Distributed Solar Power for India: Suitability and Challenges

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Growing Energy Aspirations of India

- Energy Policy Objectives:
  - Increase generation ~ 3 times by 2020
  - Energy access to all
  - Reduce CO_2 intensity to GDP by 20-25%

- How can we achieve these often conflicting objectives?

Energy Resource Crunch

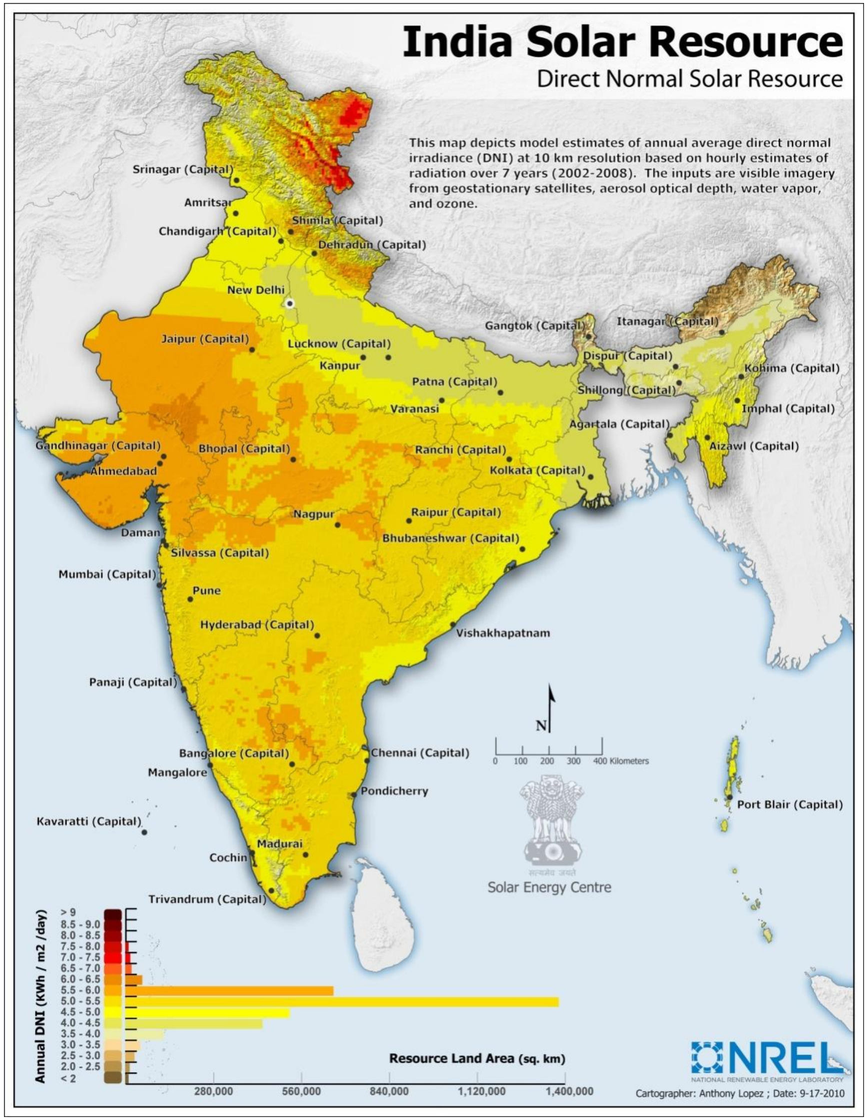
Source	Reserves	Longevity	Comments
Coal	109,798 MT (proven)	~ 50 years	High ash content and low calorific value. Production unable to meet demand. Imports growing
Oil	757 MT	~ 5 – 10 years	Domestic production stagnated
Gas	1241 BCM	~ 20 years	Priority for fertilizer sector
Hydro	148 GW	NA	Ecological concerns Most of potential is in North Eastern parts
Nuclear	70,000 ton U	40 years with Uranium	

Shortage of energy resources

Opportunity for solar & wind

Source : BP statistical review report, NHPC,NTPC

Opportunity for Solar Power



Solar Resource in India

- Approximately 650,000 km^2 receives DNI > 5.5 kWh/m^2/day
- Even 1% of this ~ 80,000 MW

Easier said than done!

* Ref: Waste Land Atlas of India, Ministry of Rural

Jawaharlal Nehru National Solar Mission (JNNSM)

Part of National Action Plan for Climate Change (2010)

Targets: (Deployment + Cost)

- Grid Connected
  - 20,000 MW by 2022 (Solar PV & Solar Thermal)
  - Tariffs proposed ~Rs. 15 per kWh

- Off-grid
  - 2000 MW by 2022
  - 15 million sq. meters solar thermal collector.

Progress under Solar Mission

Very positive response from industry

Agreements signed for 950 MW

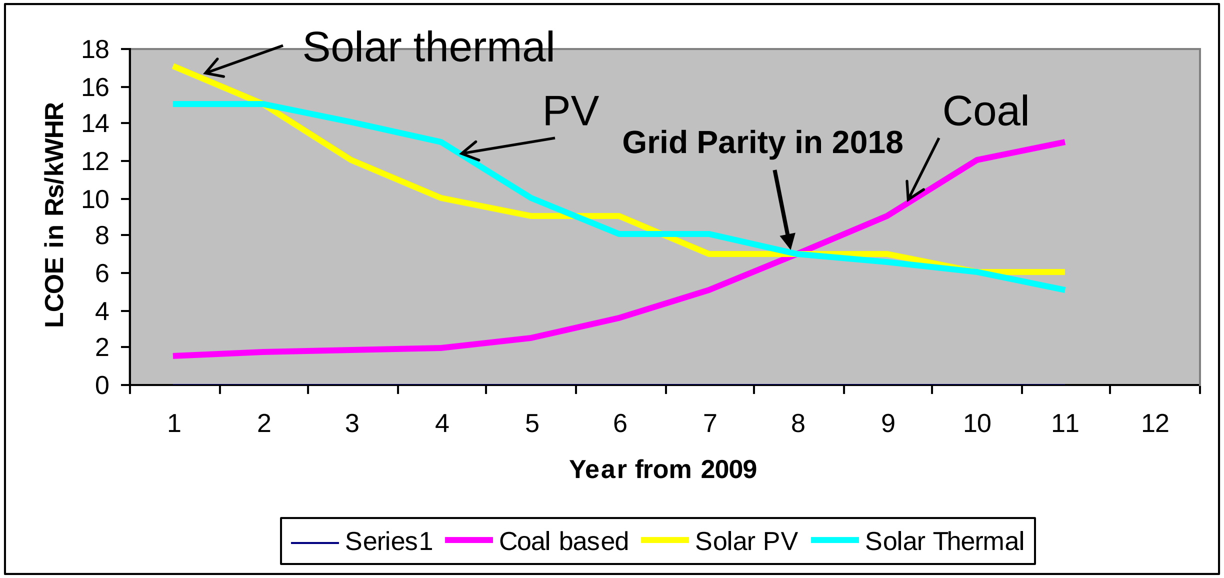
- 480 MW of PV and 470 MW of Solar Thermal
- 140 MW of PV plants commissioned in Rajasthan

Tariffs

- Bidding by solar developers
- Average tariff for PV ~ Rs. 8 per kWh (Half of tariff proposed by regulator!)

Most new projects proposed are in PV!
(weaker response for CSP)

Challenges in Solar Energy Deployment: Grid Parity – a good target to set our goals



Levelized cost of electricity (LCOE)

	Fossil (coal)	Solar
Energy Intensity	4000 kCal /kg	1000 W /m2
Efficiency	35-45%	10-40%
Capital cost	6 Cr /MWe	12-20 Cr /MWe
LCOE	2- 3 Rs /kWhr	9-18 Rs / kWhr

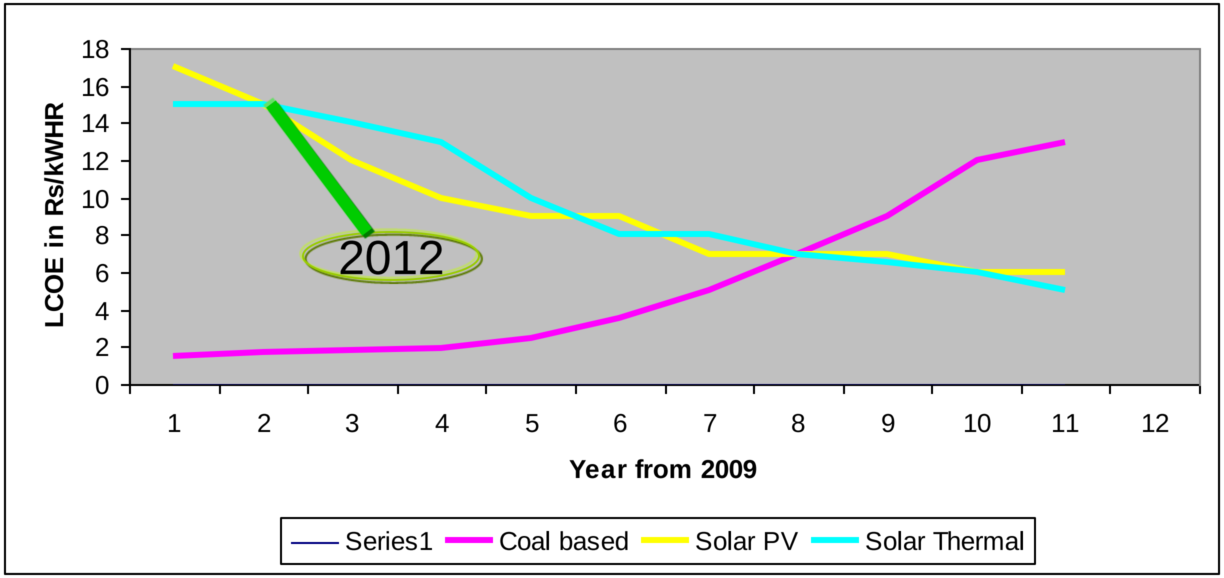
Energy density Is approx 40 times

Courtesy: Thermax

Grid Parity: Ultimate Panacea

Capital cost of Solar PV plummeted to Rs. 10 crores/MW!!!

LCOE has reduced from 34 $cents to 19 $ cents



Steep decrease in PV – almost reaching the peak grid parity

How did this non linearity take place?

Is it due to Technological break through?

Self reliance in energy?

Fossil fuel / nuclear: *fuel source, environment* √

Renewable: *energy source* ✗ *environment (?)*

technology √

materials √

manufacturing √

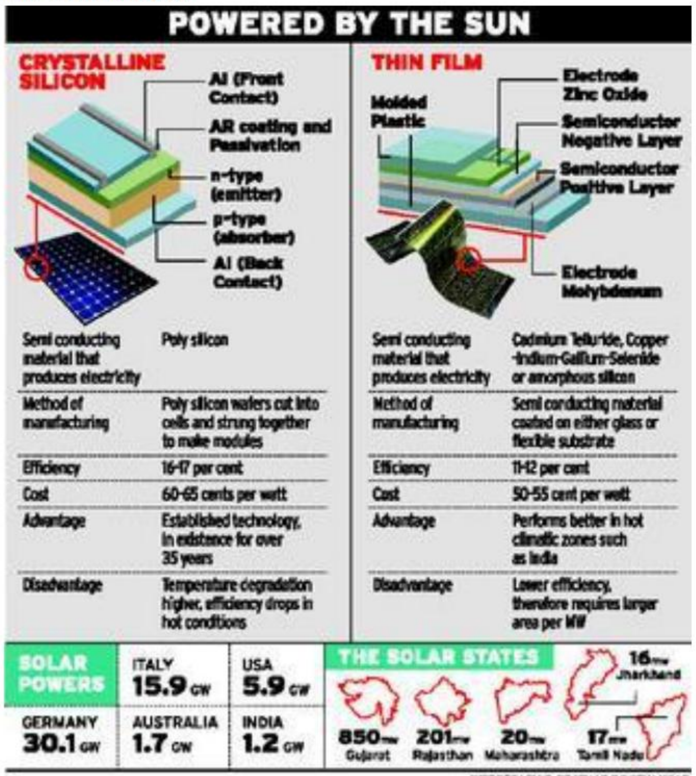
Indigenous manufacturing vs. imports: c-Si – Import vs. Domestic Costs

Components	Indian Costs~ (Rs/Wp)	Chinese Costs (Rs/Wp)	US Costs (Rs/Wp)	Indian Indigenous Manufactured Price* (Rs/Wp)
c-Si Cell	**23.56**^	**11.50**	12.02	--
Glass	2.03	2.81	3.75	
Interconnect Ribbon	1.09^	0.05	1.37	--
EVA	1.26^	2.73	2.73	1.37 – 1.64
Backsheet	1.71^	1.56	1.56	2.05 – 2.74
Al Frame	2.08	2.91	3.50	
Sealant	0.07	0.00	0.11	
Junction Box	1.46	0.98	0.98	
O&M[#]	5	4.58	8.64	
Others[@]	3.74	3.66	6.47	
Total	**42**	**30.78**	**41.12**	

THE HINDU

The solar war heats up

M Ramesh   Feb 11, 2013



- *US complaining against India in the WTO*
- *Issue over the Indian governments domestic content requirement for solar modules*
- *First phase of NSM: for crystalline silicon modules. "The NSM projects are importing thin films (mainly from the U.S.)"*
- *Second phase: extended to Thin Film based modules*
- *This domestic content requirement was only for projects awarded under the NSM*
- *"Notably, of the 1,200 MW of capacity in India today, about 850 MW has come under Gujarat's programme" by "importing crystalline silicon modules (mainly from China) "*

PV: Highly import dependent

SUSTAINABILITY

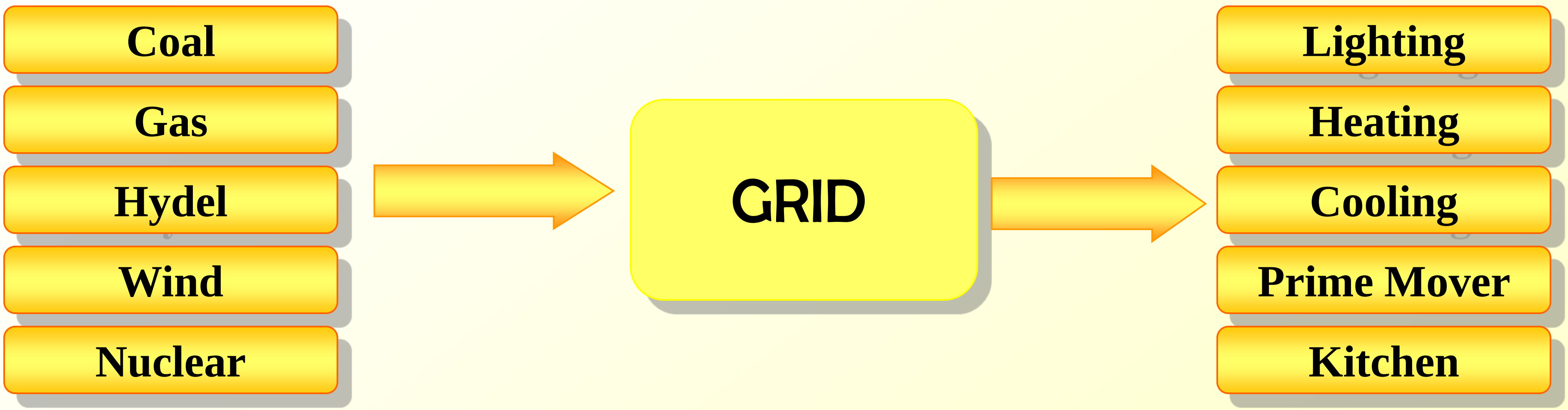
- **Building India centric technologies ?**
- **Build what is needed**

  Affordability – Reliability – Sustainability are fully met.
- **Make India *Global Leader* in complete Solar value chain (including manufacturing)**
- **Innovation**

requires a major national effort – need for active involvement of the industry, academia and government

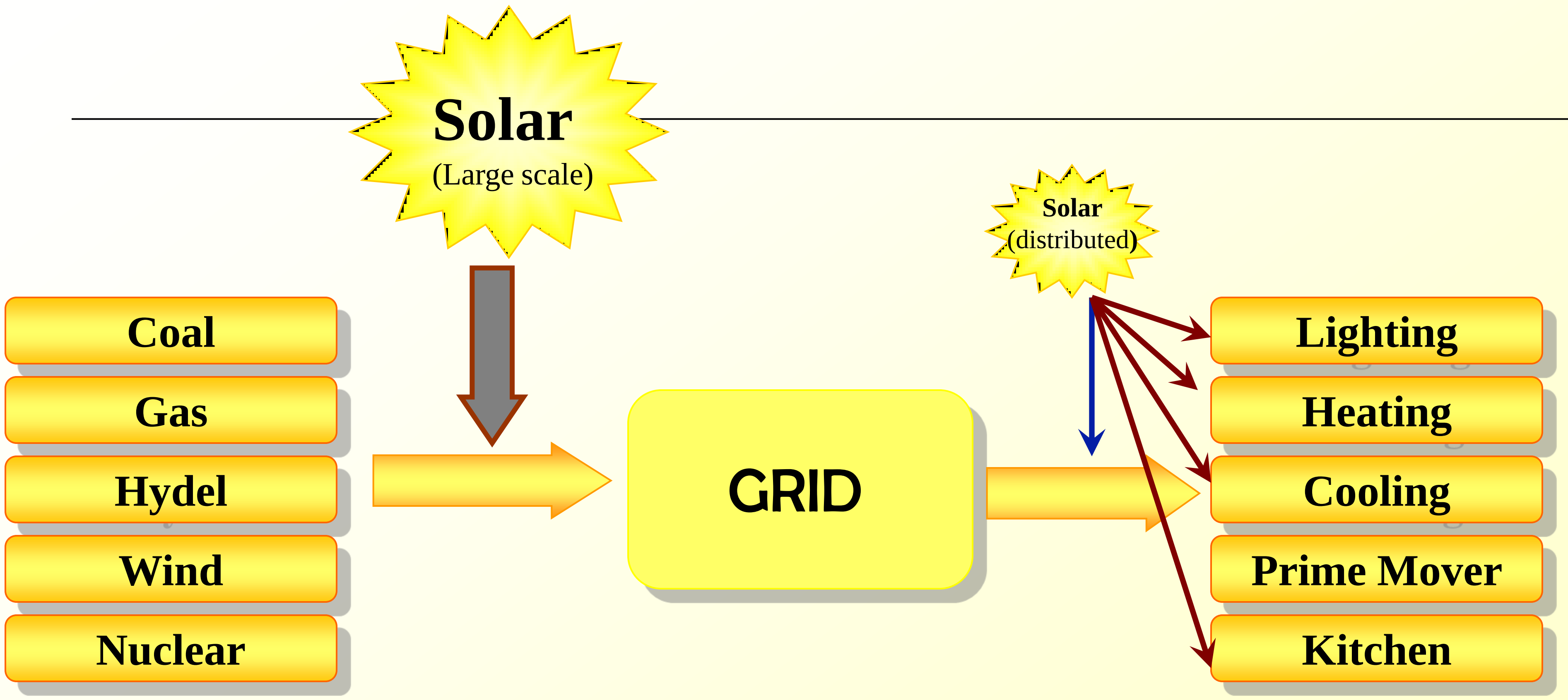
Potential for Solar Thermal ?

Solar in Central and Distributed mode….



Courtesy: Thermax

Solar in Central and Distributed mode….



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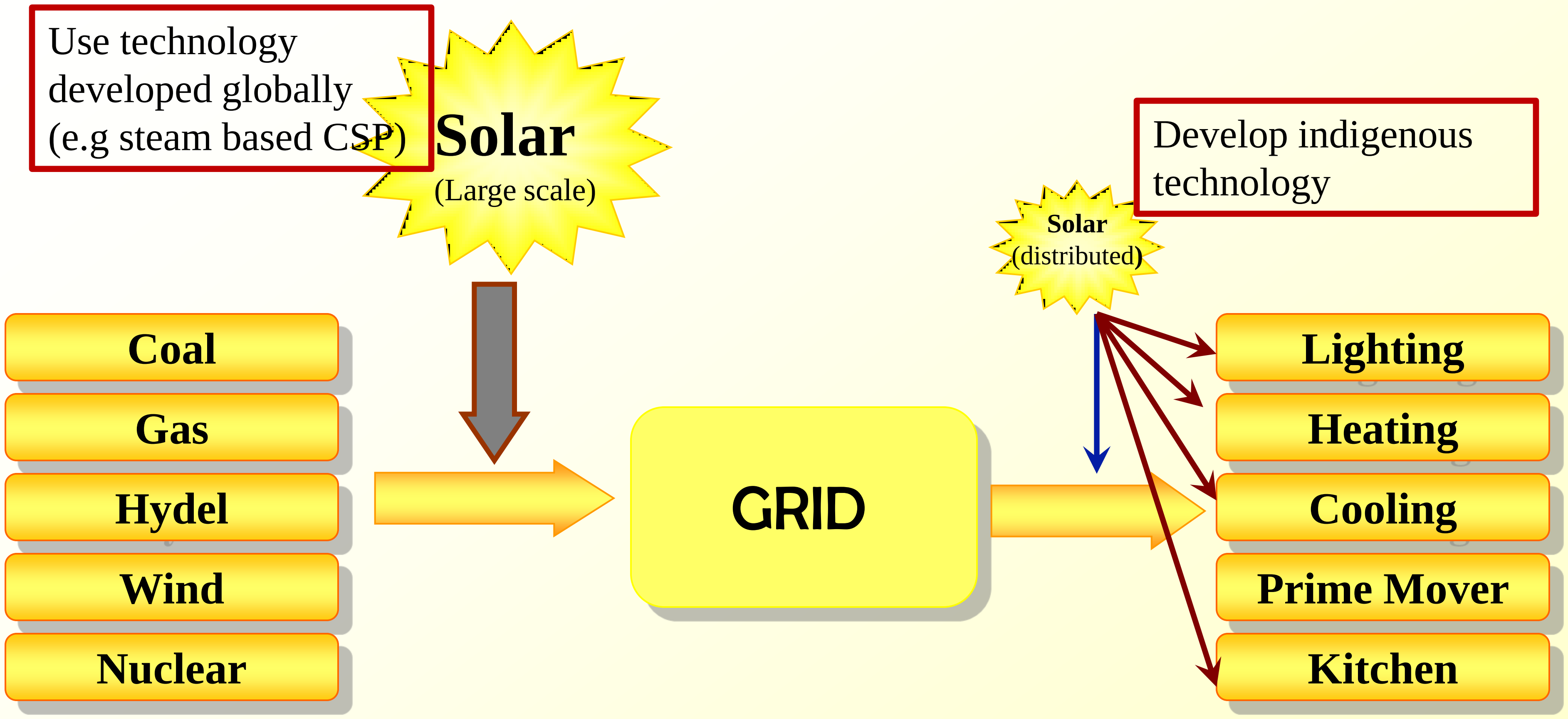
Solar in Central and Distributed mode….



Courtesy: Thermax

Small scale (distributed) solar thermal plants: *Opportunities and challenges*

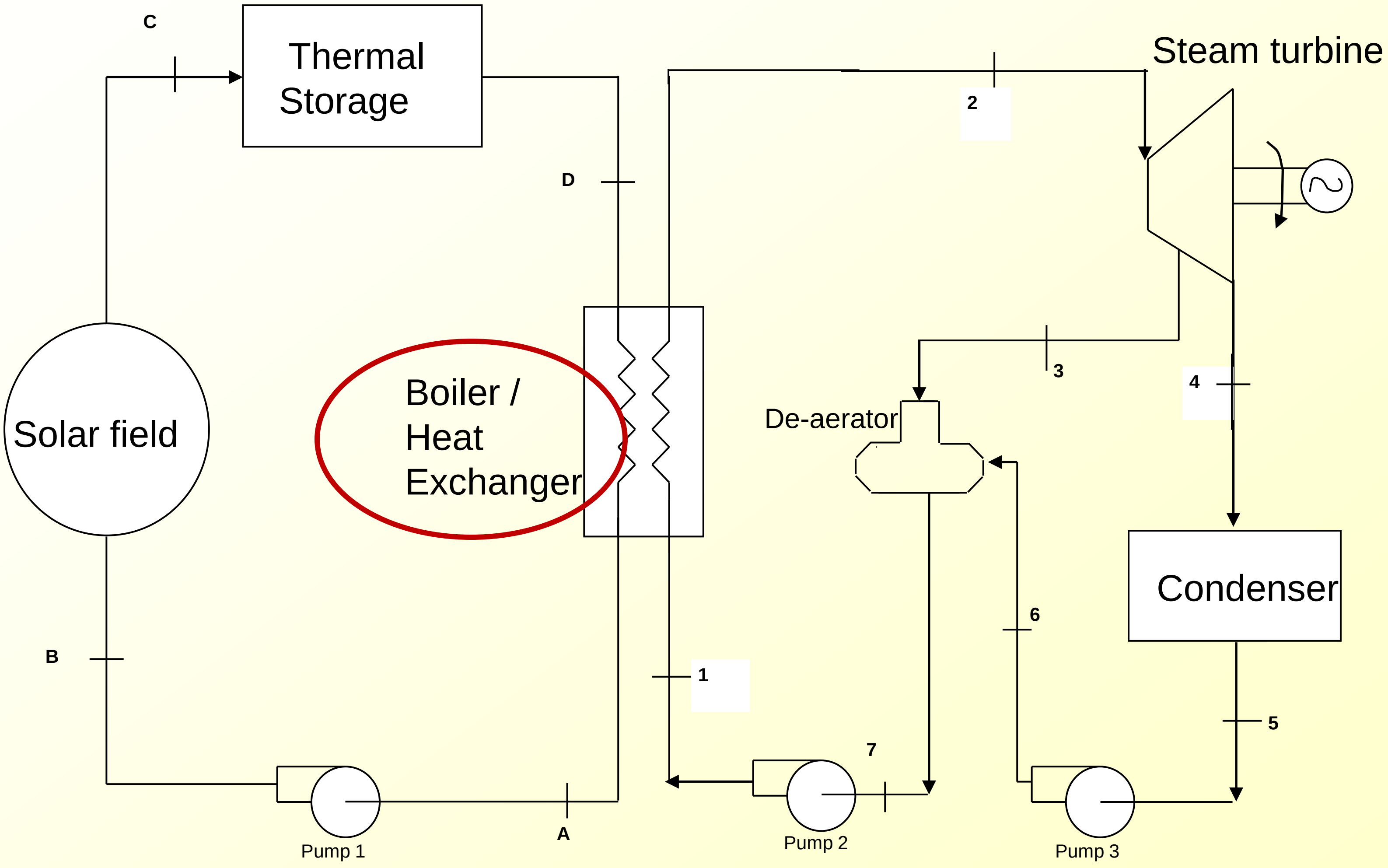
What is concentrating solar power (CSP)?

- Concentrated energy → heat up a fluid → produce steam → activate turbines → electricity
- PV : Directly converts sunlight into electricity

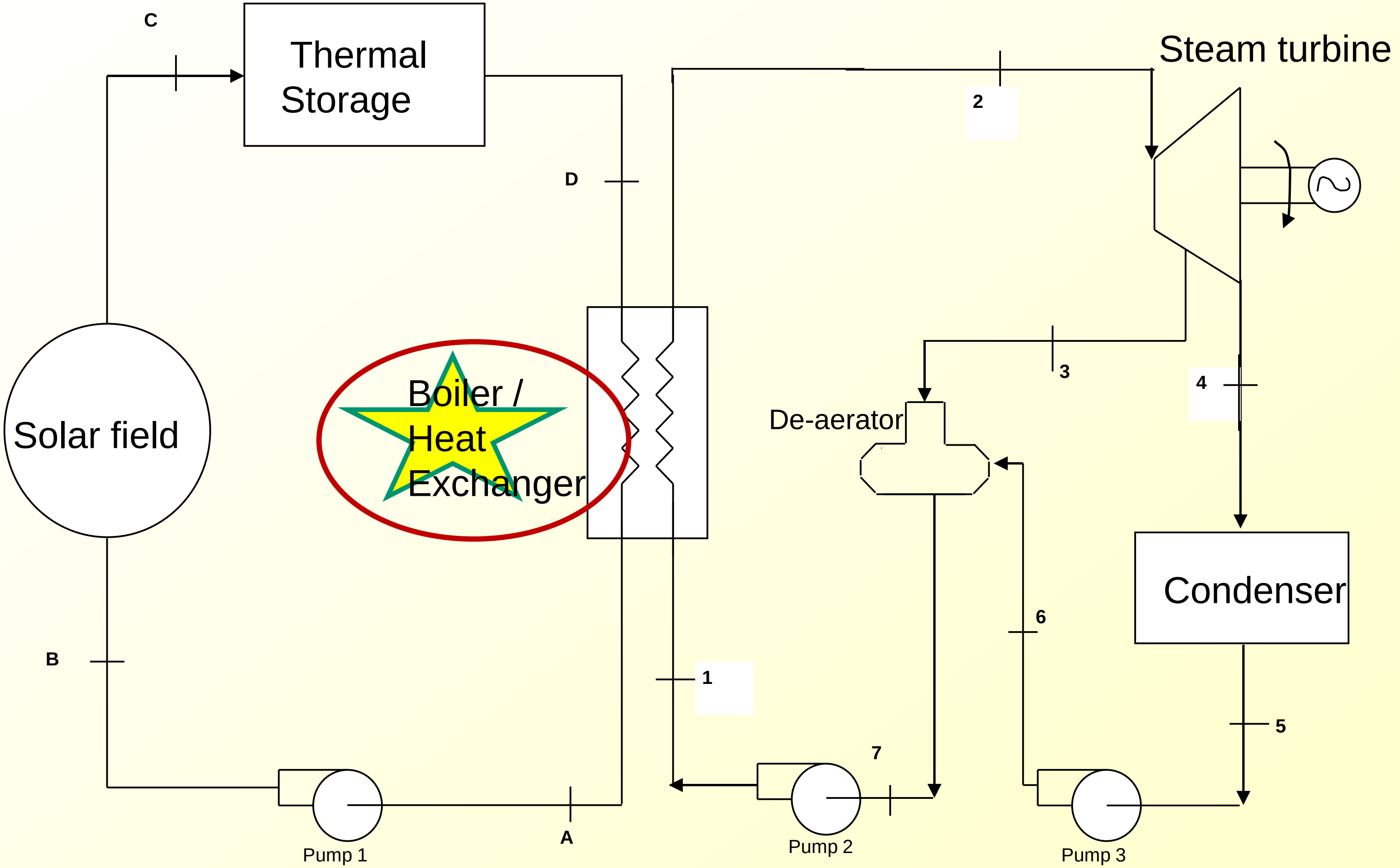
Major advantages of CSP in Indian context

- Higher conversion efficiency
- Possibility of thermal storage, hybridization
- Scalability; grid compatibility
- Easy to establish indigenous manufacturing
- Vast indigenous experience in thermal power technology

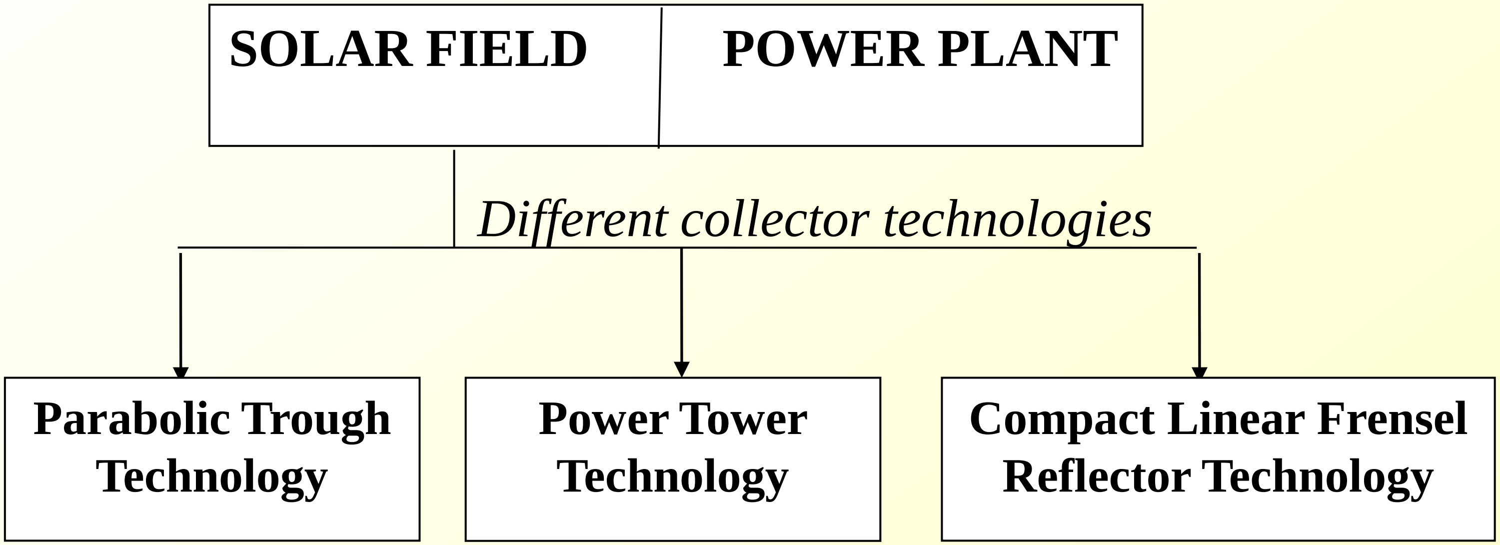
Conventional Steam based Solar Thermal Plant



Conventional Steam based Solar Thermal Plant

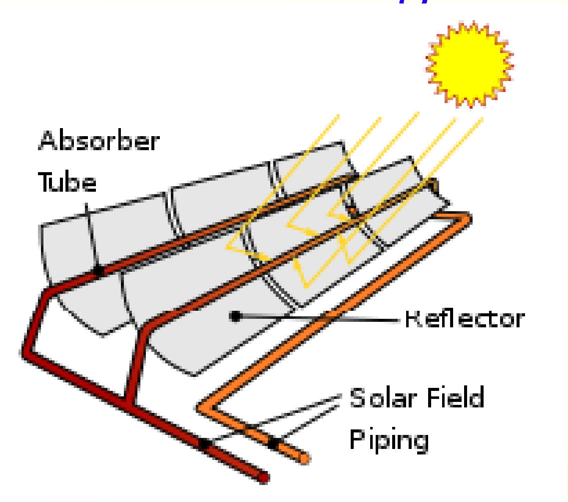


Main components of a CSP plant

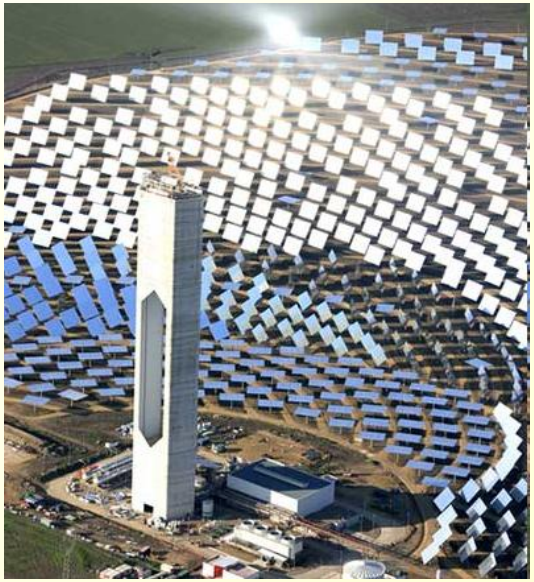


Present Collector Technology Options

Parabolic Trough



Solar Tower



Fresnel System

Collector technology fairly mature
Large scale plants (50 MW+) existing

Potential for Off Grid Solar Power

- Utility scale power plants require resource good DNI, **large tracts of flat land and water**
  - Potential problems in India

- ~10 % of villages un-electrified and supply poor

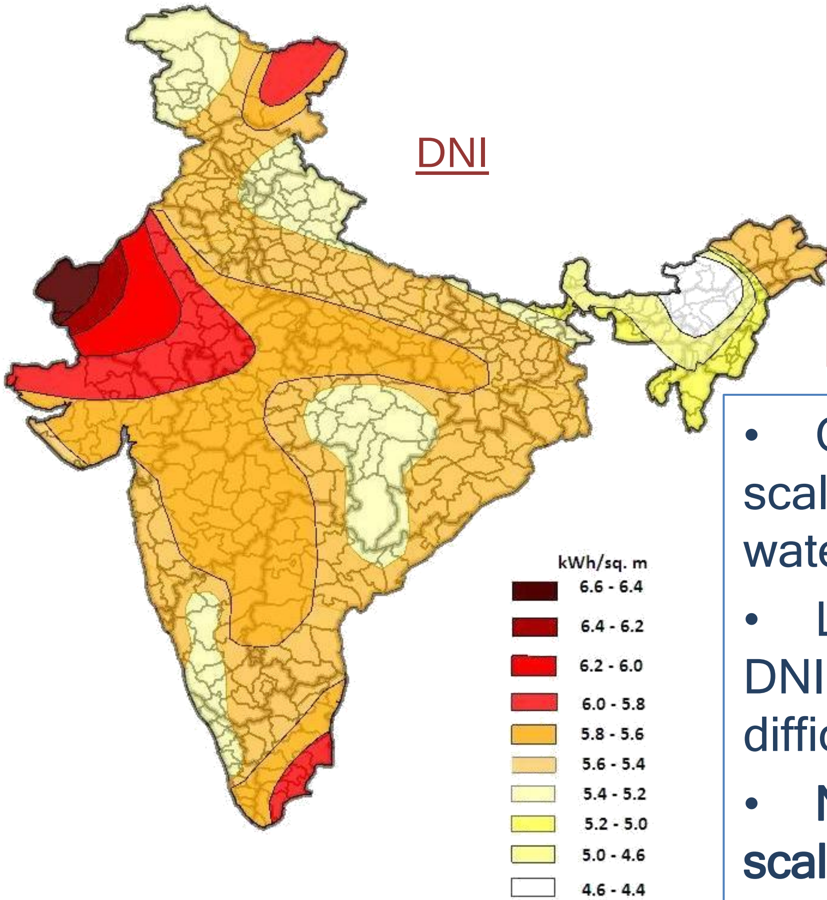
- Need to develop efficient, cost effective small scale (< 1 MW) solar power plants for village applications:
  - Dispatch with use of storage
  - Hybridization with Biomass/Natural gas
  - Include **polygeneration** (cooling, process heat, water desalination)

Steam based CSP for distributed power?

Major challenges:

1) Viable for large scale only (> 50 MW)
2) Water intensive
3) Large blocks of land difficult to acquire (socio-economic issues)
4) Viable only for high temperature (>400 C), cannot easily handle source temperature fluctuation

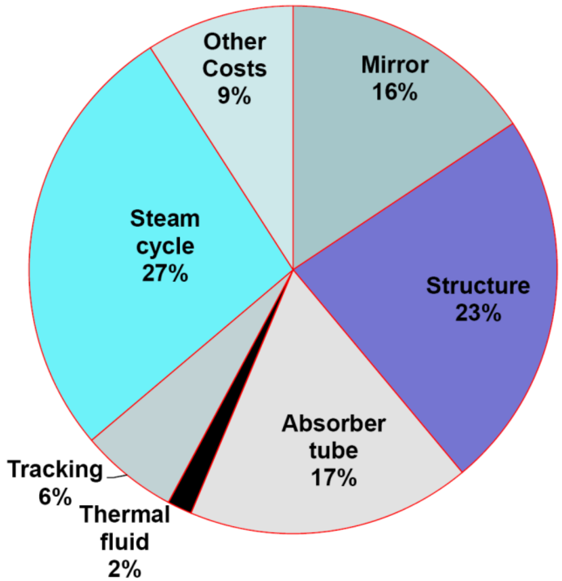
Resources for Concentrating Solar Power (CSP): Indian Scenario



- Waste Land with high solar insolation (1,96,738 Sq. km)
- Water requirement: 18,500 m^3/MW/yr
- Grid Connectivity
- Typical Land Requirement:
  5-6 acres/MW

- Conventional Steam based CSP viable for large scale only, high DNI (high operating Temperature), water intensive
- Large part of India, having moderate / reduced DNI (presence of aerosol); Large tracts of land difficult to obtain
- **Need for high efficiency, distributed (small scale) CSP requiring small land area, waterless** and for moderate operating temperature (low DNI)
- *Steam based CSP not viable; High Efficiency Brayton, Organic Rankine cycle (ORC) are potential solutions*

CSP cost Arithmetic

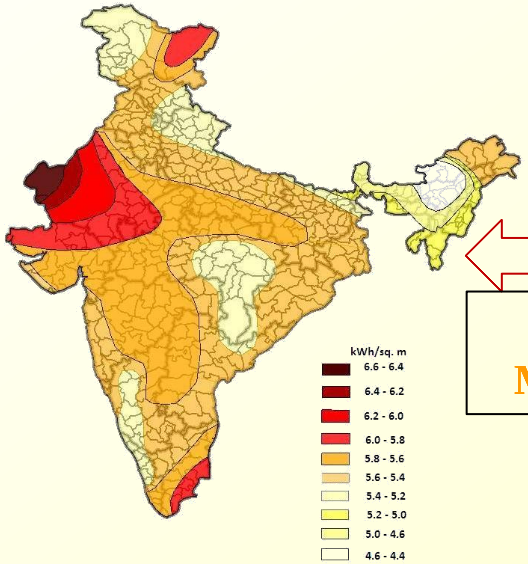


5 MW Parabolic Trough Cost Break Up (CSTEP analysis)

Solar field cost ~ 60%

Solar field	Power Plant
Aim: *decrease* cost (low cost structure, tracking, optics, coating materials)	Aim: *increase* cycle efficiency

Develop *new cycles, new engines*



Resources

High insolation
Moderate insolation

Develop "disruptive" technologies

Technology innovations chosen in distributed CSP

Track 1: **Supercritical CO_2 Brayton cycle**: >50% cycle efficiency even at 700°C receiver temperature

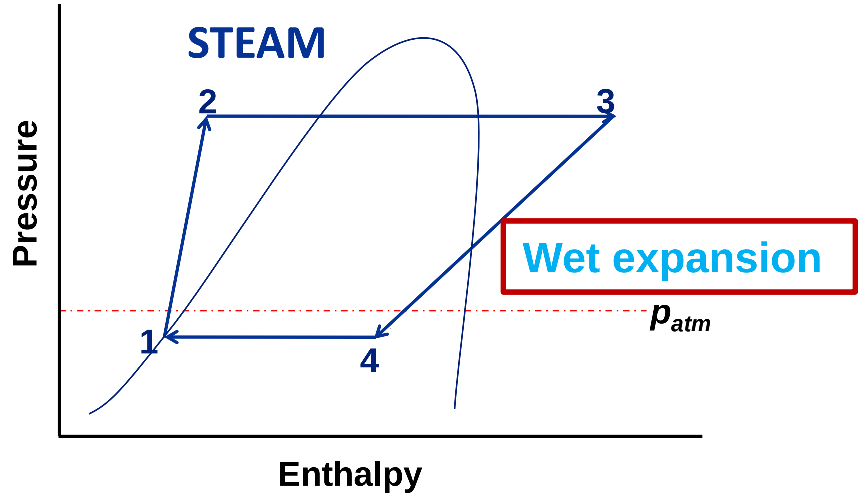
Track 2: *Organic Rankine Cycle* (ORC) systems (25 kW -1 MW)

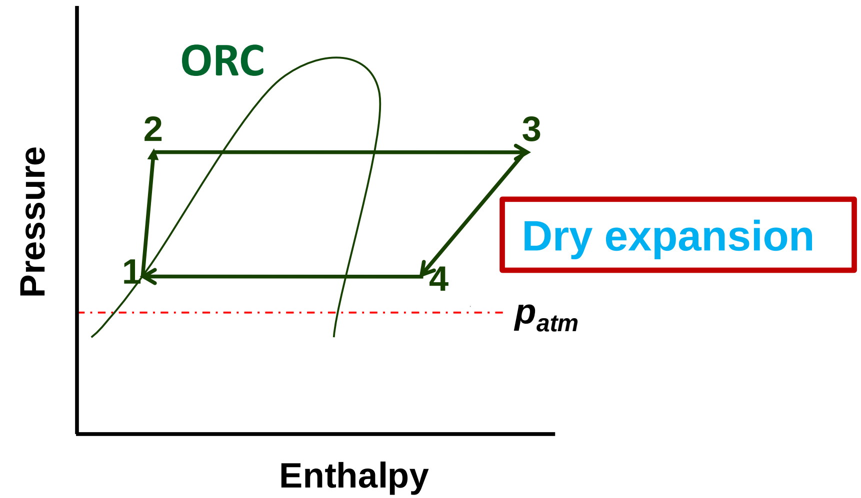
Challenge: scale down penalty

Note:

- ***No aim to build demonstration plants***.
- Identify the major ***technology gaps;*** and ***develop projects*** to address those gaps.

Conventional steam vs ORC





Parameter	Steam	ORC
Operating temperature range (°C)	400-600	100-350
Operating pressure range (bar)	0.01-200	1-100
Typical Capacity	~10 -100 MW	~0.1 to 1 MW
Turbine exhaust	Wet expansion	Dry expansion
Scale down penalty	Low isentropic efficiency of turbine at small scales	Turbine isentropic efficiency > 80 % possible at small scales
Water requirement	Make up water for cooling tower	Water-less plant possible

ORC based CSP plants ideal for Indian conditions (high efficiency at small scales, low T, waterless,)

ORC Working fluids

Fluid	Formula/ name	MW [kg/mol]	T_{crit} [°C]	p_{crit} [bar]	BP [°C]	E_{evap} [kJ/kg]
Water	H20	0.018	373.95	220.64	100.0	2257.5
Toluene	C7H8	0.092	318.65	41.06	110.7	365.0
R245fa	C3H3F5	0.134	154.05	36.40	14.8	195.6
n-pentane	C5H12	0.072	196.55	33.68	36.2	361.8
cyclopentane	C5H10	0.070	238.55	45.10	49.4	391.7
Solkatherm	solkatherm	0.185	177.55	28.49	35.5	138.1
OMTS	MDM	0.237	290.98	14.15	152.7	153.0
HMDS	MM	0.162	245.51	19.51	100.4	195.8

ORC Challenges and scope for innovation

- At 1 MW level, turbine isentropic efficiency is quite high (~75-80%)
- Efficiency drops at lower scales (25-100 kW level)
- Need to develop *high efficiency small scale* expanders (e.g. positive displacement expander)
- High temp. fluids are generally **flammable** (e.g. toluene)
- **Non-flammable R245fa: low operating temp (low efficiency)**
- Address flammability issues for high temp. fluids
- Storage, hybridization, polygeneration (e.g. solar cooling)

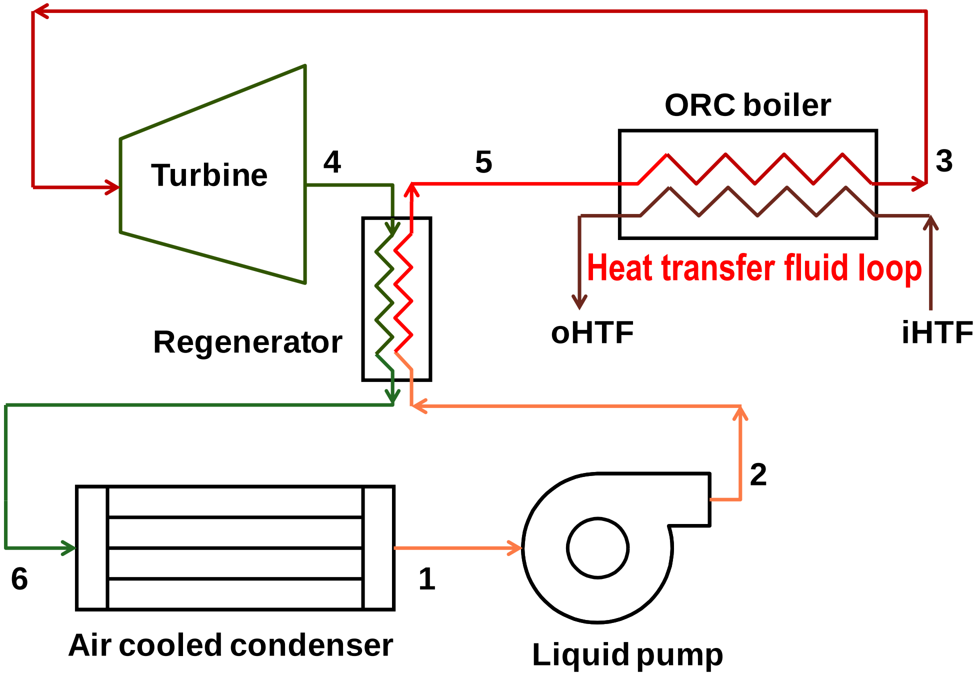
High temp. working fluid; high η small scale expander

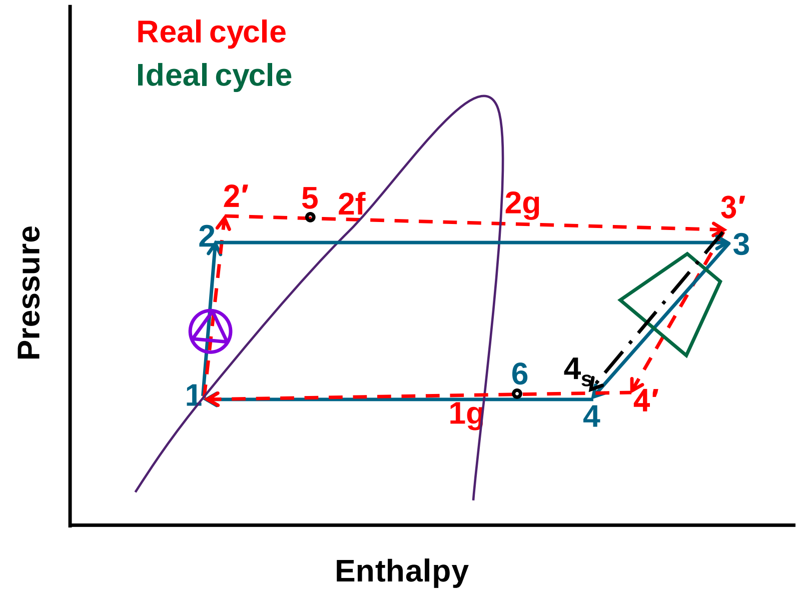
Issues with ORC fluids

- **Properties for ideal ORC fluid for solar themal:**
  - Low GWP and zero ODP
  - Non-toxic, non-flammable
  - High operating T (~ 300°C, for high cycle efficiency)
- Problems with common/available ORC fluids
  - R-245fa (high GWP, low operating temperature 150°C)
  - Isopentane (flammable , operating temperature < 200°C)
  - Toluene (flammable, a little toxic, condenser pressure < 1 bar)

Can we create **mixtures of ORC** fluids addressing the above issues?

Thermodynamic Analysis of ORC based CSP





Parametric studies
- Turbine expansion ratio
- Heat source temp. range
- Working fluids

Working fluids studied
- Pure organic fluids: R245fa, isopentane, propane
- Mixture additivies to suppress flammability, GWP

Outcome of studies
- Cycle efficiency
- Heat recoevery
- Flow rates
- Entropy generation
- Optimization

Non-Flammable Mixtures studied

Isopentane + R-245fa (70/30 by mole fraction):

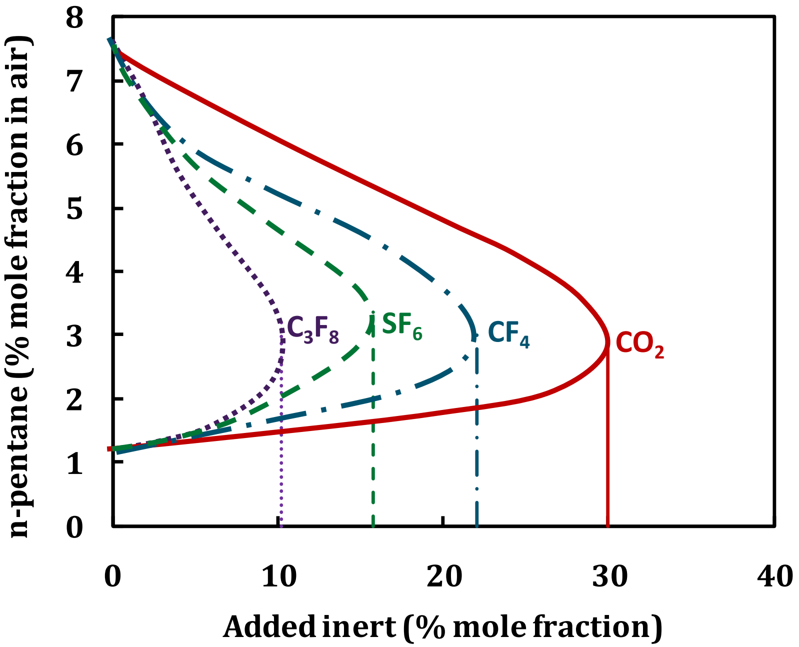
- Non flammable
- Good efficiency, but still low operating Temp.

Isopentane + CO2 (70/30 by mole fraction):

- Non flammable
- Not good efficiency, but moderate source temperature possible

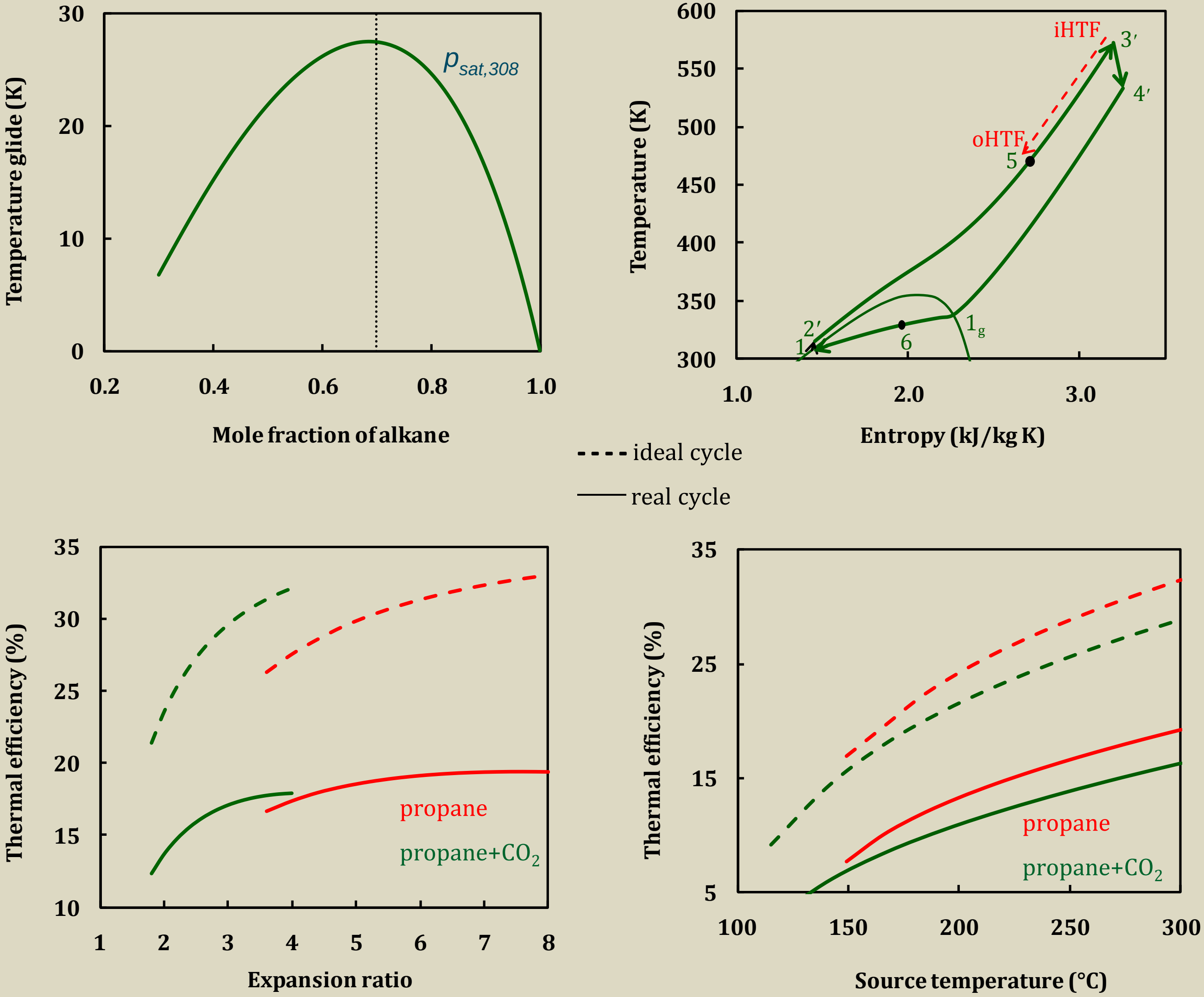
Propane + CO2 (70/30 by mole fraction):

- Non flammable
- Excellent efficiency, moderate source T possible



Flammability suppression by adding inert additive

Propane + CO_2 (70/30 mole fraction)



Issues / remarks

—Moderate temp. glide

— Heat recovery extended to two phase dome

Thermax's ORC Project at Shive

Distributed solar systems (Sponsor: Karnataka Govt.)

RESEARCH CENTRE FOR SOLAR POWER IN CHALLAKERE CAMPUS

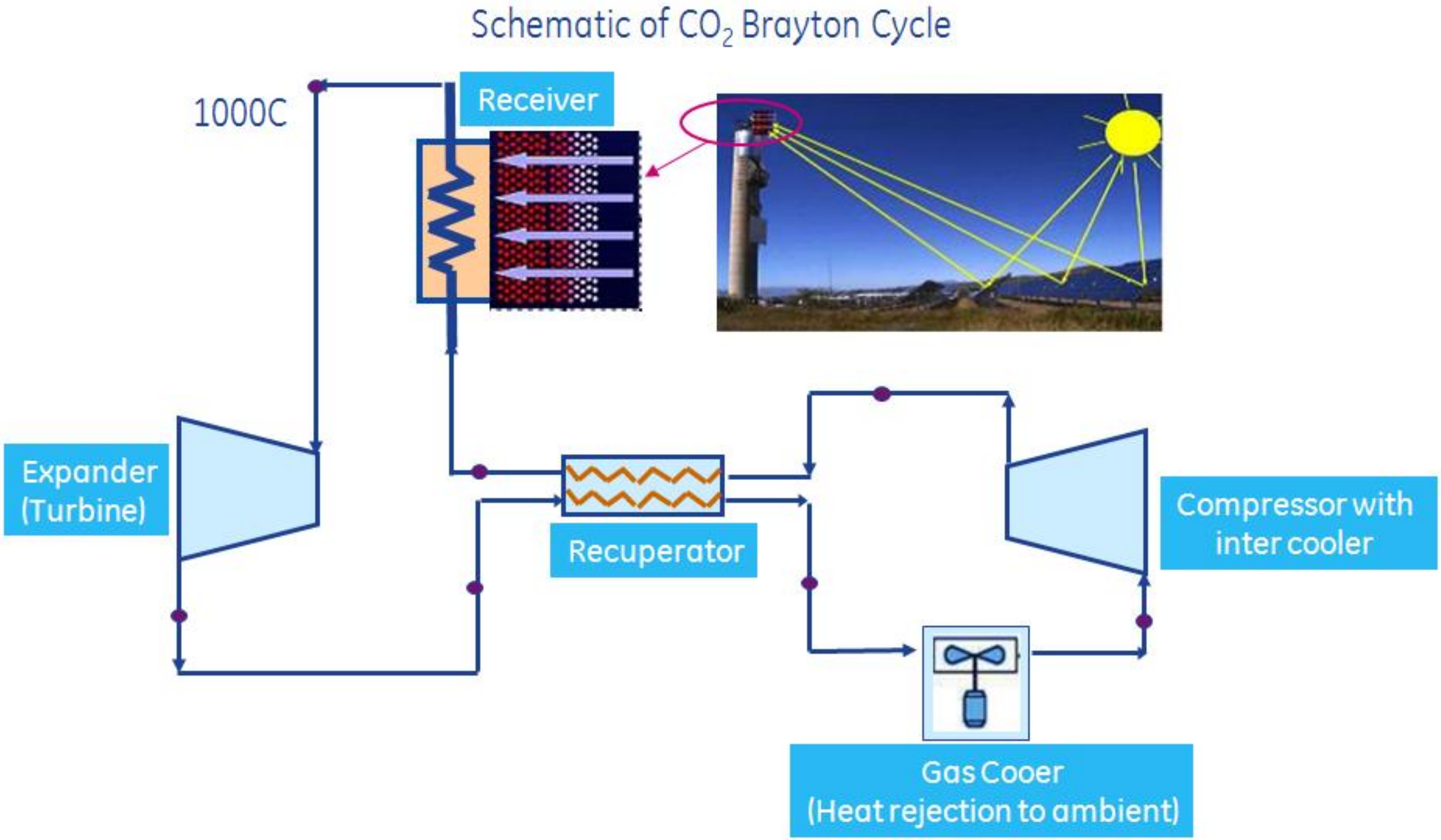
2 Research Test Beds

- **100 kWe Organic Rankine Cycle CSP**
- PV Test Bed (60 kW)

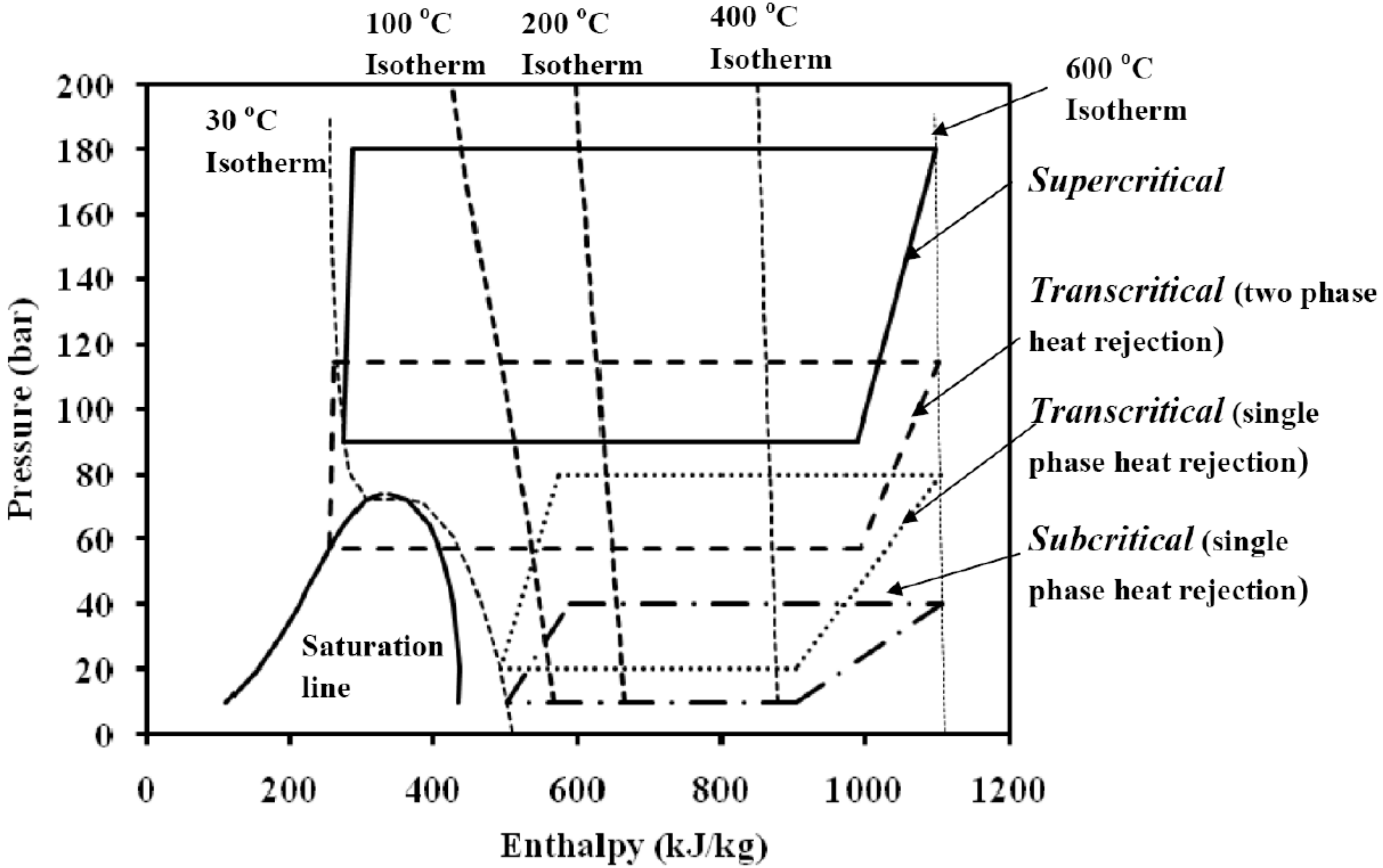
Industrial Collaborator:
Thermax Ltd, Pune
Project roll out: July 17, 2013

First major research establishment at IISc's Challakere Campus

High Efficiency Closed loop CO_2 Brayton cycle



CO2 Brayton Cycles

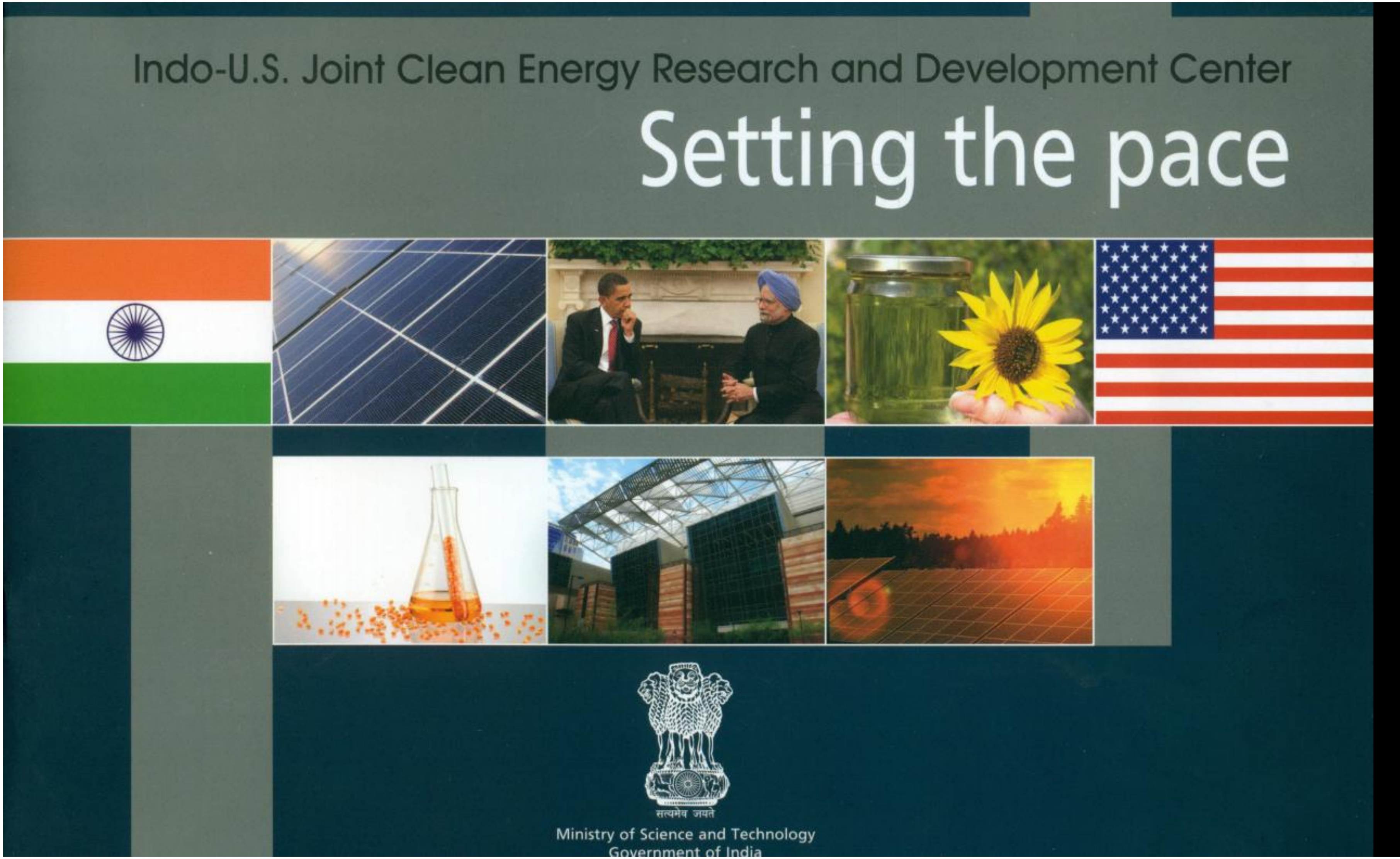


Supercritical CO_2 Brayton: >50% cycle η even at 700ºC

With SCO_2, compression work comes down significantly

Being developed for nuclear

Thermodynamic cycle (schematic cycle diagrams shown in Fig. 1 below)	Salient features	Cycle efficiency range	Suitability (locations/ applications)	Technology gaps / challenges identified for research projects
1. ***High Efficiency Closed Cycle CO_2 Brayton cycle* (100 kW – 1 MW)**				Development of a cost effective heliostat field is common to all the sub systems identified in this category
(a) Supercritical CO2 Brayton cycle	• 70 – 170 bars • High η even for low to moderate Tmax (400-600C)	50 – 60% with single stage compression and regeneration	• Low to Moderate DNI • Higher capital cost, hence good for larger installations for grid feeding	High pressure receiver; high pressure turbo-expander, high pressure heat exchangers
(b) Transcritical CO2 Brayton cycle (two-phase)	• 20 – 80 bars • High η even for moderate Tmax (600-800C) • CO2 condensation temperature <30C	50-55% with single stage compression and regeneration	• Moderate to high DNI • Low temperarure ambient (<25C) • Several locations in US • Winter climate, hill stations, Himalayan locations	Moderate pressure receiver with storage, moderate pressure CO2 turbo-expander, moderate pressure heat exchangers; CO2 pump,
(c) Transcritical CO2 Brayton cycle (single-phase)	• 20 – 80 bars • High η even for moderate Tmax (600-800C)	50-55% with two stage compression and regeneration	• Moderate to high DNI • Can work with high temperature ambient	Moderate pressure receiver with storage, moderate pressure turbo-expander, moderate pressure heat exchangers; hybridization with auxiliary heating (e.g. biomass combustor)
(d) Subcritical CO2 Brayton cycle (single-phase)	• 5 – 20 bars • High η for high Tmax (800- 1000C)	~ 50% with two stage compression and regeneration	• Moderate to high DNI •	High temperature receiver, high temperature turbo-expander for CO2, heat exchangers; hybridization with auxiliary heating (e.g. biomass combustor)



Indo-U.S. Joint Clean Energy Research and Development Center
Setting the pace
सत्यमेव जयते
Ministry of Science and Technology
Government of India

Recognizing the need to address climate change, ensure mutual energy security, and build a clean energy economy that drives investment, job creation, and economic growth; Prime Minister Manmohan Singh and President Barack Obama launched the U.S.-India Partnership to Advance Clean Energy (PACE) under the U.S.-India Memorandum of Understanding to enhance cooperation on Energy Security, Energy Efficiency, Clean Energy and Climate Change. This MoU was signed on November 24, 2009 during Prime Minister Singh's visit to the United States.

As a priority initiative under the PACE umbrella, the U.S. Department of Energy (DOE) and the Government of India signed an agreement to establish the **Joint Clean Energy Research and Development Center (JCERDC)** on November 4, 2010 during President Obama's head of state visit to India. The JCERDC is the first bilateral initiative designed specifically to promote clean energy innovation by teams of scientists and engineers from India and the United States.

2009

SERIIUS

Solar Energy Research Institute
for India and the United States

Solar Energy Research Institute for India and the United States (SERIIUS)

A Joint Research Consortium for Accelerating Solar Electricity Development

U.S.-India Joint Clean Energy Research and Development Centre

India	United States
Consortium Leads	
Indian Institute of Science–Bangalore	National Renewable Energy Laboratory
Research Thrust Leadership	
Indian Institute of Technology Bombay	Sandia National Laboratories
Center for the Study of Science, Technology and Policy	RAND Corporation

Solar Energy Research Institute for India and the United States

Solar Energy Research Institute for India and the United States (SERIIUS)

A Joint Research Consortium for Accelerating Solar Electricity Development

India	United States

Consortium Leads

India	United States
Indian Institute of Science–Bangalore Dr. Kamanio Chattopadhyay	**National Renewable Energy Laboratory** Dr. Lawrence Kazmerski

Research Thrust Leadership

India	United States
Indian Institute of Technology Bombay	Sandia National Laboratories
Center for the Study of Science, Technology and Policy	RAND Corporation

Consortium Partners

Institutes and National Laboratories

India	United States
International Advanced Research Centre for Powder Metallurgy and New Materials Solar Energy Center	Lawrence Berkeley National Laboratory

University Partners

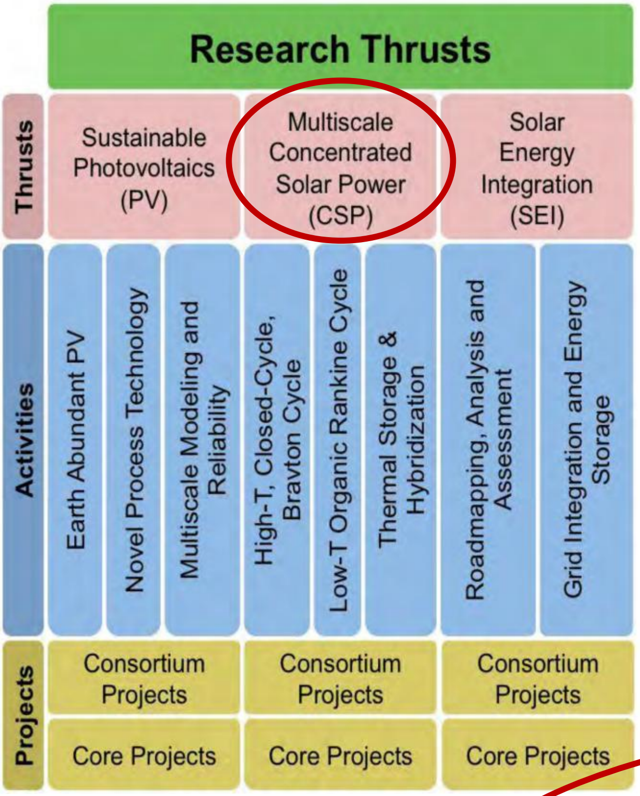
India	United States
Indian Institute of Technology Madras	Arizona State University
Indian Association for the Cultivation of Science	Carnegie Mellon University
	Colorado School of Mines
	Massachusetts Institute of Technology
	Purdue University Stanford
	University University of
	Central Florida University of
	South Florida
	Washington University in St. Louis

Industry Partners

India	United States
Bharat Heavy Electricals Ltd	
Clique Developments Ltd. Hindustan	Corning Incorporated
Petroleum Corporation Ltd.	Konarka Technologies, Inc.
Moser Baer India Ltd.	MEMC Corporation
Thermax Ltd.	Solarmer Energy, Inc.
TurboTech Precision Engineering Ltd.	
Wipro Ltd.	

DE-FOA-0000506: U.S.-India Joint Clean Energy Research and Development

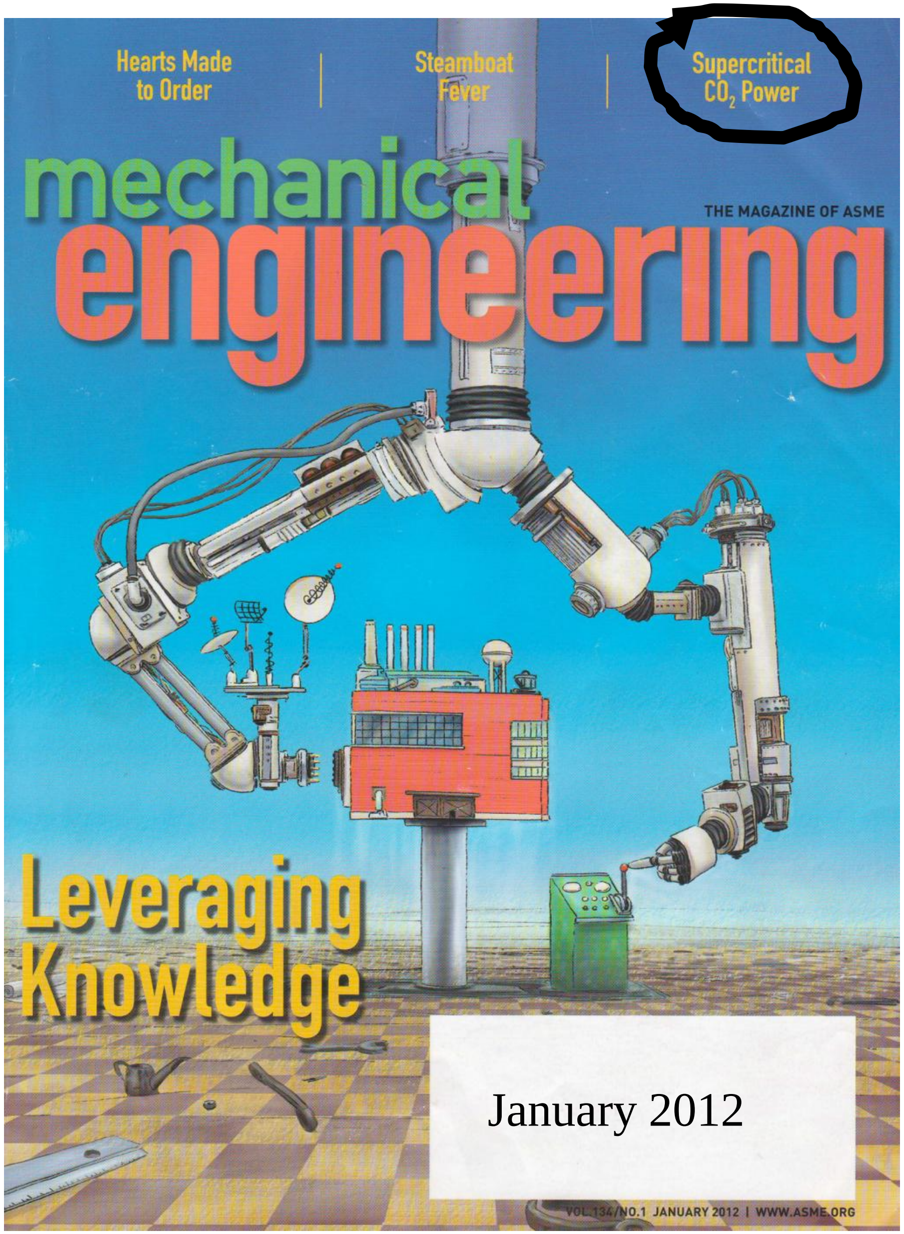
Our Team:



Sustainable Photovoltaics		
Earth-Abundant PV	**Novel Process Technology**	**Multiscale Modeling & Reliability**
Objectives		
Develop new scalable absorbers based on Earth-abundant materials and processes	*Develop ink-based processes for PV elements based on new flexible substrates and printing techniques*	*Couple materials to module modeling with real-world reliability testing to provide direct feedback to the materials and process development tasks*

Multiscale Concentrated Solar Power		
High T, Closed-Cycle CO_2 Brayton Cycle	**Low T Organic Rankine Cycle (ORC)**	**Thermal Storage & Hybridization**
Objectives		
Develop supercritical 20-80 bar 600-800°C Brayton cycle with >50% efficiency (100 kW to 1 MW)	*Develop organic Rankine cycle with operating at <330°C and wit efficiency >20% (25 kW to 1 MW)*	*Develop hybridized storage systems for the diverse temperature ranges of the Brayton and Rankine converters in the first two tasks*

Solar Integration	
Roadmapping, Analysis, and Assessment	**Grid Integration & Energy Storage**
Objectives	
Analyze the necessary market, policy, and technology data to develop roadmaps for the bankable deployment options for solar electric conversion	*Quantify the interactions of a diverse set of solar electric generators on the grid in India and predict optimum deploymentand interconnection, validate the modeling. Look at the impact of localized storage and validate with test systems.*



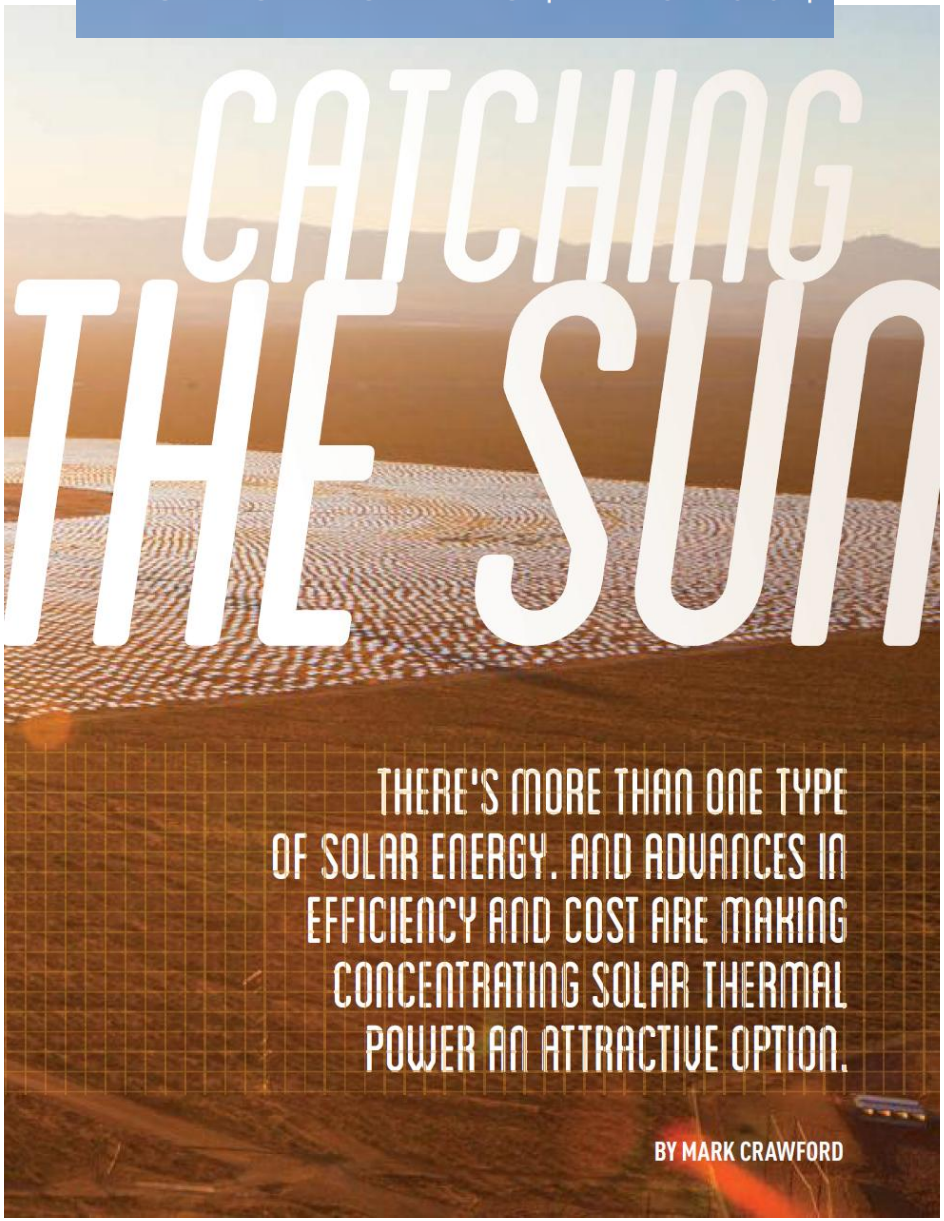
MIGHTY MITE

A turbine that uses supercritical carbon dioxide can deliver great power from a small package.

By Steven Wright

In most respects, carbon dioxide is an energy problem. The gas is mixed to varying degrees with methane in underground formations and must be stripped before natural gas is injected into pipelines. It's created by the combustion of carbon fuels and must be vented away from engines. And the build-up of that CO_2 in the atmosphere has been implicated in global climate change.

Carbon dioxide has some interesting properties, however. Blocks of frozen carbon



NEW HEAT-TRANSFER FLUIDS CAN BE USED TO REACH CONVERSION EFFICIENCIES OF 50 PERCENT OR GREATER.

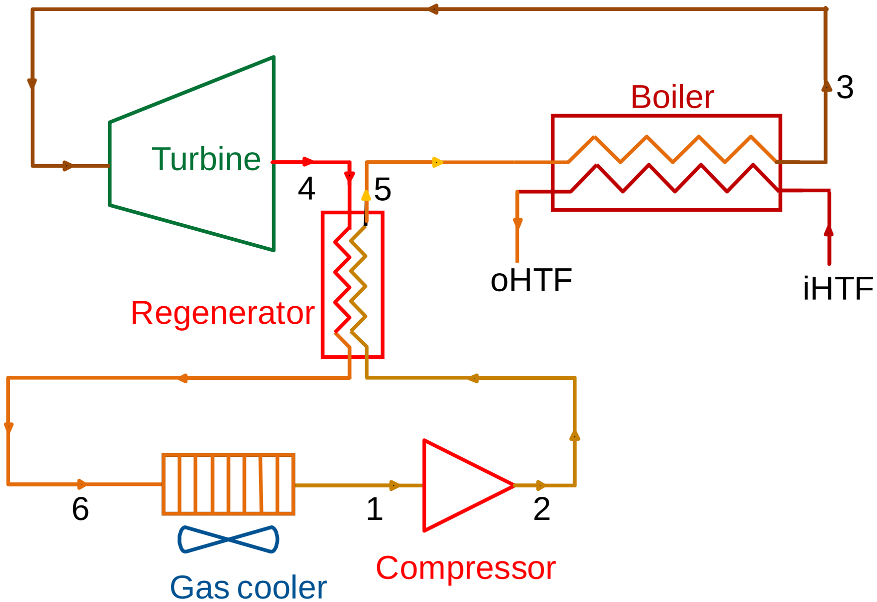
INDUSTRIAL SOLAR

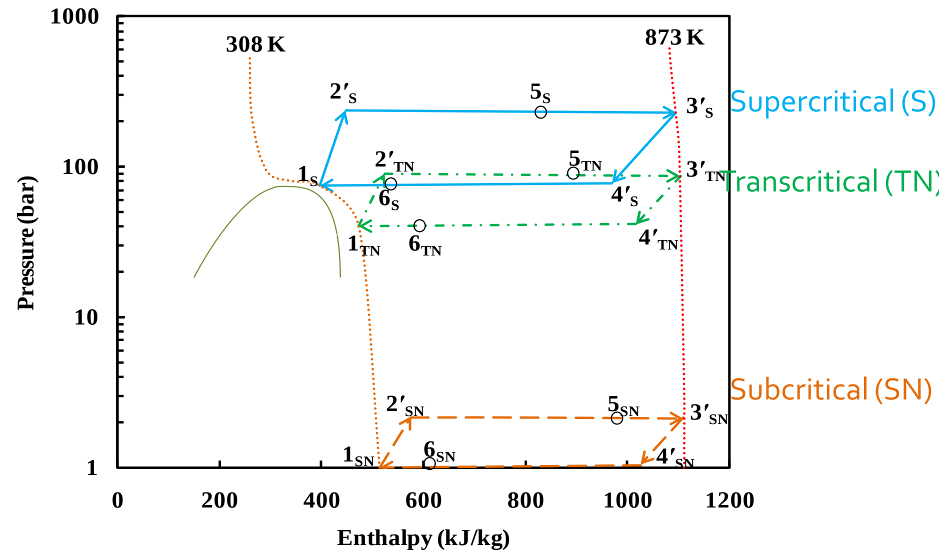
The SunShot Initiative is funding other research that might be able to deliver new technologies to meet various technical and cost targets within the next three to five years, Pitchumani said. These include highly efficient reflector materials integrated with low-cost structures for collectors, lean solar field manufacturing and assembly approaches, self-aligning and tracking heliostats, self-cleaning mirrors, solar selective coatings for enhanced absorption with lower radiative loss, and corrosion-resistant materials and coatings.

"High-temperature, higher-efficiency power cycles, such as the supercritical CO_2 cycle at the 1 MW and 10 MW scales, and the solar-integrated Brayton cycle, will trend toward higher (greater than 50 percent) efficiency operation with dry cooling," Pitchumani said. "Some of these have broader relevance beyond the solar industry to the nuclear and fossil industries as well."

Performance studies of Brayton cycles

Working fluids
- Air, CO_2

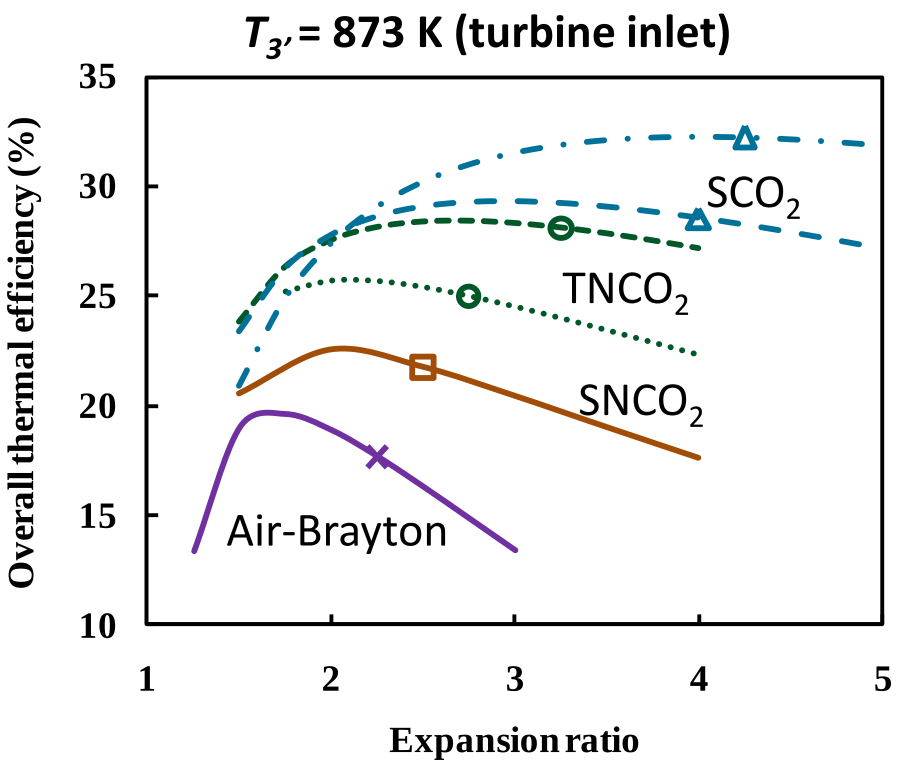




Parametric studies
- Turbine expansion ratio
- Low side pressure
- Heat source temp. range

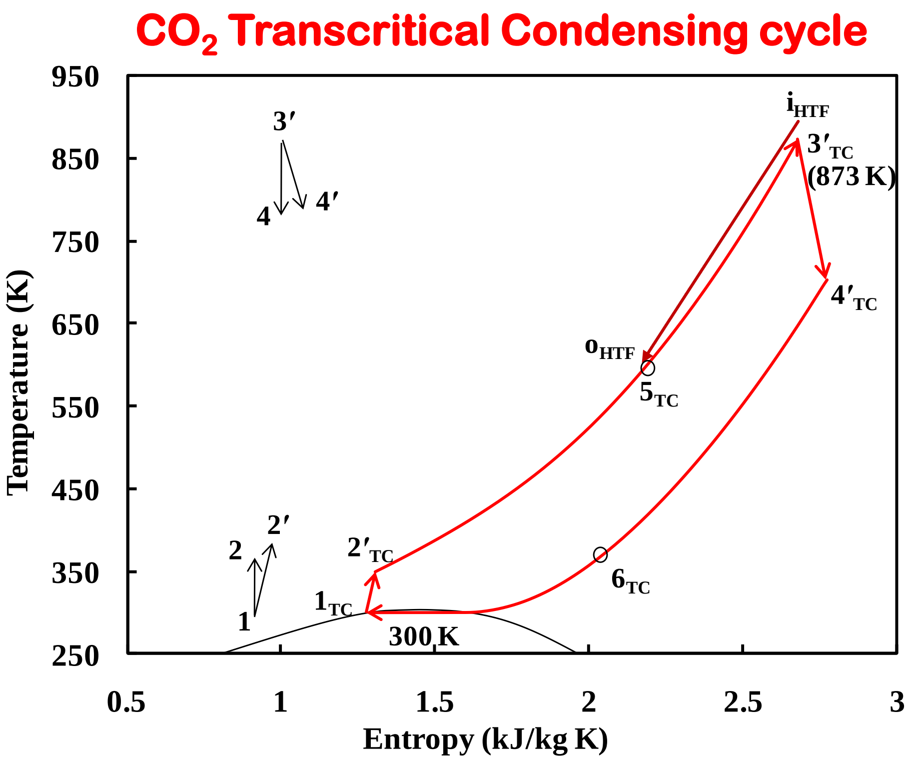
Outcome of studies
- Cycle efficiency
- Heat recovery
- Flow rates
- Entropy generation
- Optimization

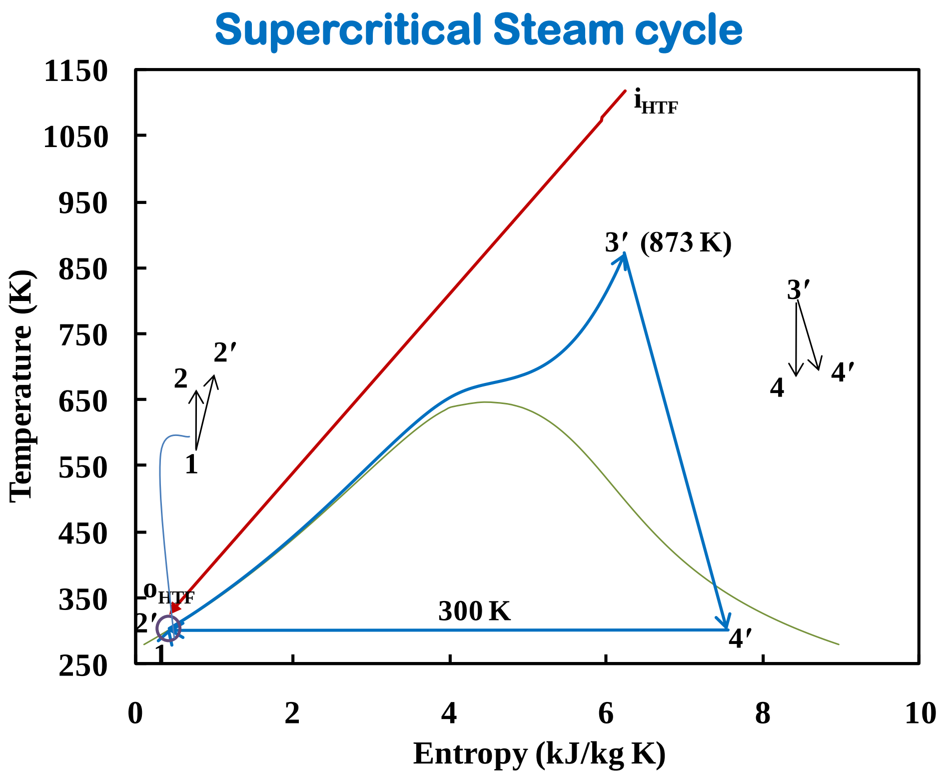
Real cycle efficiency and its optimization



—— p_1= 1 bar, ·········· p_1= 40 bar, ------ p_1= 70 bar,
- - - - p_1= 75 bar, – · – · – p_1= 85 bar,
□ SN-CO_2 cycle, ○ TN-CO_2 cycle, Δ S-CO_2 cycle,
× air Brayton cycle at low side pressure of 1 bar

CO_2 vs Steam



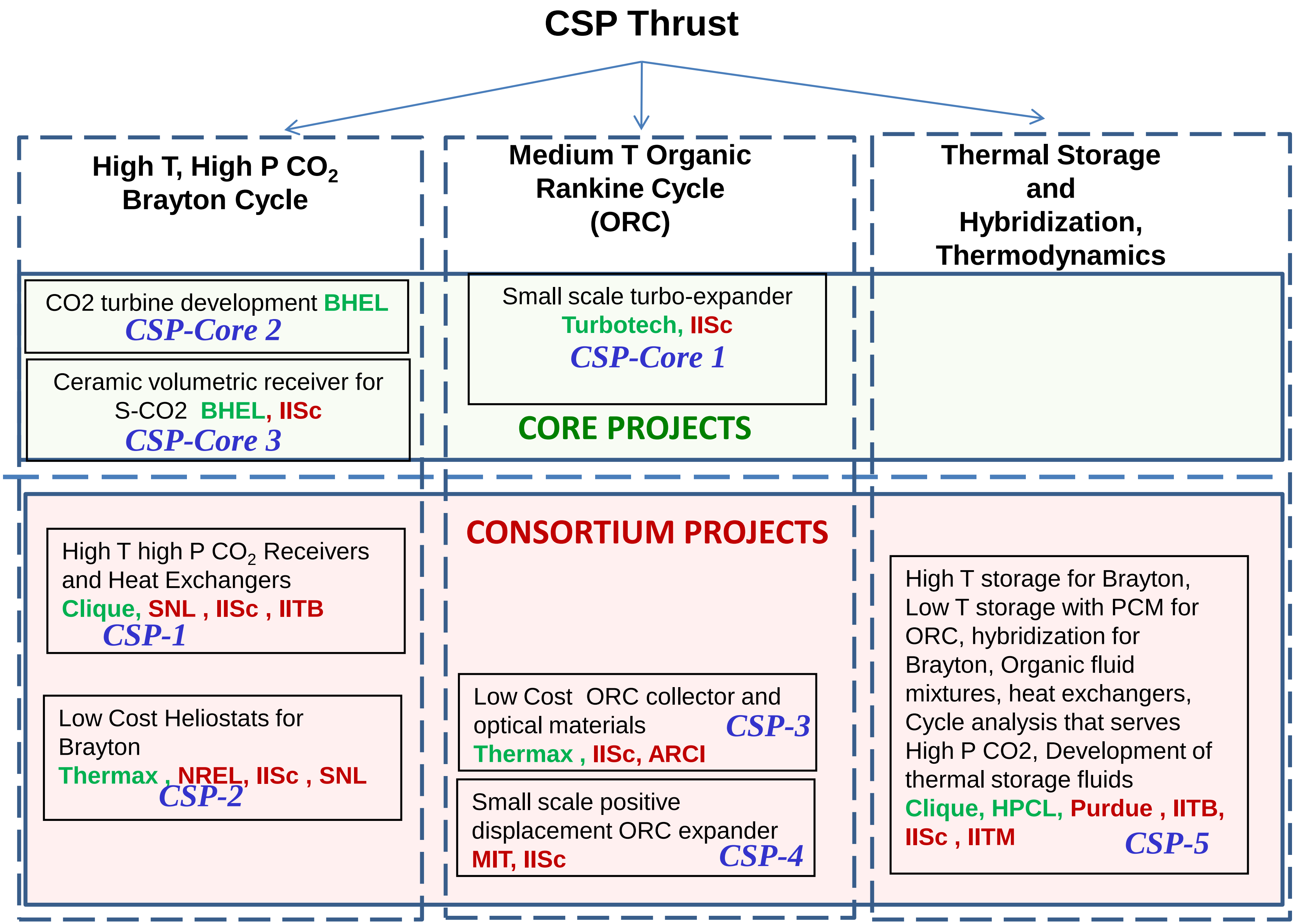


More heat source temperature required for the same turbine inlet temperature for steam.

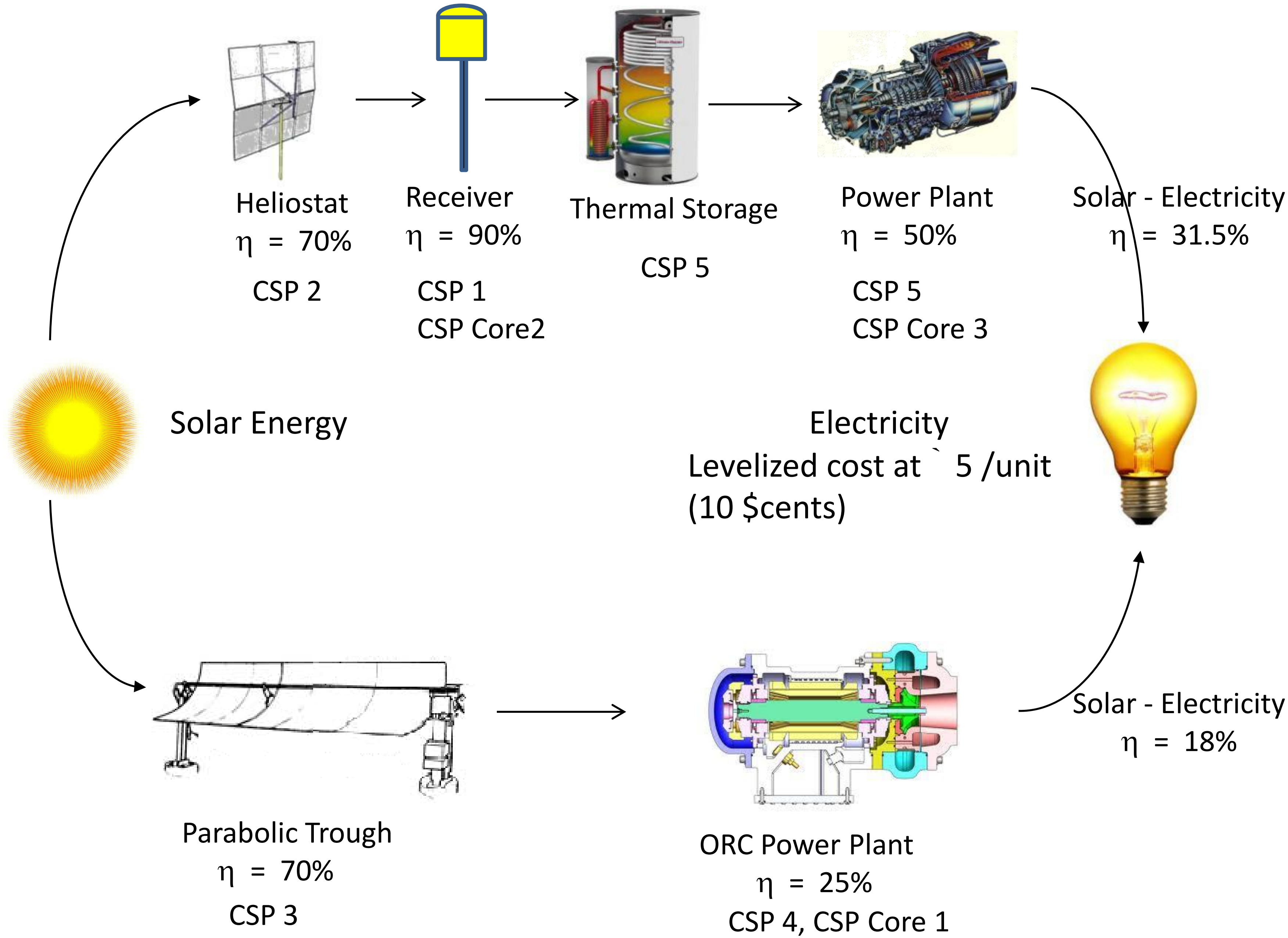
Easier choice of Heat transfer fluid (HTF) for CO_2 .

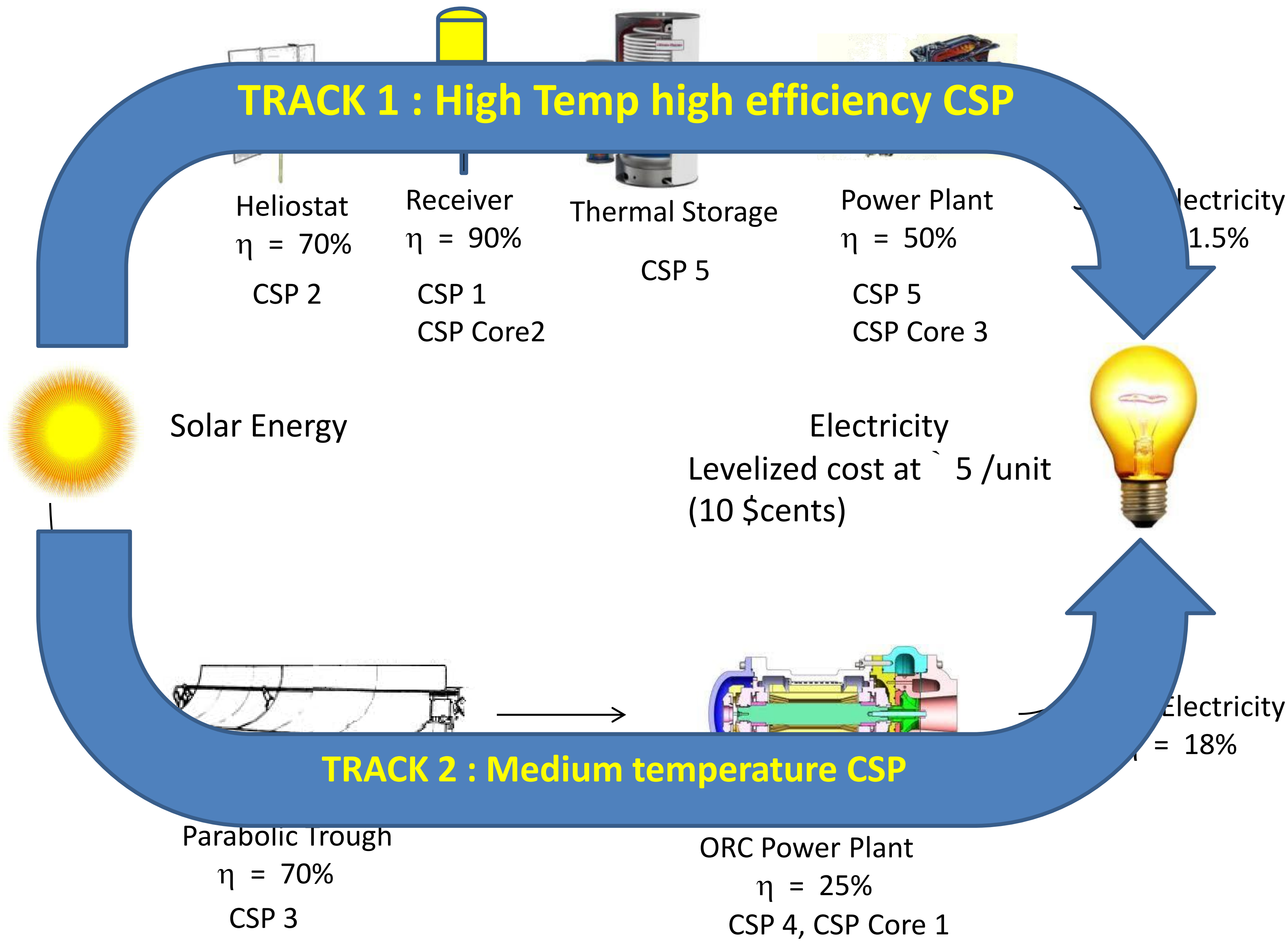
CO_2 Brayton: Critical science and engineering challenges

- High *T* high *P receivers* for CO2.
- *Hybridization* for stable and reliable power
- High *T thermal energy storage* system for Brayton cycle : molten salt, PCM? Heat Transfer Fluid ?
- *Heat exchangers* for auxiliary heating
- High efficiency and low cost *reflectors* for power tower system
- High efficiency *compressors and turbo-expanders*



CSP Thrust
High T, High P CO_2 Brayton Cycle
Medium T Organic Rankine Cycle (ORC)
Thermal Storage and Hybridization, Thermodynamics
CO2 turbine development BHEL
CSP-Core 2
Ceramic volumetric receiver for S-CO2 BHEL, IISc
CSP-Core 3
Small scale turbo-expander
Turbotech, IISc
CSP-Core 1
CORE PROJECTS
CONSORTIUM PROJECTS
High T high P CO_2 Receivers and Heat Exchangers
Clique, SNL , IISc , IITB
CSP-1
Low Cost Heliostats for Brayton
Thermax , NREL, IISc , SNL
CSP-2
Low Cost ORC collector and optical materials
CSP-3
Thermax , IISc, ARCI
Small scale positive displacement ORC expander
MIT, IISc
CSP-4
High T storage for Brayton, Low T storage with PCM for ORC, hybridization for Brayton, Organic fluid mixtures, heat exchangers, Cycle analysis that serves High P CO2, Development of thermal storage fluids
Clique, HPCL, Purdue , IITB, IISc , IITM
CSP-5


Heliostat
η = 70%
CSP 2
Receiver
η = 90%
CSP 1
CSP Core2
Thermal Storage
CSP 5
Power Plant
η = 50%
CSP 5
CSP Core 3
Solar - Electricity
η = 31.5%
Solar Energy
Electricity
Levelized cost at ` 5 /unit
(10 $cents)
Parabolic Trough
η = 70%
CSP 3
ORC Power Plant
η = 25%
CSP 4, CSP Core 1
Solar - Electricity
η = 18%


TRACK 1 : High Temp high efficiency CSP
Heliostat
η = 70%
CSP 2
Receiver
η = 90%
CSP 1
CSP Core2
Thermal Storage
CSP 5
Power Plant
η = 50%
CSP 5
CSP Core 3
lectricity
1.5%
Solar Energy
Electricity
Levelized cost at ` 5 /unit
(10 $cents)
TRACK 2 : Medium temperature CSP
Parabolic Trough
η = 70%
CSP 3
ORC Power Plant
η = 25%
CSP 4, CSP Core 1
Electricity
= 18%

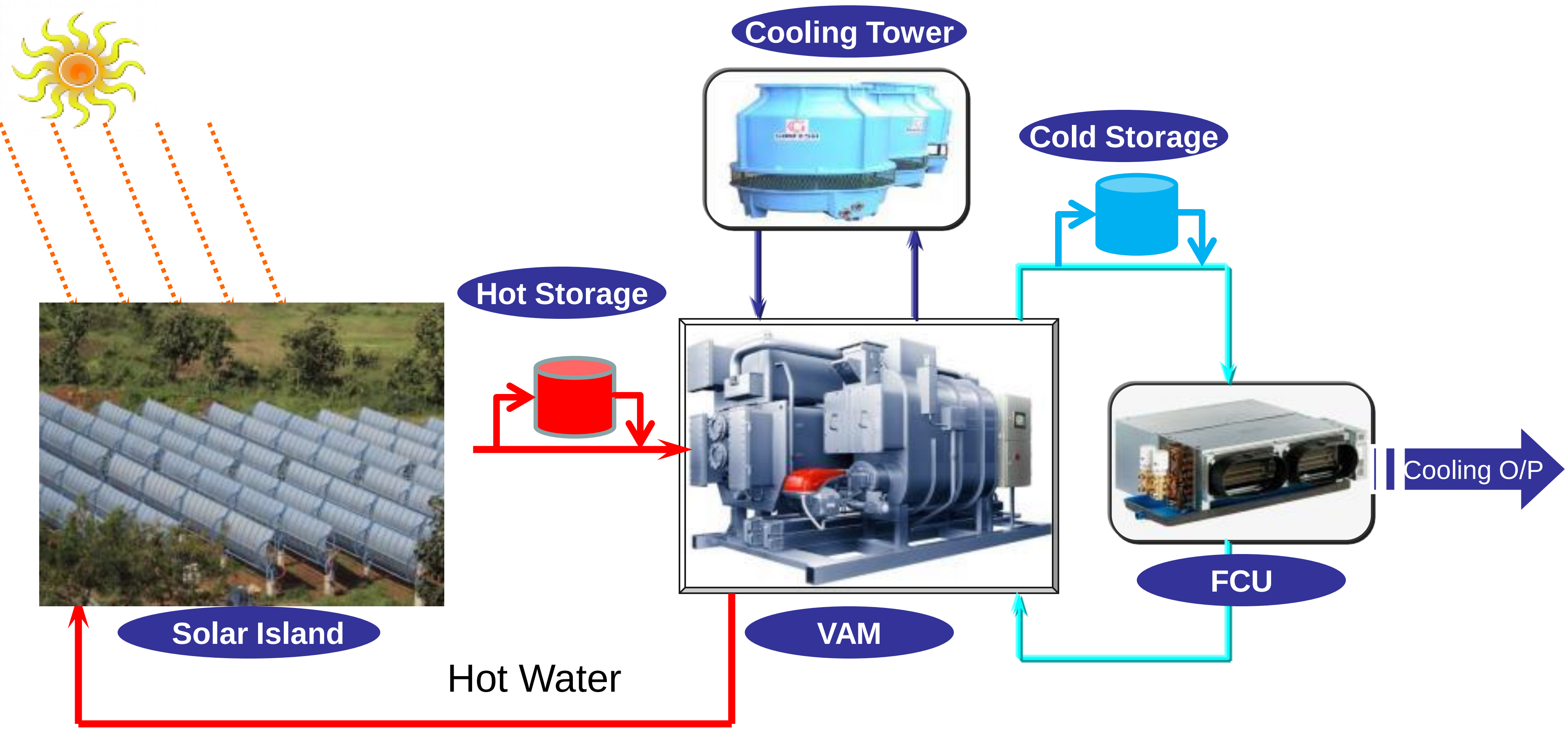
Solar Cooling

- Vapour Absorption Cycle
- Vapour Compression Cycle (thermal compression with adsorption)
- Flash evaporation + Thermal compression (Cooling + Desalination)

Solar Cooling

- Vapour Absorption Cycle √ (mature)
- Vapour Compression Cycle (thermal compression with adsorption)
- Flash evaporation + Thermal compression (Cooling + Desalination)

Solar Cooling by Vapour Absorption (THERMAX)



Approved : Jun 2010 - Commissioned : July 2011

Solar Cooling

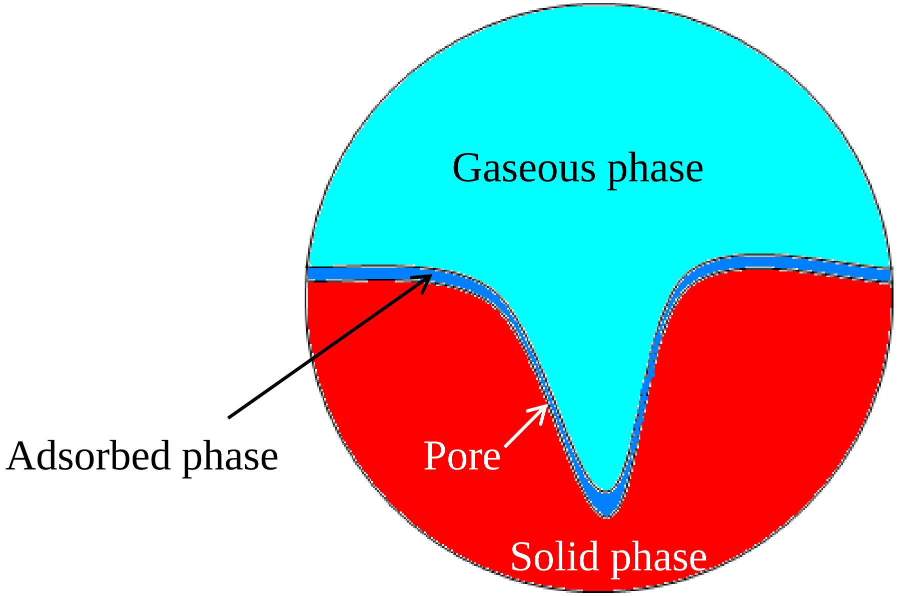
Innovations with solar

- Vapour Absorption Cycle
- Vapour Compression Cycle (thermal compression with adsorption)
- Flash evaporation + Thermal compression (Cooling + Desalination)

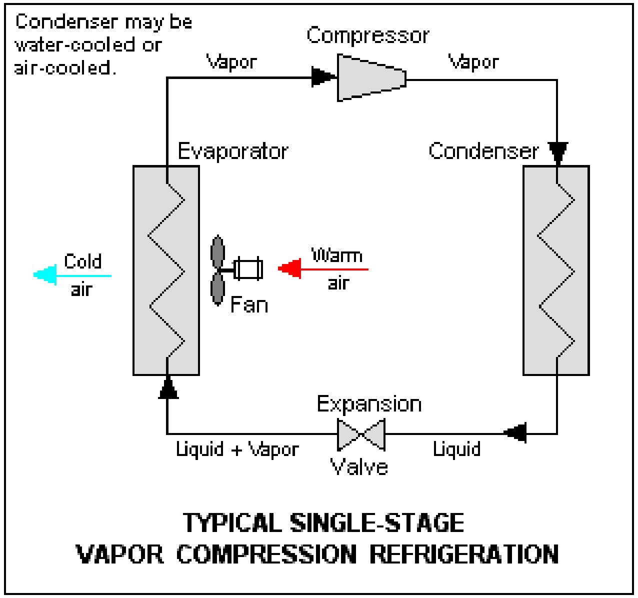
Adsorption basics

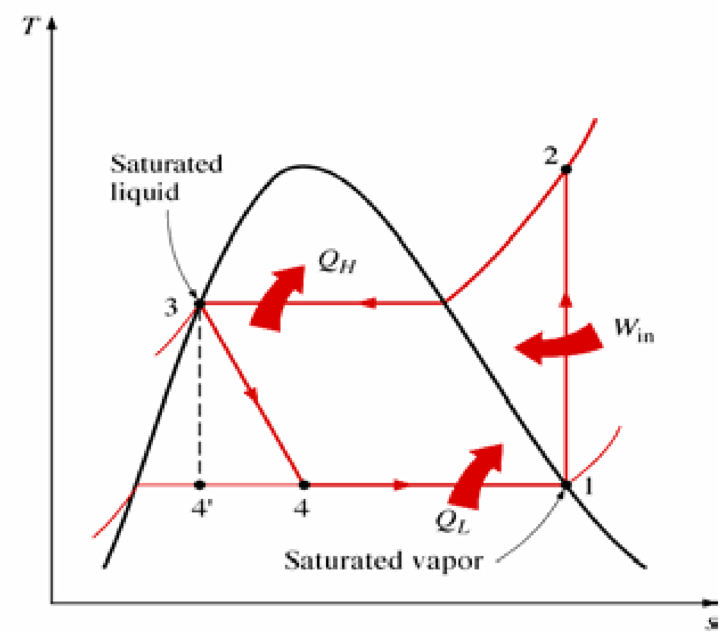
- **Adsorption**: Atoms (gas or liquid) adhering to a surface
- **Silica gel + water system**: steam (gaseous phase) is adsorbed on the surface of porous silica gel (solid phase); Steam adsorbed in micro (<2 nm) /meso (2-50 nm) pores of silica gel.
- **activated carbon + refrigerant (e.g R290 + R218 mixture)**

- **Heat of adsorption** is released during adsorption process and **heat of desorption** has to be supplied during desorption.

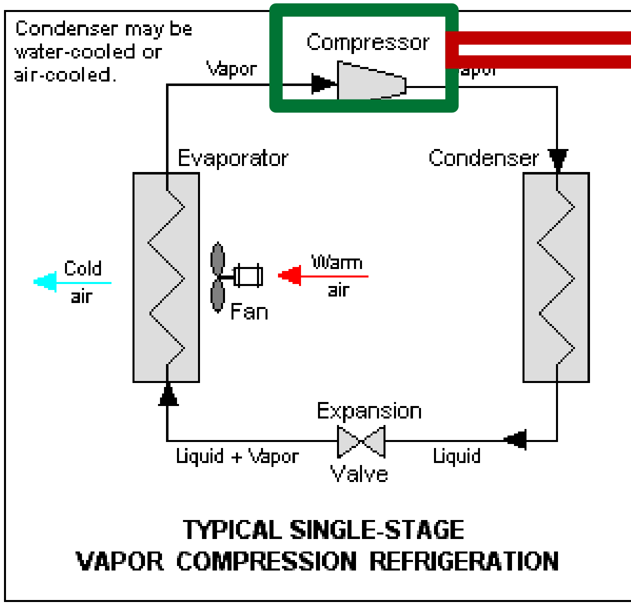


VAPOUR COMPRESSION COOLING CYCLE





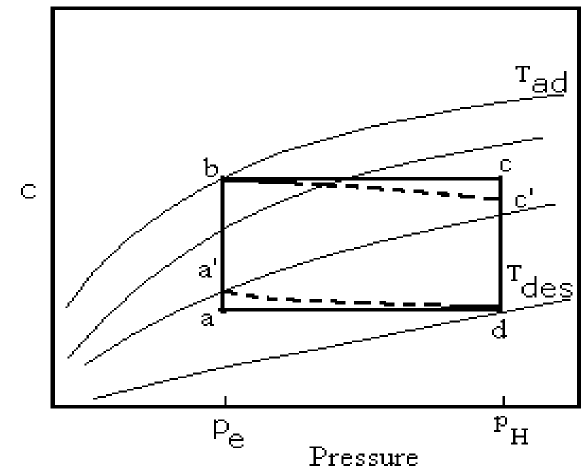
Vapour Compression Cooling Cycle



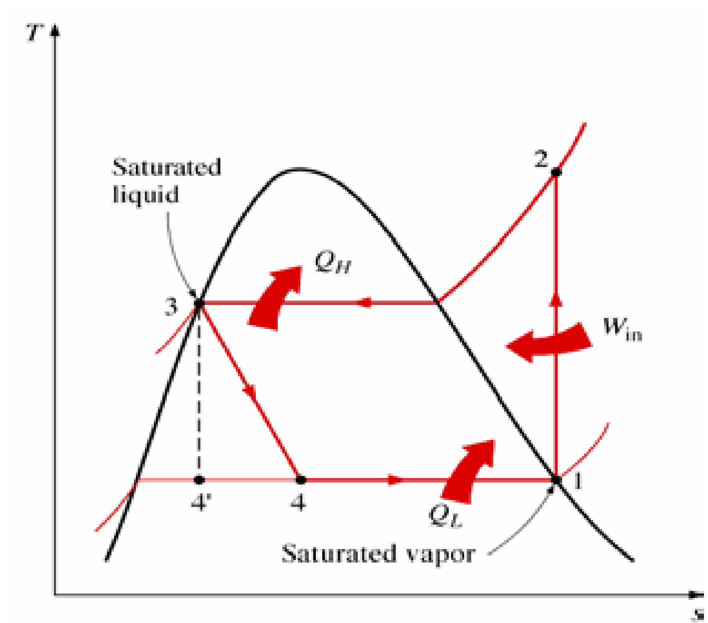
Replace with thermal compression

Thermal compression with adsorption: how does it work?

Activated carbon + refrigerant

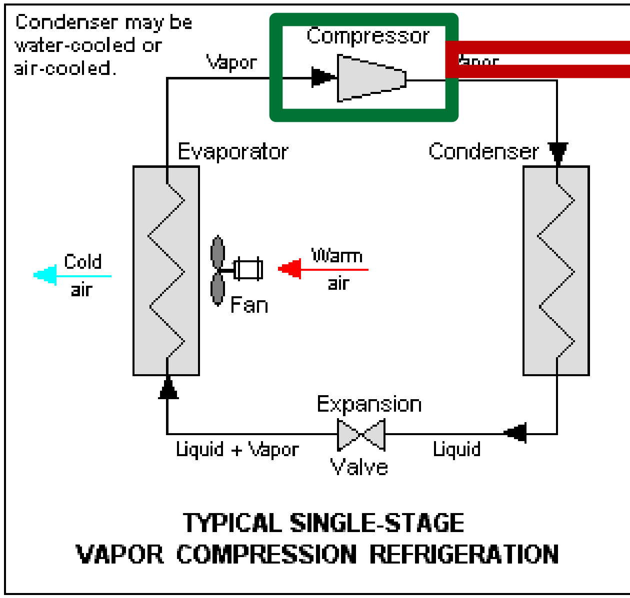


a-b: Cooling and adsorption
b-c: Heating and pressurisation
c-d: Heating and desorption
d-a: Cooling and depressurisation
a-a': adsorption loss due to void volume
c-c': desorption loss due to void volume



Flexibility of various combinations of adsorber and adsorbent

VAPOUR COMPRESSION COOLING CYCLE



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Thermal compression with adsorption: how does it work?

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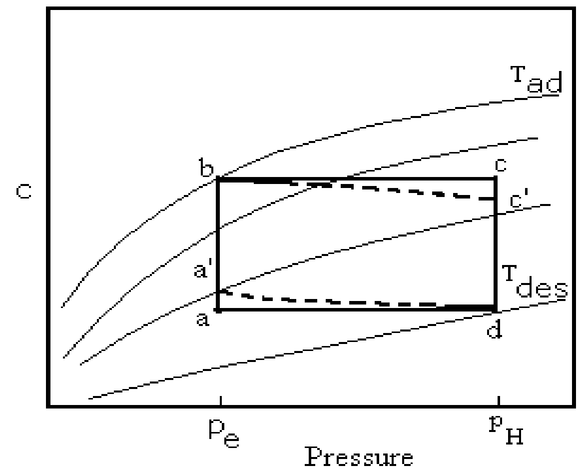
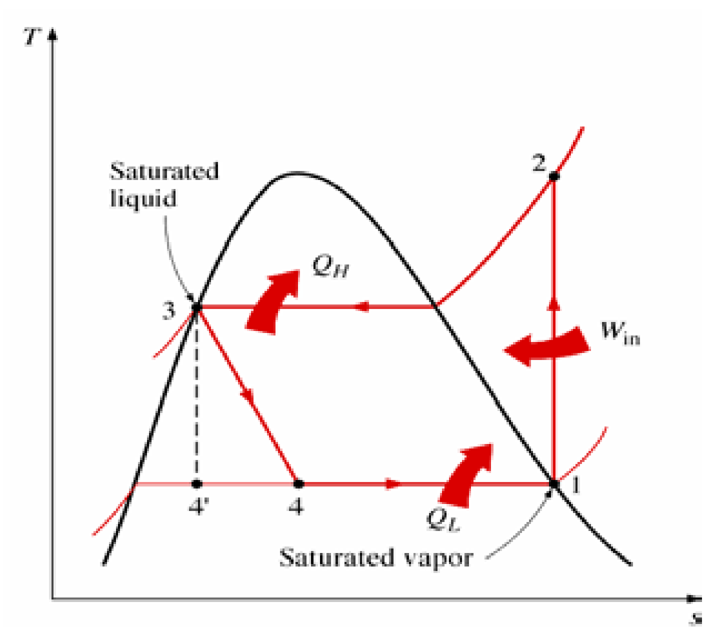


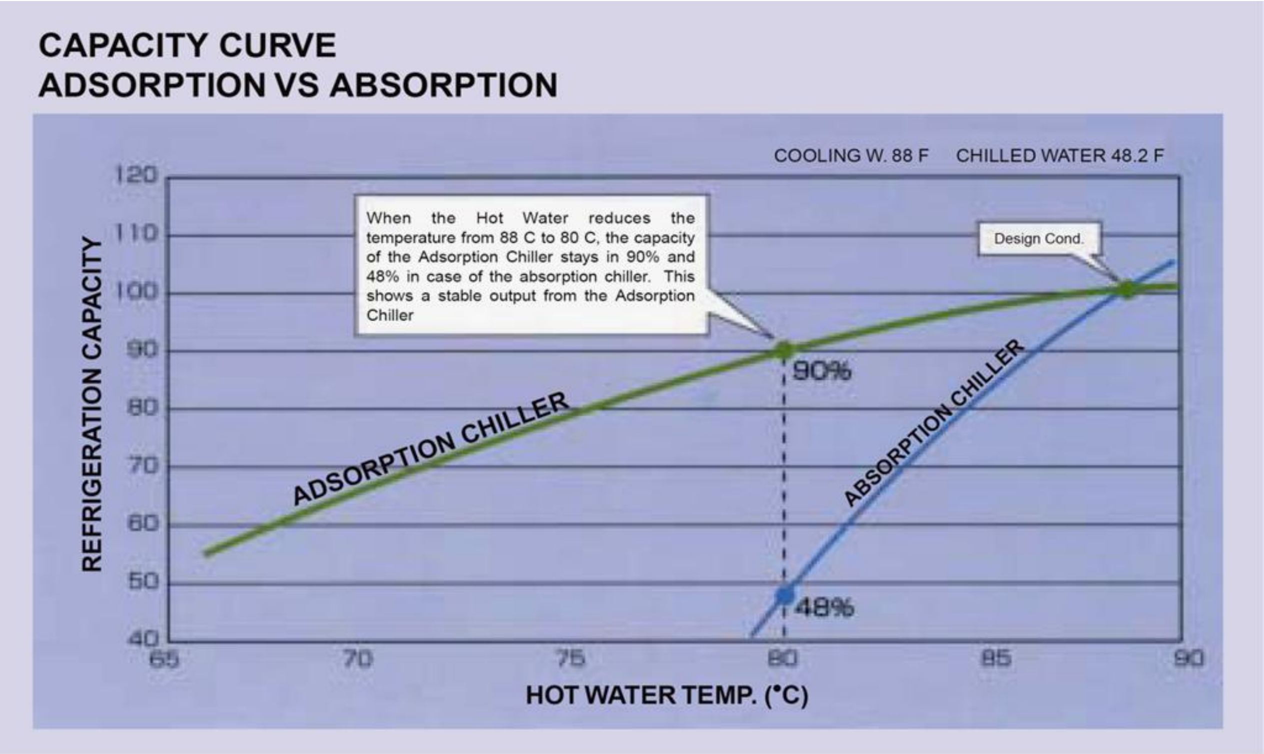


a-b: Cooling and adsorption
b-c: Heating and pressurisation
c-d: Heating and desorption
d-a: Cooling and depressurisation
a-a': adsorption loss due to void volume
c-c': desorption loss due to void volume

Flexibility of various combinations of adsorber and adsorbent

Adsorption System vs *Absorption System* (e.g. Li-Br water)

- Environment friendly and non-corrosive materials
- No solution pump, solution heat exchangers, fewer moving parts
- No danger of crystallisation *(LiBr water- messy recrystallization problems and possible stoppage if desorption temperature is not controlled)*
- **Can work with lower heat source temperatures**
- Simpler construction and high potential for cost reduction
- **Steady operation and better part-load performance**



SOLAR COOLING AND PRODUCTION OF POTABLE WATER WITH TWO STAGE SILICA GEL WATER ADSORPTION SYSTEM

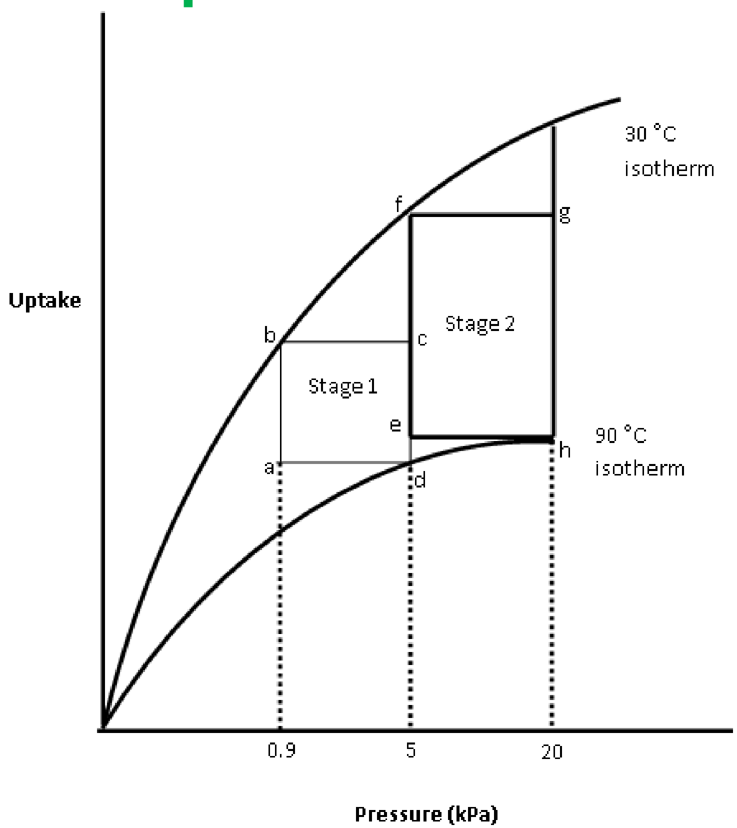
R & D PROJECT PROPOSAL
Sponsored by
DEPARTMENT OF SCIENCE AND TECHNOLOGY
GOVERNMENT OF INDIA

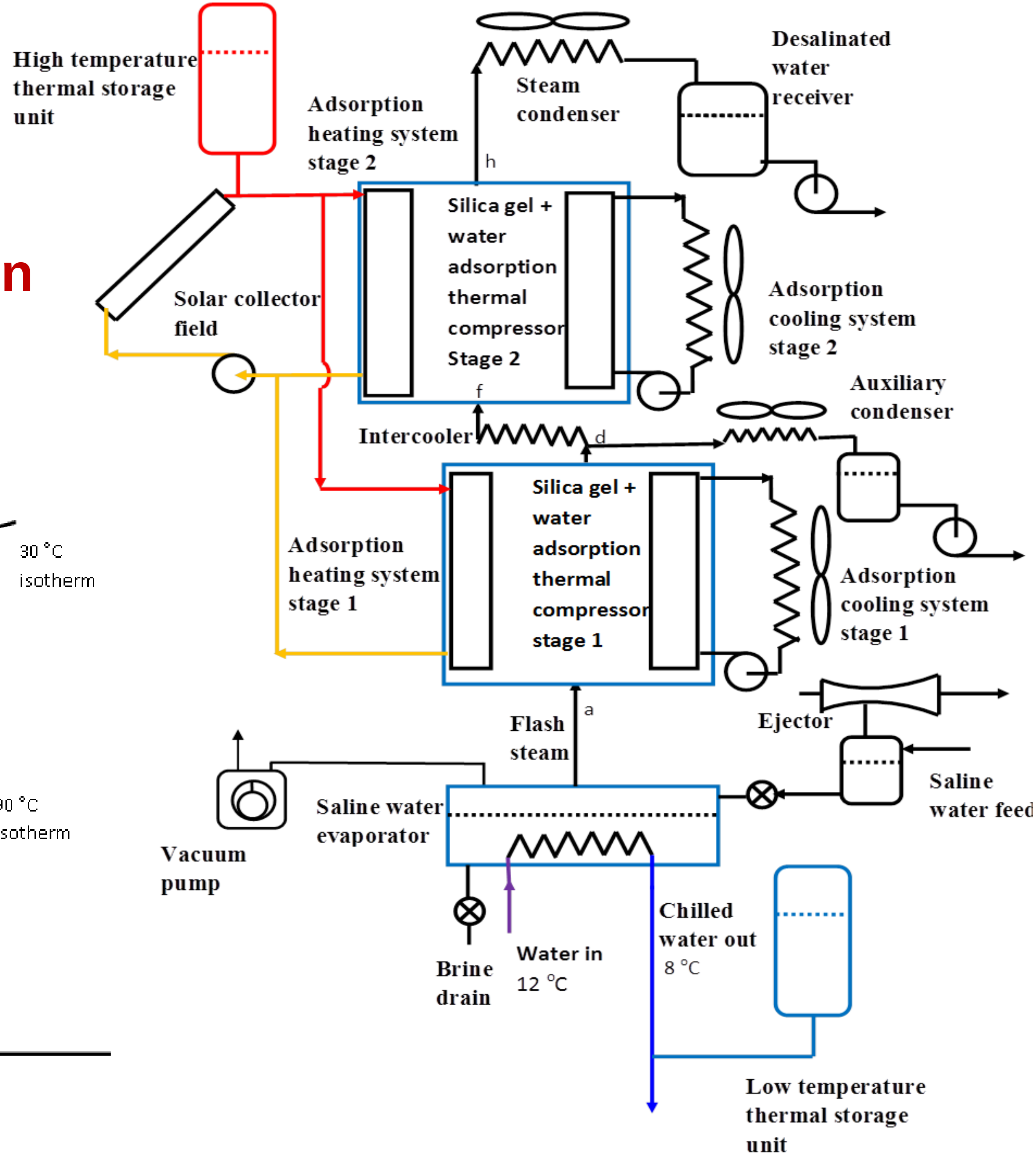
- Rural areas: need for
  1) refrigeration for food preservation
  2) potable water
- Both are generally energy intensive. If low grade thermal energy such as *solar energy* can be used for meeting the above objectives, then solution is *affordable* as well as *sustainable* – boost for rural economy

Solar Cooling + Desalination

Flash evaporation + thermal compression

2-Stage Silica Gel Adsorption

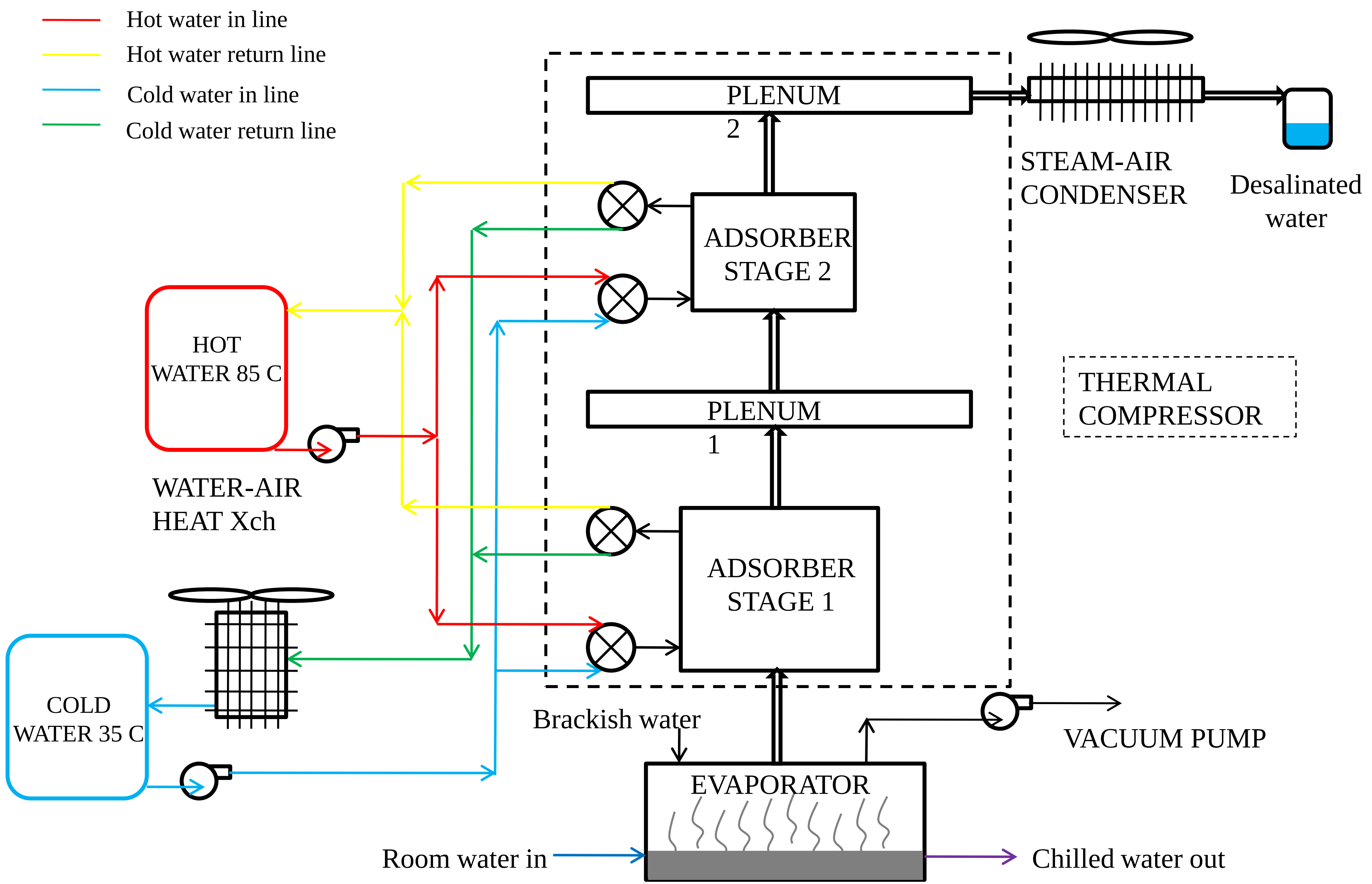




Solar Cooling + Desalination

Sponsor: DST

Flash evaporation + thermal compression (2-stage)



Summary

- India specific CSP options evaluated
- Steam based CSP not viable
- Steam good for process heat, cooking etc.
- CO_2 Brayton for high T applications (high efficiency, scalable, waterless)
- ORC (mixtures) for low T (low/moderate insolation, scalable, low cost storage, low cost collector, hybridization)
- Solar for process heating or cooling has high conversion efficiency

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Thank you