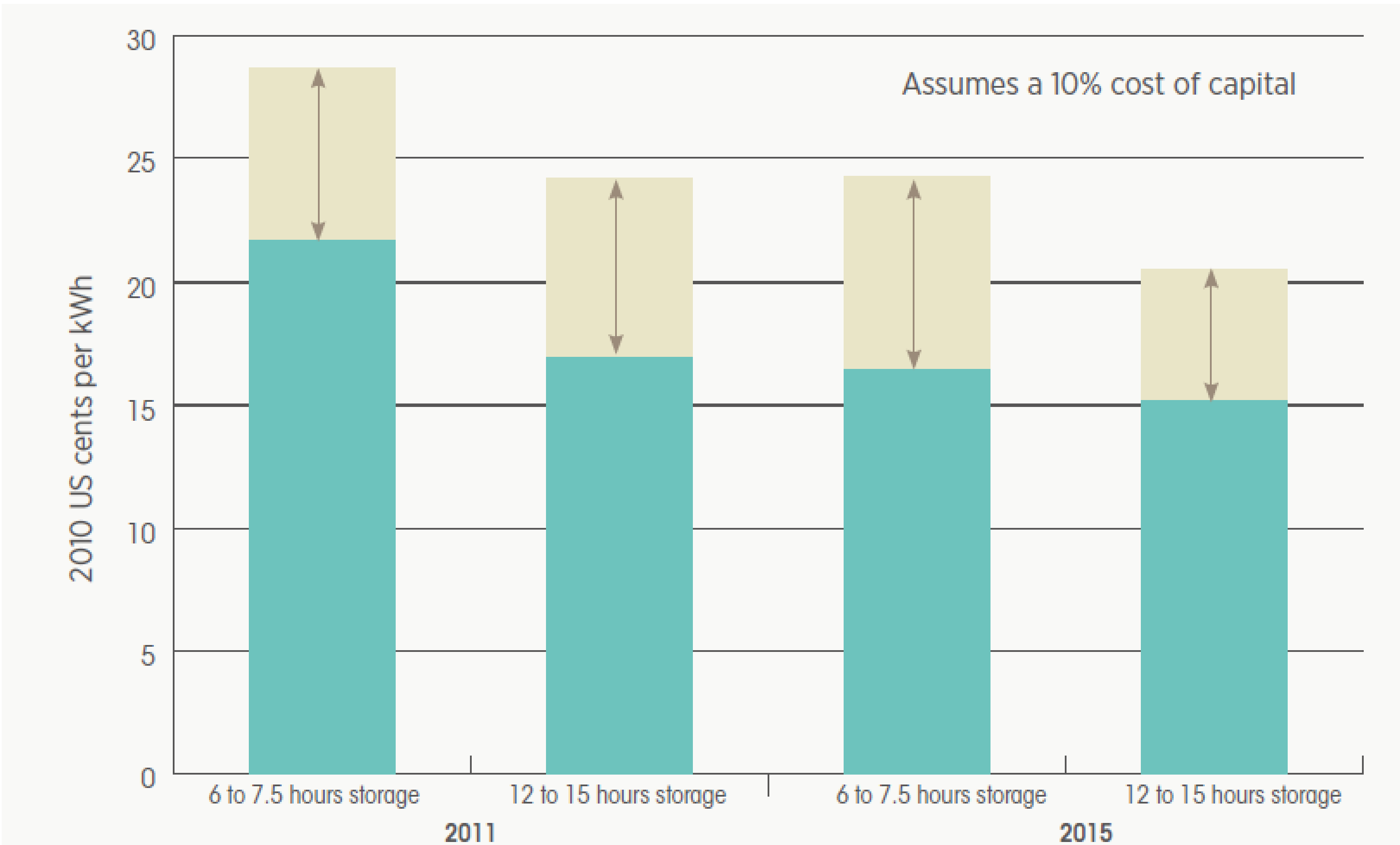
Source: Nelson et al, **2012**

CGE- CSP



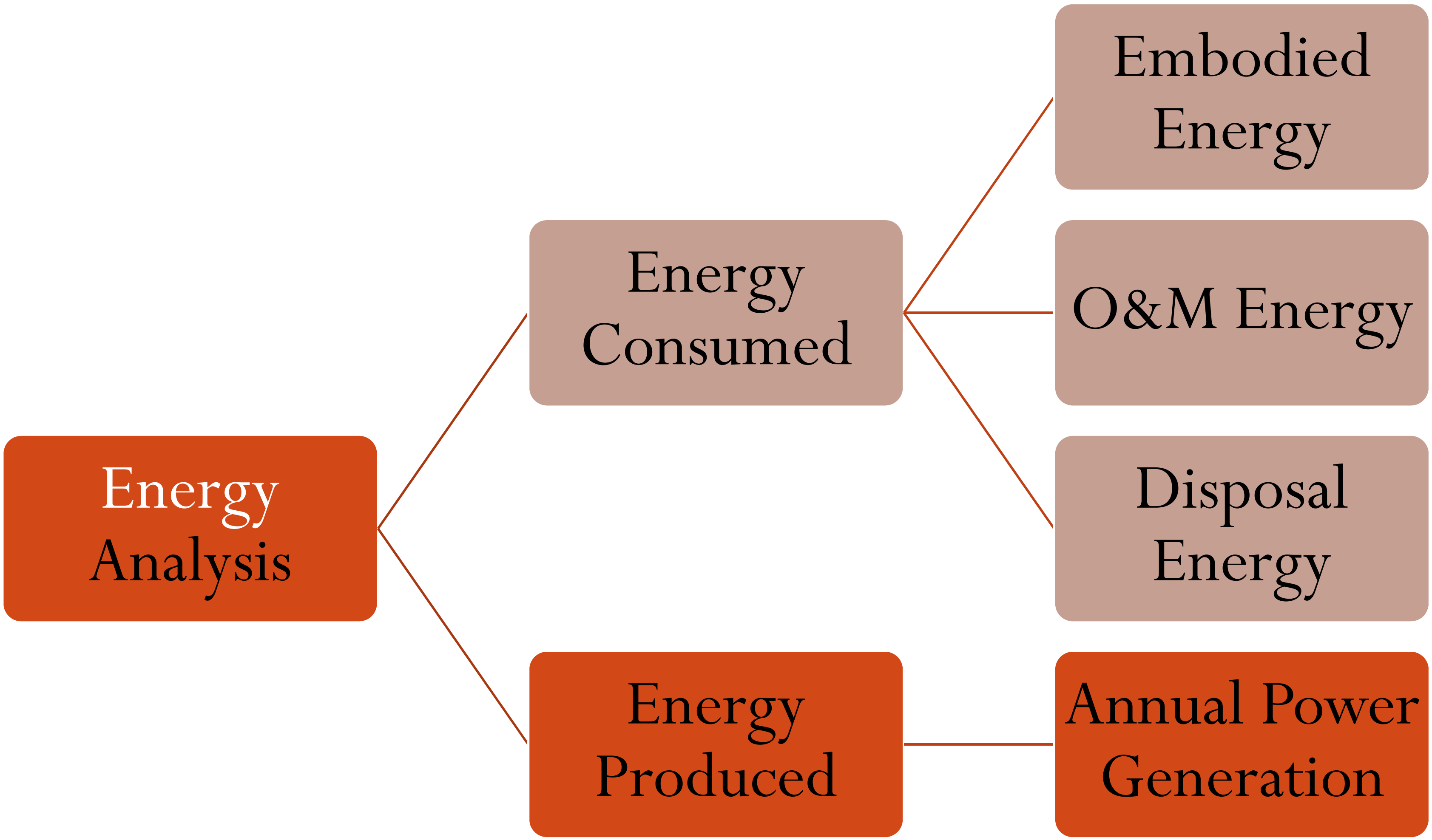
Source: IRENA, 2012

CGE- Solar Tower

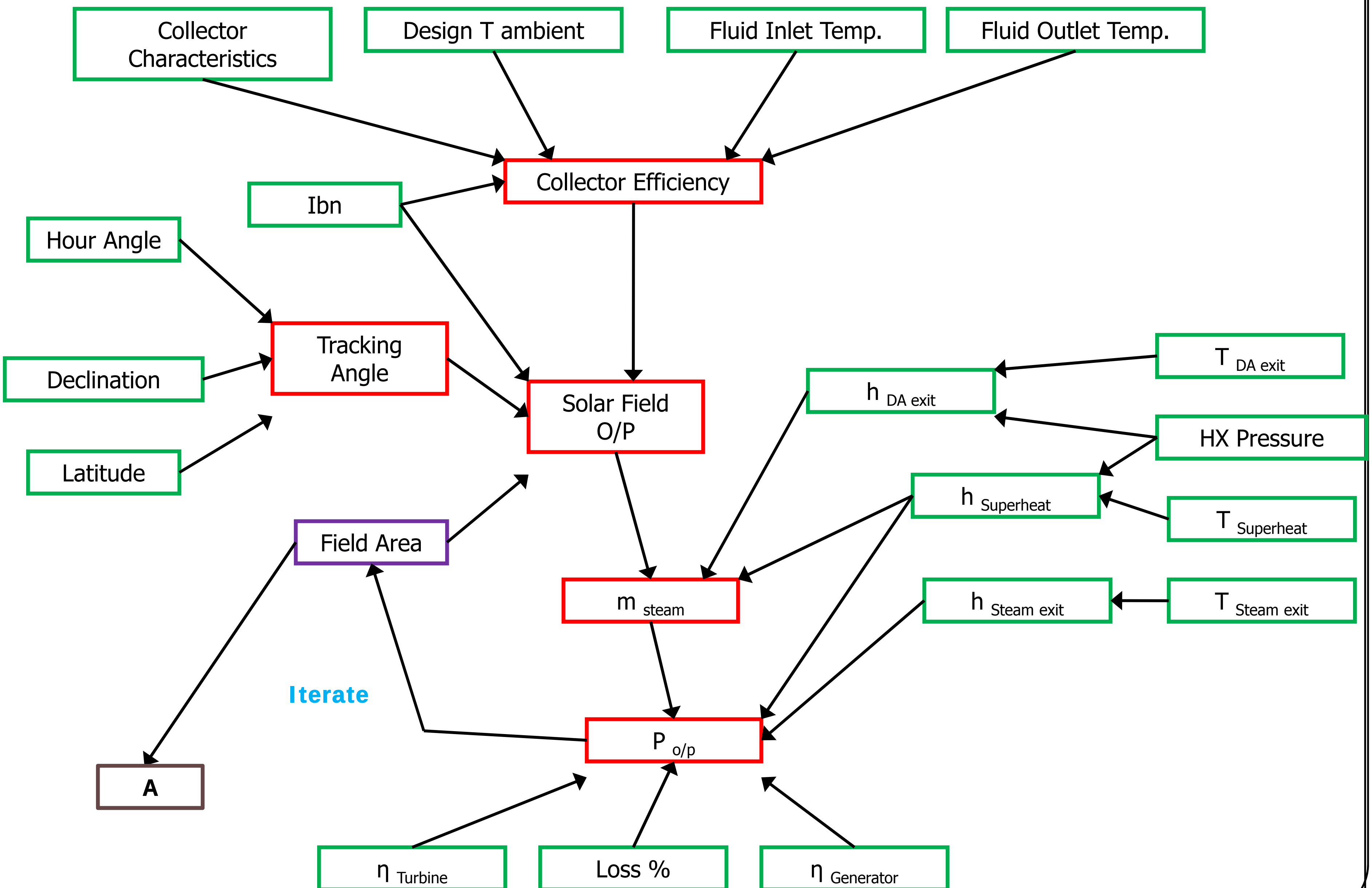


Source: IRENA, 2012

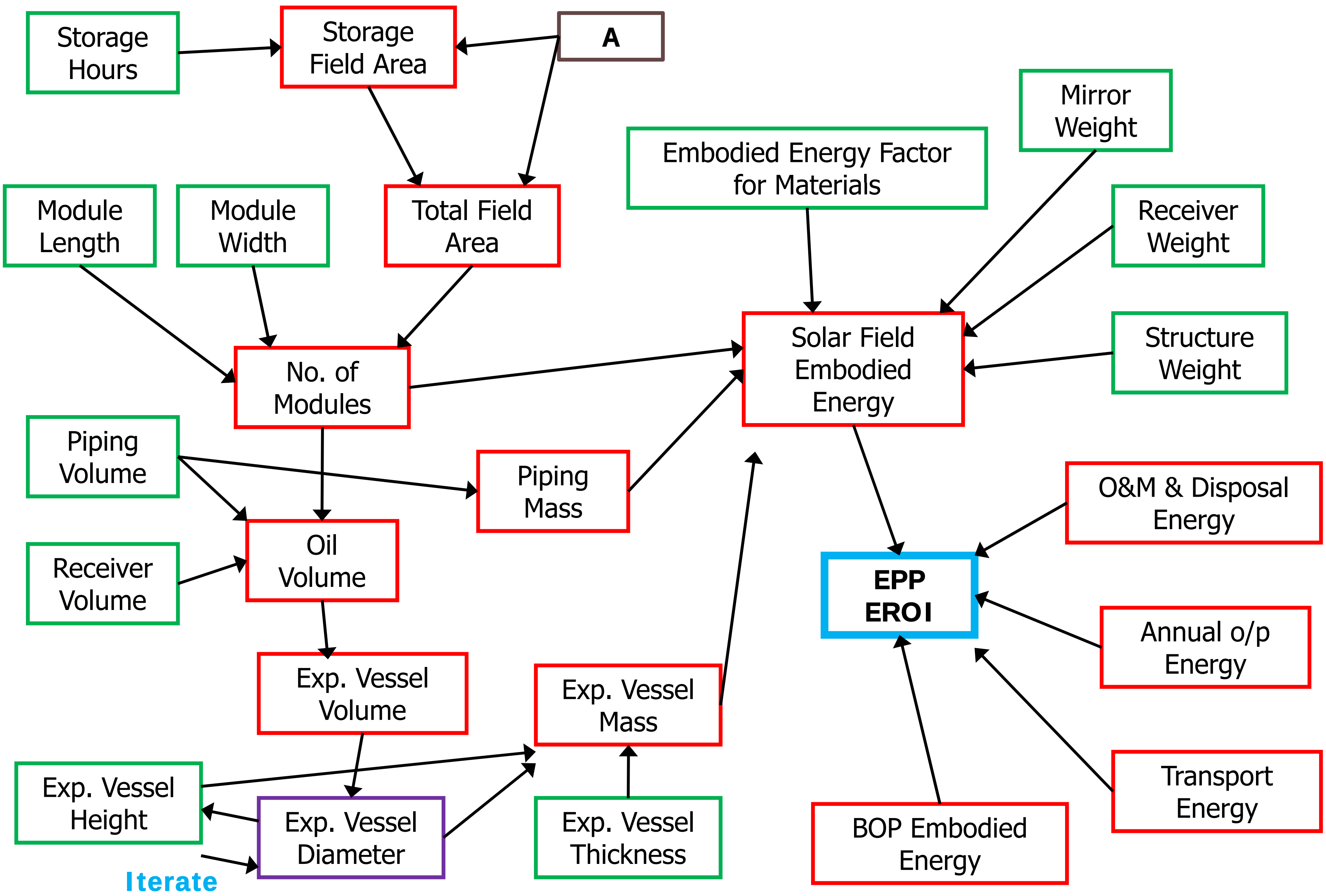
Energy Analysis



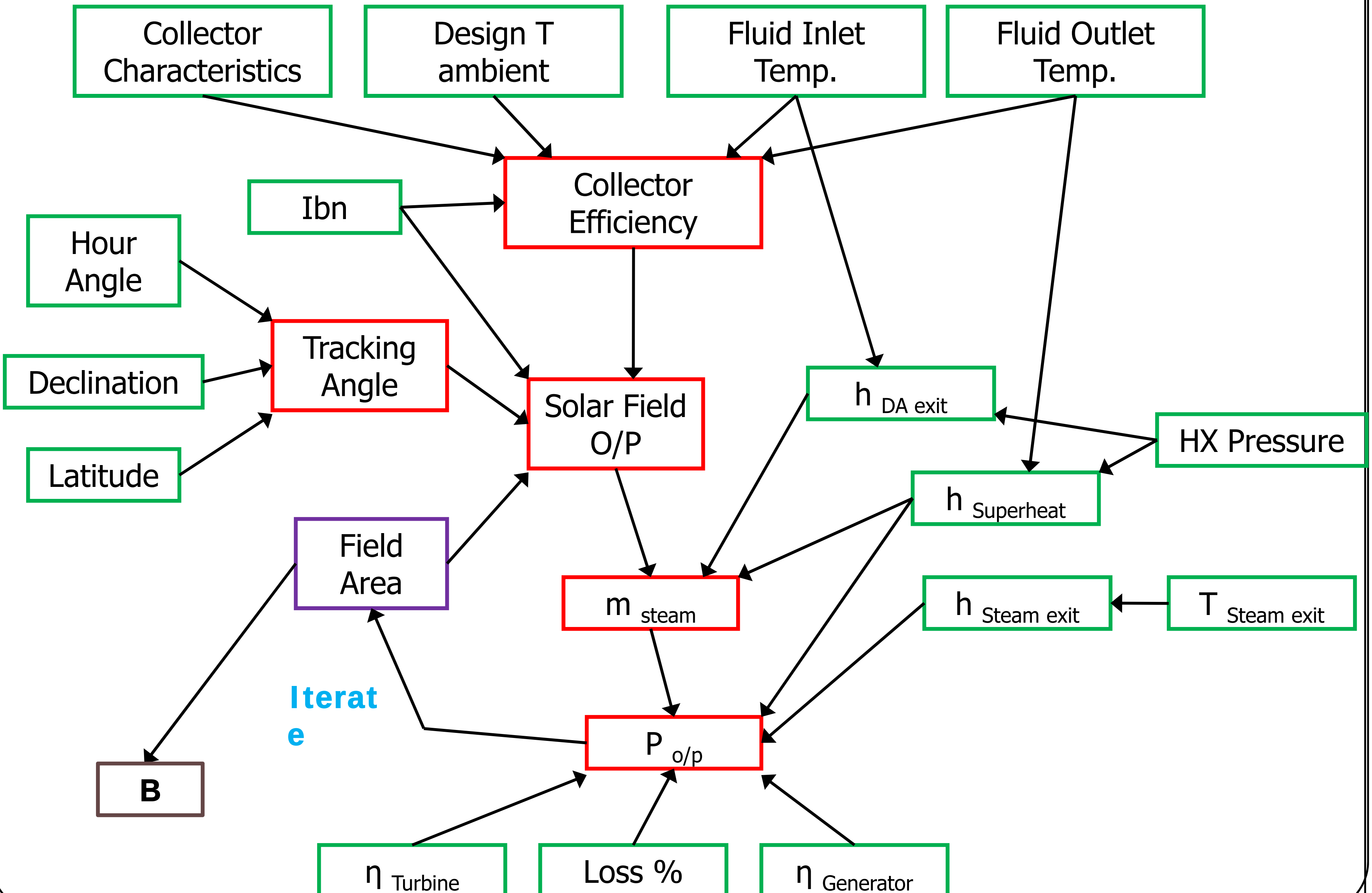
Methodology – Oil Loop



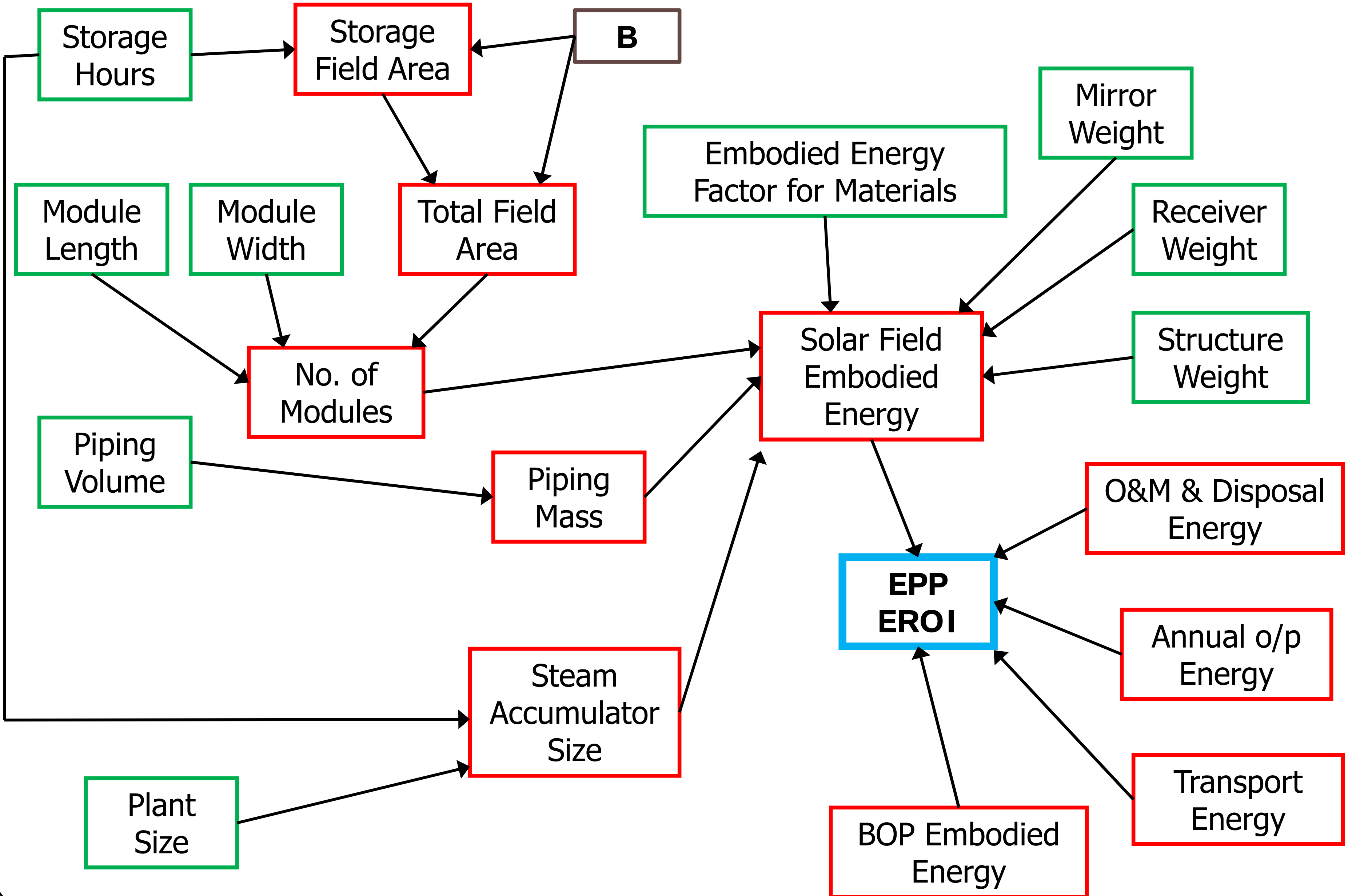
Methodology – Oil Loop



Methodology – Direct Steam



Methodology – Direct Steam



Assumptions – Energy Analysis

Factor	Value	Unit	Remarks
Plant Size	5 - 100	MWe	Range
Turbine Efficiency	50	%	Assumed Constant
Generator Efficiency	98	%	Assumed Constant
Piping and Heat loss	25	%	For Oil Loop Configuration
	20	%	For Direct Steam Configuration
Life of Plant	25	Years	
Disposal Energy	5	%	Of Total Embodied Energy
Auxiliary Consumption	10	%	Of Annual Power Generation
T_{amb}	25	^oC	
Collector Transport distance	200	km	By truck average

Material Use – Solar Collectors

Parabolic Trough – Per Module(69 m²)

Component	Weight/ Area	Unit	Material
Glass Mirrors	76.6	m2	Float Glass
HCE	8.6	kg	Borosilicate Glass
	39.4	kg	Steel
Torque Box	597	kg	Steel
End Plate	186	kg	Steel
Cantilever Arms	384	kg	Steel
HCE Supports	113	kg	Steel
Torque Transfer	32	kg	Steel

CLFR – Per MWe (@650 W/m²)

Component	Weight/ Area	Unit	Material
Steel	44000	kg	Steel
Glass	12545	m2	Float Glass
Concrete	64	m3	Concrete

BOP Material Use – Oil Loop

Material	kg/MWe
Aluminum	255
Chromium	122
Concrete	74257
Copper	454
Manganese	112
Molybdenum	42
Nickel	10
Steel	39681
Stainless Steel	612
Vanadium	4

BOP Material Use – Direct Steam

Component	Material	MJ/MWe
Foundation	Concrete	400000
	Steel	700000
TG		649333
Boiler		2246667
Cooling Tower		151333
De-Aerator		576000
Steam Seal Heater		138667
Condenser		126667
Transformer	Silica	12240000
	Steel	252000
	Copper	134400

Summing Up

- Solar Thermal – Sustainable from energy input
- EPP = 3 to 5 years
- Effect of variation in parameters
- Material variation
- Framework for sustainability analysis
- Limited experience in power plant and solar field,Sub-critical base of researchers
- Not much evidence of cost reduction
- Need for public domain performance data
- Most collaborations – 'turnkey plants' –no focus on indigenisation
- CSP – significant potential for cost reduction

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Thank you