Consulting Group

Session 7

HTF, Supplementary Firing , ISCC & Hybridisation with other RE

REC III CSP Training workshop,
Kaushal Chhatbar

18 November, 2015

Contents

Objectives for efficient Heat Transfer Fluids (HTF) for CSP plants

- Collect & transport heat from the absorbers / solar field with temperatures as high as possible
- Feed absorbers with low temperatures
- Max & min temperatures limited by type of HTF
  => both affect max power cycle efficiency
- Selection of HTF type also affects type of thermal storage

Desired characteristics

- High operating temperature
- Stability at high temperature
- Non-corrosive
- Safe to use
- Low vapour pressure
- Product life cycle
- Low freezing point
- Low viscosity
- Low material maintenance and transport
- **costs**: low cost

Heat Transfer Fluids in CSP plants

Heat Transfer Fluid types

- Synthetic oils
- Water/steam
- Molten salts
- Air and other gases

R&D
- Mineral based HTFs (e.g., GlobalthermTM M)
- Liquid metals

Praveen Kumar V, Madhu Sharma *Analysis of Heat Transfer Fluids in Concentrated Solar Power (CSP) A Review Paper* Published in: International Journal of Engineering Research & Technology Vol. 3 - Issue 12 (December - 2014) e-ISSN:2278-0181

Renewable Energy Focus, *Volume 16, Issue 3*, *May–June 2015*, *Pages 24-29, 42*Christopher Ian Wright, Thomas Bembridge, Edward Anthony Wright

Heat Transfer Fluids in CSP plants

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Heat Transfer Fluid types

Heat Transfer Fluid	CSP Technology	Pressure	Temperature	Power Generation System	Storage Type
Synthetic Oil	PT, LF	15 bar	400 °C	Steam turbine	Indirect Molten Salt (two tank system)
Water/Steam (saturated/ superheated)	CR, PT, LF	40-120 bar	250-550 °C	Steam turbine	Steam Accumulator
Molten salt	CR, PT, LF	1 bar	400-600 °C	Steam turbine	Direct Molten Salt (two tank system)
Air (open / Pressurized)	CR	1-15 bar	700-1100 °C	Gas turbine, Stirling engine	Concrete (porous storage material -

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Heat Transfer Fluids in CSP plants

Synthetic HTFs

- specifically based on eutectic hydrocarbon mixtures of biphenyl and diphenyl oxide such as GlobalthermTM Omnitech
- can cost up to $100 per kg (Vignarooban et al. 2012)
- used according to operating temperature:
  - glycol based fluids: applications below 175°C
  - synthetic fluids: applications above 400°C

Water

- not frequently used
- will get oxidized quickly on high temperatures
- can encourage the materials of the absorber tube to react
- can cause corrosion in the inner parts of the tube

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Heat Transfer Fluids in CSP plants

Molten salts

- tendency to get solidified when it reaches low temperature
- tendency of decomposition at high temperature

Air

- not frequently used
- upon heating will increase by volume
- so larger heat exchanger has to be installed for efficient heat transfer
- increases the investment cost

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Heat Transfer Fluids in CSP plants

Practical aspects

- Anti-freezing
  - Particularly important in colder regions
  - HTFs anti-freezing properties for fluid lifetime of over 20 years.
  - Adding antifreeze agents to **water**: negative impacts on system performance (boiling point is increased, and thereby viscosity and higher power consumption;reduced heat transfer efficiency reduced because of decrease of thermal conductivity and specific heat)
- Corrosion
  - **salts** are corrosive; effect cannot be protected by corrosion inhibitors
  - **glycols and alcohols** without corrosion inhibitors are corrosive (glycol produces acid on oxidation, resulting in lower pH value due to high temperature -> pH buffers and proper corrosion inhibitors)

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Heat Transfer Fluids in CSP plants

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Practical aspects

- Corrosion
  - controlled by design and operation:
    - selection of materials, temperature limit and exposure to oxygen
    - usage of corrosion inhibitors
    - purity level of fluid
    - **metals** should be maintained in the passive state

- Health, safety and environmental aspects
  - Toxicity (**alcohols and glycols**: moderately toxic; propylene glycol: no adverse health & safety effects)
  - **Alcohols:** flammability and due to fire safety concerns it avoided

Praveen Kumar V, Madhu Sharma *Analysis of Heat Transfer Fluids in Concentrated Solar Power (CSP) A Review Paper* Published in: International Journal of Engineering Research & Technology Vol. 3 - Issue 12 (December - 2014) e-ISSN: 2278-0181

Heat Transfer Fluids in CSP plants

Common HTFs in PT commercial operating plants

- Eutectic mixture of diphenyl oxide (DPO) and biphenyl (BP)
- Most popular products :
  - Therminol® VP-1
  - Dowtherm® A
  - Diphyl®
- Liquid between 12 °C and upper operating temperature of 400 °C (provided system is pressurized always above the vapor pressure , 10.9 bar at 400 °C)
- Above 400°C: decomposition rate of DPO/BP is rapidly increasing

  ->400°C upper bulk temperature limit
- Film temperature in boundary layer of externally heated receiver tubes may be higher. Maximum film temperature: 430 °C (VP-1 datasheet)

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Heat Transfer Fluids in CSP plants

Mainly used HTFs characteristics (Dec-2014):

HTF	T_{max} (K)	C_p (KJ/kg.K)	ρ (kg/m^3)	K (W/m.K)	μ (mPa.s)
Xceltherm	580	3	672.36	0.113	0.252
Biphenyl	500	2.03	869	0.118	0.32
Phenyl-naphthalene	600	2.6	849	0.077	0.11
Dowtherm A	678	2.73	672.5	0.0771	0.12
Therminol 66	648	-	1011	0.09	0.29
Nitrate Salts	873	1.495	1899	-	3.26
Hitec	720	2.319	1992	-	6.37

*Source: NREL, ORNL for Heat Transfer Fluids

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Contents

<u>Session 7</u>

Supplementary Firing

Hybrid power systems combine two or more energy conversion mechanisms, or two or more fuels for the same mechanism, that when integrated, overcome limitations inherent in either. Hybrid systems provide a high level of energy security and reliability through the integrated mix of complementary generation methods, and often will incorporate a storage system (battery, fuel cell) or fossil-fueled power generation to ensure consistent supply.

Hybridisation approaches:

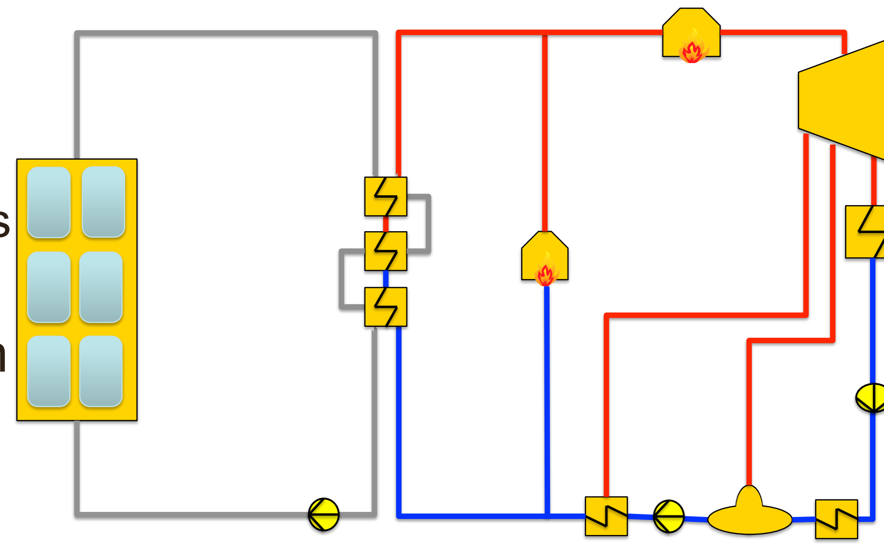
- Fossil backup and boosting – supplementary firing
- Integrated solar combined cycle (ISCC) plants
  - in coal-fired power plants
- CSP hybridisation with other REs
- Novel and advanced hybrid systems

Lovegrove & Stein, 2012, *Concentrating Solar Power Technology*
Massachusetts Institute of Technology, May 2015, *The Future of Solar Energy,*
http://cleantechnica.com/2015/04/02/csp-pv-hybrid-plants-gain-sway-chile/ (06 Nov 2015)

Supplementary Firing

Characteristics:

- Decoupling / shifting of energy production from solar irradiation
- Reliable base load energy supply from within the same plant
  - no external back-up or storage facilities required
- Mitigates fluctuation in generation from PV and wind energy
- Support stability of electric distribution systems (primary and secondary frequency control)

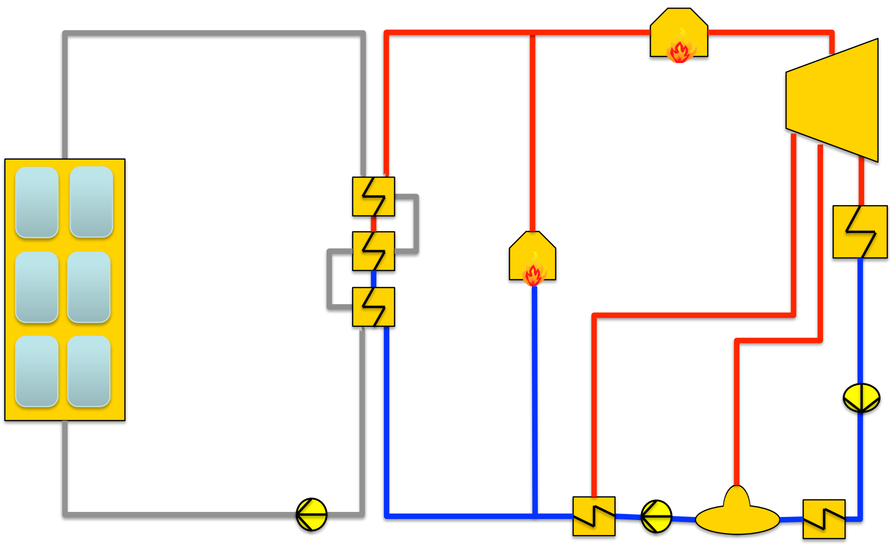


Lovegrove & Stein, 2012, *Concentrating Solar Power Technology*
Massachusetts Institute of Technology, May 2015, *The Future of Solar Energy,*
http://cleantechnica.com/2015/04/02/csp-pv-hybrid-plants-gain-sway-chile/

Supplementary Firing

Characteristics

- Large and small scale – plant sizes could range from small industry and off-grid scale (0,5 - 10 MW) to large utility scale (up to 250+ MW)
- Integrate with fossil fired generation (existing or new) and substitute conventional fuel (fuel saver, gradual approach)
- Off-grid power island capability (rural regions, off-grid industry developments)



Lovegrove & Stein, 2012, *Concentrating Solar Power Technology*
Massachusetts Institute of Technology, May 2015, *The Future of Solar Energy,*
http://cleantechnica.com/2015/04/02/csp-pv-hybrid-plants-gain-sway-chile/

Supplementary Firing

Advantages of Supplementary Firing

- Higher reliability of energy production (electricity demand vs. electricity production)
- Balancing of solar resource fluctuations (additional to TES)
- Short response time (auxiliary heat can be provided flexible and fast)
- Auxiliary heat for warm up of solar field and power block
- Auxiliary heat for trace heating systems (prevent HTF from freezing)

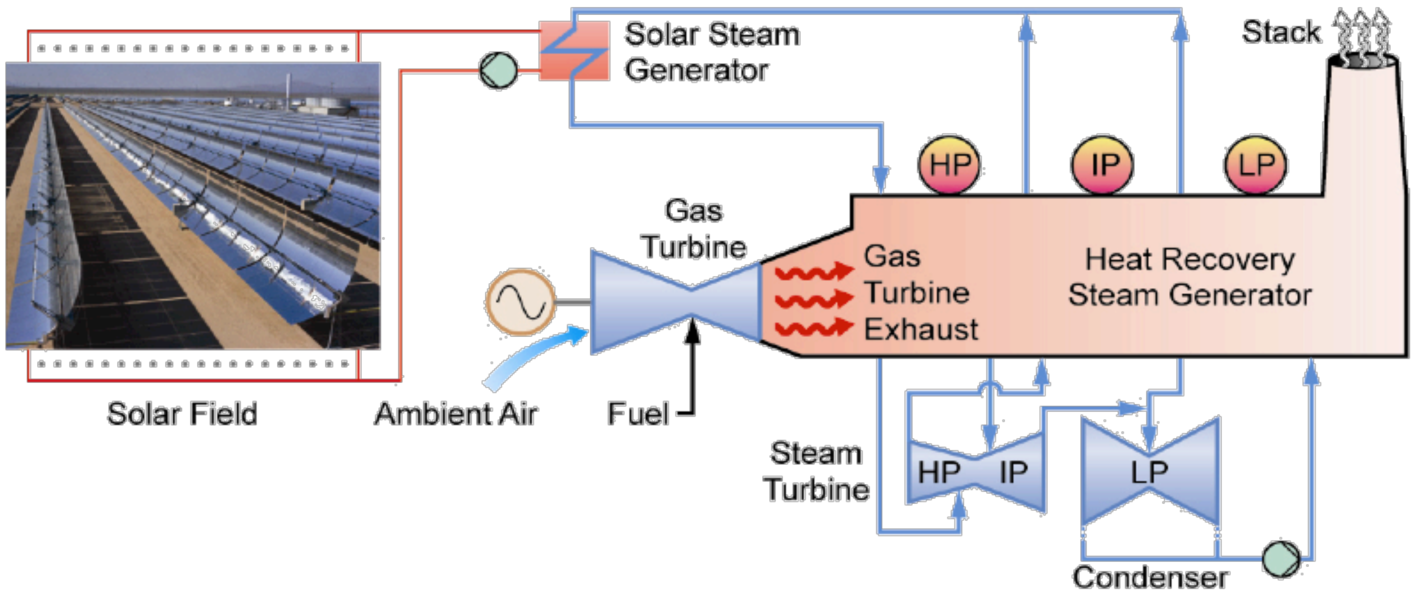
Disadvantages of Supplementary Firing

- Cost for fossil fuels
- Costs for additional auxiliary heater system components (combustion chamber, heat exchanger, pumps, piping, control system, fuel supply etc.)
- Complexity of the system increases
- Possible restrictions due to FIT/governmental support structures

Contents

ISCC

Integrated Solar Combined Cycle (ISCC) = Integration of solar thermal energy into a conventional power plant



ISCC as combined-cycle power plant with normal gas and steam turbines but with an additional component: the solar field

(C. Libby, "Solar Augmented Steam Cycles for Natural Gas Plants," 2008)

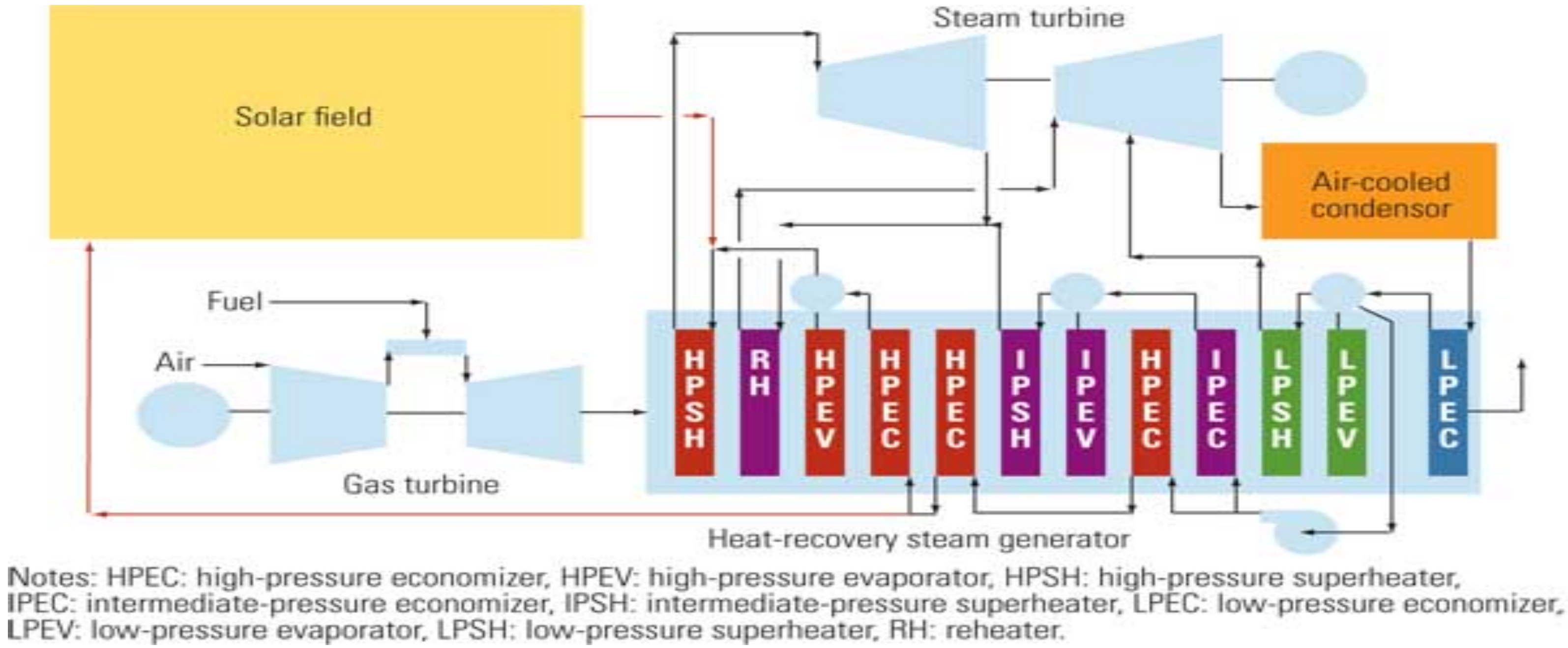
Integration concepts

- Possible at multi-points and multi-levels
  - e.g. by replacing part of steam extraction in the regenerative Rankine cycle
- Strategy depends on the type of project
  - solar augmentation in coal plants
  - in combined cycles
- Highly dependent upon the ("solar") steam conditions:
  - temperature, mass flow, pressure…
- Three categories based on the heat transfer fluid temperature capabilities:
  - high temperature (>500 °C)
  - medium temperature (around 400 °C)
  - low temperature (250 °C – 300 °C)

Integration concepts categorized by HTF temperature:

Concept	Temperature	Collector technology	Temperature
High temp.	>500 °C	Solar tower	mostly aiming at temperatures greater than 500 °C
Medium temp.	around 400 °C	Parabolic trough	highest: 400- 500 °C (molten salt as HTF: up to 500 °C), limited to the thermal oil capacity: 400 °C
Low temp.	250°C – 300°C	Linear Fresnel	usually: direct steam generation process, saturated steam at around 270 °C to 300 °C upgrades in demonstration plants: 400-500 °C

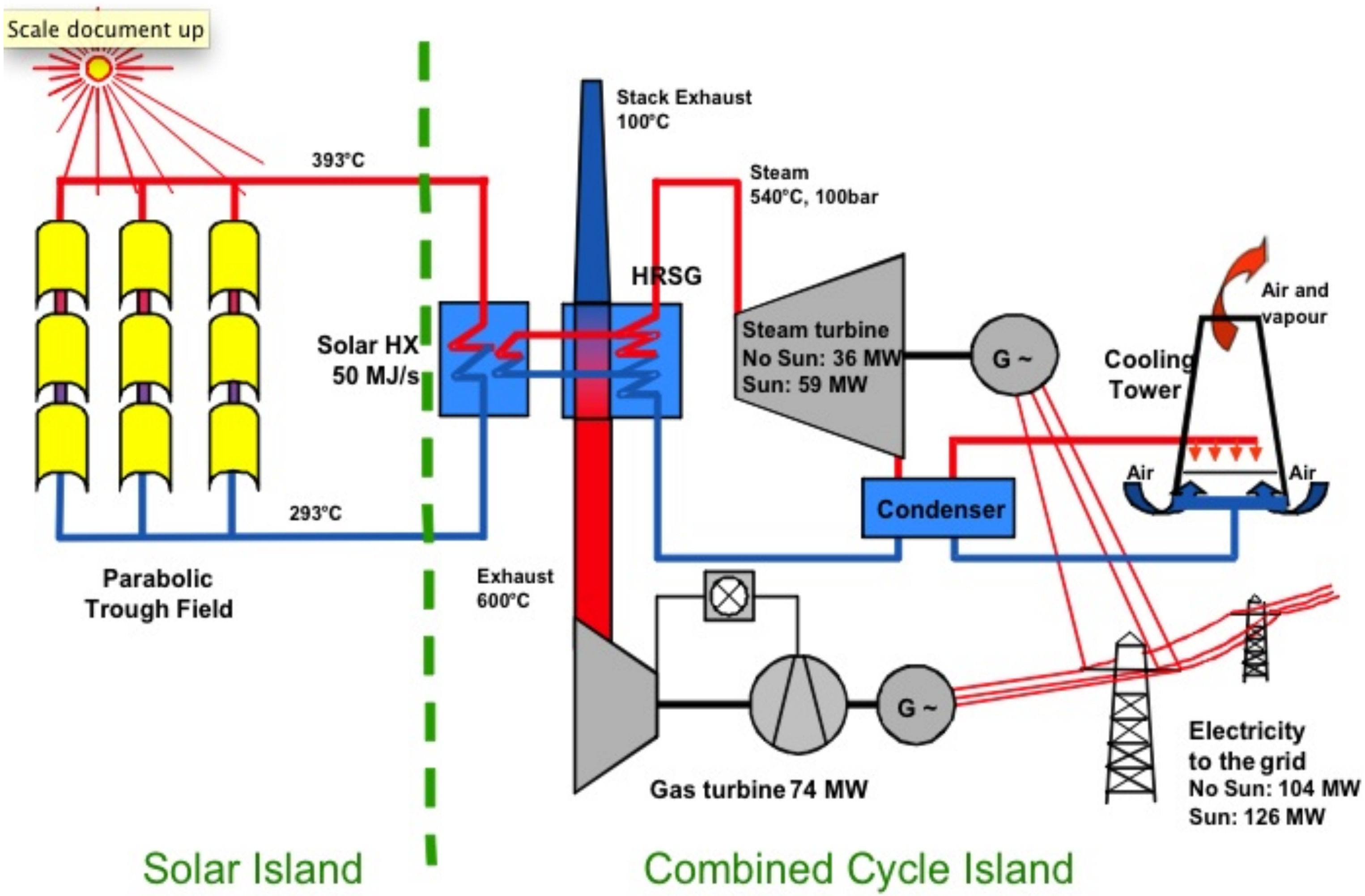
ISCC with parabolic trough



- HTF temperature leaving the solar steam generator: typically around 290 °C,
  ->ideal injected feedwater (from HRSG) should be around 260 °C
- most convenient place to integrate feedwater into the HTF heat exchanger (solar boiler) is from the discharge of the high pressure feedwater pump, where temperature is around 260 °C

(D. Ugolini and J. Zachary, *Options for Hybrid Solar and Conventional Fossil Plants*, United States: Bechtel Technology, 2009)

ISCC - Components

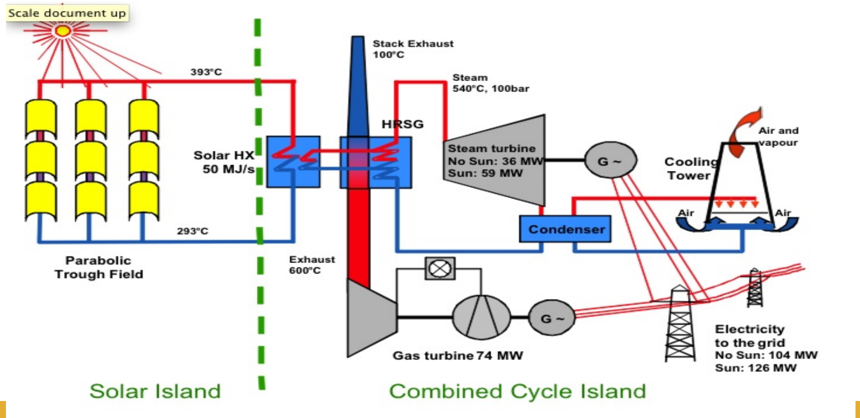


ISCC - Components

Name of the component	Description
Solar steam generator	Composed of − high-pressure super-heater − evaporator − high pressure economizer
Steam turbine	Several stages, defined by inlet pressure and efficiency
Condenser	Parameters: enthalpy and amount of the steam
Cooling tower	Wet or dry cooling
Generators	Parameters: efficiency, characteristic lines
Pumps / motors	− define pressure of the flow system / drive pumps (-> power consumption) − feed pump pressure defined by the boiler − required power: based for water on an isentropic compression and for oil on density and pressure difference

ISCC - Operation

- Solar steam is generated in parallel to the HRSG system
- Preheated feedwater for the solar steam generator is drawn from the deaerator at approximately 74 bar and 150 °C, and injected in the HTF economizer, then evaporated and slightly superheated up to 329 °C in the solar steam generator,
- returned back to the HRSG system and injected into the steam from the conventional high pressure evaporator,
- finally superheated to the live steam temperature at 559 °C and injected in the high pressure stage of the steam turbine



ISCC - Operation

Start up of ISCC:

- **Pre start conditions**
  - electrical grid should be available and without anomalies
  - start conditions of plant components
- **Gas Turbine start**
  - generator first used as motor, then declutches and becomes a generator
  - Before starting gas turbine (ignition): HRSG must be purged
- **HRSG start**
- **Steam Turbine start**
  - gas turbine load is ramped-up to a level whereby the high-pressure steam temperature matches critical temperatures of the steam turbine
  - Live steam matches inlet conditions - steam first partly, then fully injected in the steam turbine

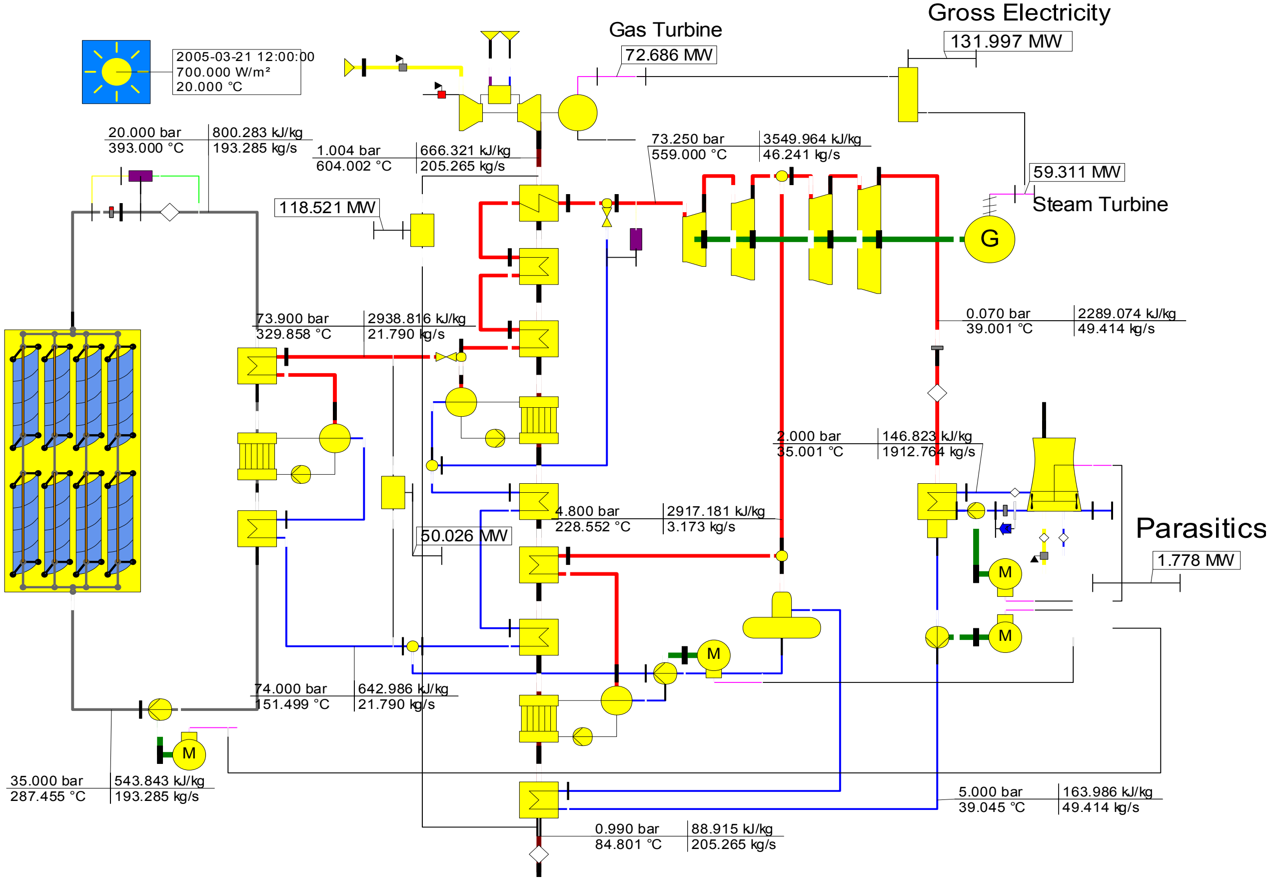
ISCC - Operation

- **HTF heat exchangers start-up**
  - Pressurization with steam from the HRSG;
  - following admission of feedwater from the HRSG to the HTF heat exchanger
  - HTF reaches 393 °C: starts to flow through HTF heat exchangers
- **ISCC Normal Operation**
  - HRSG will follow the normal load changes of the gas turbine and import steam from the HTF heat exchangers system.
  - Operation of solar thermal power plants is similar to other large Rankine Steam Power Plants

ISCC - Simulation

Simulation: e.g. with Ebsilon

- input data a file generated from METEONORM with hourly DNI, ambient temperature and relative humidity data



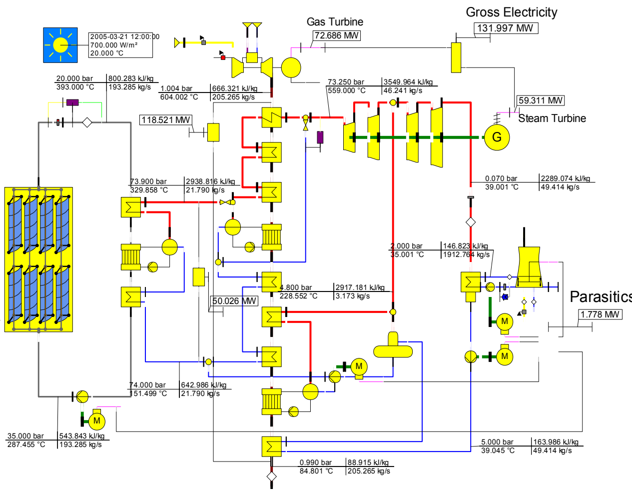
Operation modes:

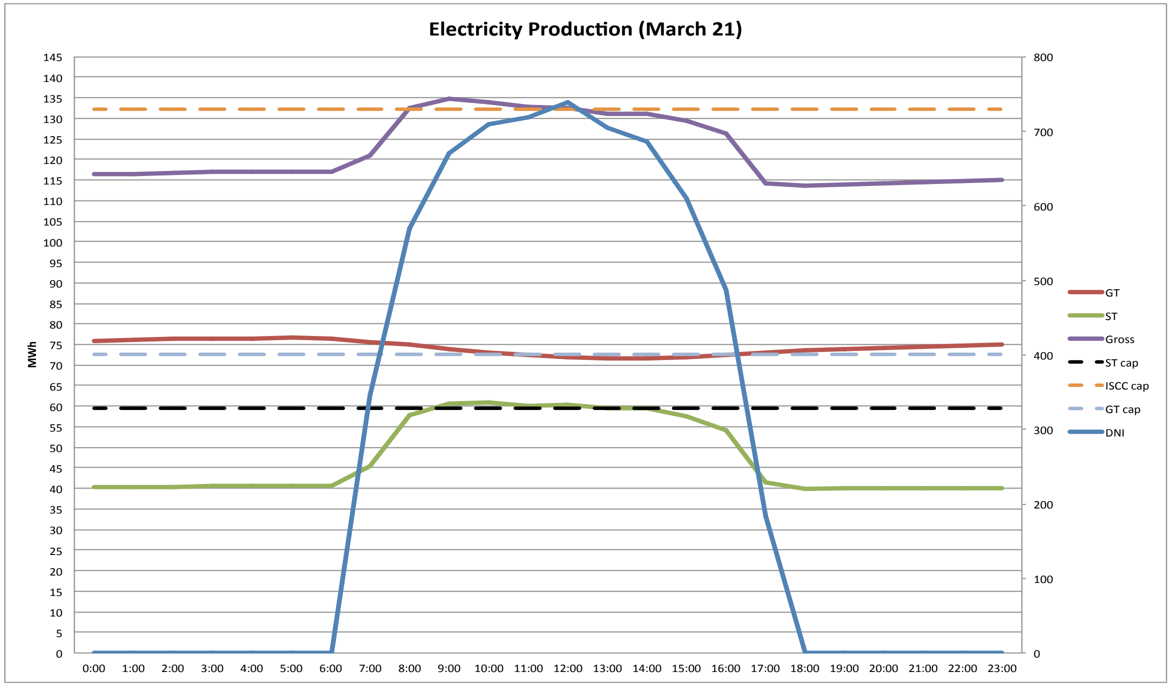
- Clear sky
- High levels of solar irradiation
- Cloudy days
- Night
- Fuel saving mode

ISCC - Simulation

Simulation: Clear sky

- Suitable ambient conditions for operation of solar field with combined cycle
- all steam generated from the solar field is used
- gas and steam turbine operate at their nominal power



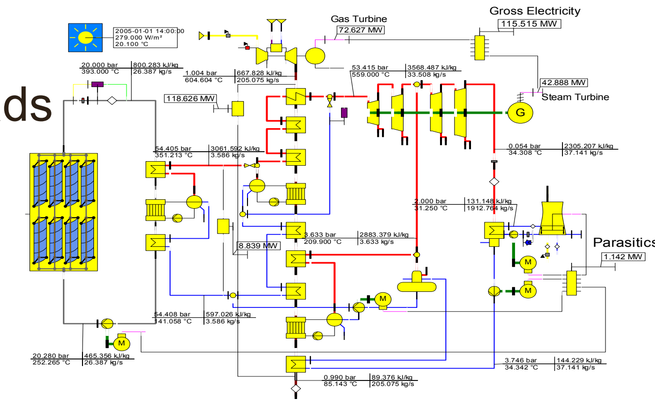


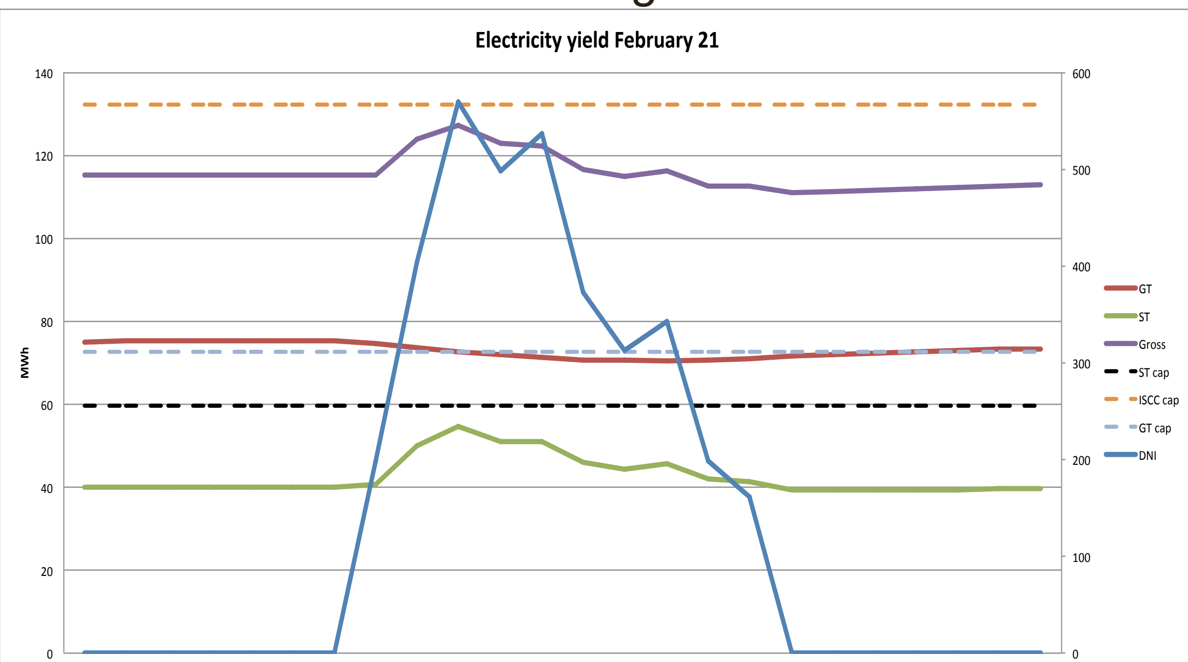
Gross electricity output	**2922**	**[MWhel]**
A. Gas turbine output	1782	[MWhel]
B. Steam turbine output	1140	[MWhel]
B.1 HRSG equivalent	978	[MWhel]
B.2 Solar Field equivalent	162	[MWh_e]
Solar share	**5.54**	**%**
Fuel consumption	**366 998**	**[kg]**

ISCC - Simulation

Simulation: cloudy days

- steam turbine is working under sudden changes in loads
- low irradiation, ambient conditions are not enough to achieve the minimum outlet temperature of the HTF
- by-pass valves in the HTF heat exchangers will be opened in order to circulate the HTF and not generate steam in the solar steam generator





Gross electricity output	2774	[MWhel]
A. *Gas turbine output*	1752	[MWhel]
B. *Steam turbine output*	1022	[MWhel]
B.1 *HRSG equivalent*	*956*	[MWhel]
B.2 *Solar Field equivalent*	*66*	[MWhel]
Solar share	**2.37**	**%**
Fuel consumption	**362721**	**[kg]**

ISCC - Simulation

Simulation operational modes:

High levels of solar irradiation

- DNI conditions are higher than design parameters, the amount of solar steam is greater than what actually the steam turbine can handle
- Parts of the collectors would be defocused in order to control the steam production from solar field

Night

- Solar resource is not available and only the combined cycle is working. The HTF system is shutdown.
- Gas turbine is still operating at full load while the steam turbine is operating at partial load, lacking the steam from solar field

Examples: CSP with coal-fired power plants (ISCC)

- Proposed for countries with large resources and demand (e.g. Australia, China, India)
- For repowering of older coal-fired power plants with capacity < 300 MW
- Enhancement of output without oversizing the steam turbine
- Cameo, Colorado Integrated Solar Project (Abengoa, U.S. Department of Energy):
  - hybrid CSP-Coal test plant, parabolic trough solar field (4 MWe) provided thermal energy to produce supplemental steam for power generation at Xcel Energy's Cameo Station's Unit 2 (approximately 2 Mwe, total plant: 44 MW)
  - built between September 2009 and February 2010, operational from spring 2010, decommissioned when coal plant was retired (Dec 2010)
  - positive results

Lovegrove & Stein, 2012, *Concentrating Solar Power Technology*
http://social.csptoday.com/markets/india-makes-solar-hybrid-comeback
http://www.cspworld.org/cspworldmap/cameo
http://inhabitat.com/worlds-first-hybrid-coal-solar-power-plant-goes-online-in-colorado/cameo-ss-photo/
http://www.nrel.gov/solar/news/2010/870.html

Examples: CSP with coal-fired power plants (ISCC)

- Kogan Creek Solar Boost, Australia (CS Energy Ltd.)
  - Coal: 750 MW air-cooled supercritical steam turbine (plant commissioned in 2007)
  - Solar CSP AREVA compact linear fresnel reflector (CLFR), water/ direct steam energy transfer (start of construction in Dec 2011, expected completion: 2016)
- "hundreds of megawatts of hybrid-CSP in more than a dozen hybrid projects in various stages of development (or de-commissioning)" (by 2012)
  - Sundt generation station, Tucson (Tucson Electric Power (TEP) Areva Solar) working on a CSP "booster" to the 156-megawatt Unit 4 (dual-fueled unit capable of using coal or natural gas), Linear Fresnel Reflector (CLFR) solar steam generators to produce up to 5 megawatts of power during peak power demand
  - Tri State G&T in Escalante, New Mexico: 245-megawatt coal plant with 36 megawatts of proposed solar
  - FPL project, Florida: 75 megawatts of solar
  - Areva has a 44 MW solar booster project for an coal-fired power plant in progress and has more than 540 megawatts of CSP projects in operation, under construction, or in development

http://www.nrel.gov/solar/news/2010/870.html
http://www.cleanenergyactionproject.com/CleanEnergyActionProject/CS.Kogan_Creek_Solar_Boost_Project___Hybrid_Renewable_Energy_Systems_Case_Studies.html
http://www.greentechmedia.com/articles/read/can-solar-csp-be-integrated-with-a-fossil-fuel-plant

Example: NTPC Dadri power plant

- In 2013, NTPC commissioned its first solar power project at Dadri thermal power station: a **5 MW PV** plant (power fed through gas-based Dadri plant's transmission line, inverters and step-up transformers into the grid, capital costs of Rs. 48.59 crore) together with weather station
- Now planned: **14 MW CSP plant** (limiting land area) near the 1,820 MW coal-based Dadri thermal power plant (TPP, 4X210 MW + 2X490 MW) in Uttar Pradesh state, established at one of the 210 MW units
- Steam generated by solar at 390 °C, further heated up to 550 °C shall support turbines for electricity generation

(Mr. Lavleen Singal, President of Acira Solar)

http://articles.economictimes.indiatimes.com/2013-03-29/news/38125570_1_solar-plant-ntpc-dadri-first-solar-power-project (13 Nov 2015)
http://www.szwgroup.com/csp-focus-india-2015/EB/4.14/ (13 Nov 2015)
http://renewables.seenews.com/news/to-the-point-indias-ntpc-calls-tender-for-csp-unit-near-dadri-tpp-470601 (13 Nov 2015)
http://www.ntpc.co.in/power-generation/coal-based-power-stations/dadri (13 Nov 2015)
http://www.livemint.com/rf/Image-621x414/LiveMint/Period1/2012/08/07/Photos/Copy%20of%20Power%201--621x414.jpg (13 Nov 2015)

Economic analysis: example scenarios

ISCC plant in Egypt

- selling price of electricity from an IPP to the Egyptian electricity distribution company: around 31.7 USD/MWh (2010)
- Natural gas is highly subsidized, averaging around 1 USD/MMBTU, compared to the current world market price of 4 USD/MMBTU
- Main results on total revenues (two operation strategies):

	Electricity Sales	Fuel expenses	Revenues
	[USD]	[USD]	[USD]
Defocusing	83 941	16 952	**66 989**
Load reduction	79 535	16 006	**63 529**
Difference	4406	946	3460 (gained if defocusing)

ISCC plant in Algeria

- feed-in tariffs (2004) are differentiated by technology, including CSP
- tariff is reduced when only portion of plants generation
- expressed as a percentage of the average electricity price (set annually by power market operator), paid both for own consumption and sales to the grid

	Electricity Sales	Fuel expenses	Revenues
	[USD]	[USD]	[USD]
Defocusing	167 883	16 952	**150 931**
Throttling	159 070	16 006	**143 064**
Difference	*8 812*	*946*	*7 867 (gained if defocusing)*

ISCC plant in Mexico

- no feed-in tariff (2011), but IPPs are allowed to sell the electricity to the state-owned electricity company CFE at a price of around 60 USD/MWh

	Electricity Sales	Fuel expenses	Revenues
	[USD]	[USD]	[USD]
Defocusing	158 880	67 809	**91 071**
Throttling	150 540	64 025	**86 515**
Difference	*8 340*	*3 784*	*4 556 (gained if defocusing)*

Contents

Session 7

Hybridisation of CSP plants

CSP hybridisation with PV

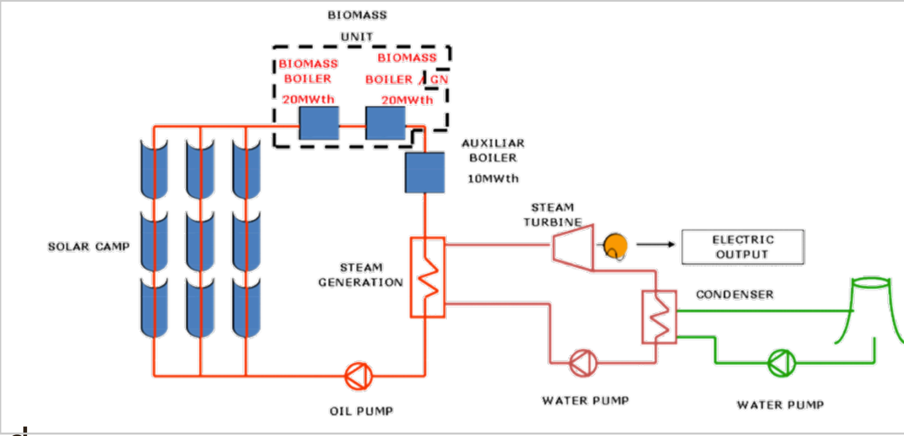
- Chile
  - Copiapó (SolarReserve, LLC): two 130 MW CSP solar towers with 14 hours of molten salt-based storage, combined with a 150 MW PV plant (totally 260 MW of 24/7 baseload electricity) announced in 2014 by US-based SolarReserve
  - Atacama II (Abengoa) Antofagasta: 100MW of solar PV, 110MW CSP tower, storage capacity of 15 hour, granted permission to build in June 2015
- South Africa (ACWA Power, technology: SolarReserve LLC)
  - Redstone, Northern Cape Province
  - CSP tower technology (100 MW), with Molten Salt Thermal Energy Storage Size: (12 hours of full load), Dry cooling, annual electricity Production: 480,000 MW-hours
  - bidding won by ACWA in January 2015

Source:
http://cleantechnica.com/2015/04/02/csp-pv-hybrid-plants-gain-sway-chile/
http://www.solarreserve.com/en/newsroom/in-the-news/csp-pv-hybrid-plants-gain-sway-in-chile,
http://reneweconomy.com.au/2015/mega-hybrid-solar-projects-ready-to-take-on-baseload-fossil-fuels-17409
http://www.abengoa.com/web/en/noticias_y_publicaciones/noticias/historico/2015/01_enero/abg_20150126.html

Hybridisation of CSP plants

CSP hybridisation with biomass

- similar to CSP-gas hybrids
- first such plant: Termosolar Borges (Abantia, Comsa EMTE, components: MAN, Siemens)
  - Les Borges Blanques, Spain
  - 22.5-MW parabolic trough, wet cooling tower, biomass burners 2x22MWth, Natural gas as additional backup
  - operational since 2012
- Rende CSP-plant in Calabria, Italy (Falck Renewables): 1-MW Fresnel-type CSP system added as retrofit to existing biomass plant (built in 2000), came online in 2014
- Number of other such plants have been proposed in the U.S., and North Africa, but so far none are online



Picture and basic diagram Termosolar Borges

Hybridisation of CSP plants

CSP hybridisation with biogas

Example: **Off-Grid Hybrid Electricity Plant, AORA Solar Ltd.**

- Small and modular Tulip stations, producing 100kW of electricity +170kW of heat, occupying < 3,500 square meters (0.86 acres)
- Inline microturbine running on solar radiation, + gaseous or liquid fuel, (biogas, biodiesel, natural gas,…) -> variety of operational modes: solar-only mode, hybrid-mode, (when sunlight insufficient), to fuel-only mode (during night hours, heavily overcast periods)

  - Firstly installed in Israel, June 2009
  - Ethiopia: Construction of the first pilot plant (solar-biogas hybrid power as off-grid solution) by mid-2015
  - Following the trial, Ministry intends to expand deployment of installations for rural economic development to off-grid communities in selected areas of the country

Source: G. Meyers, Dec 2014, *AORA Slates First Off-Grid Solar-Biogas Hybrid Electricity Plant for Ethiopia* (http://cleantechnica.com/2014/12/04/aora-slates-first-grid-solar-biogas-hybrid-electricity-plant-ethiopia/, accessed 06 Nov 2015), World's First Hybrid Solar Power Plant Opens in Israel, June 2009 (http://inhabitat.com/worlds-first-hybrid-solar-plant-almost-complete/)

Hybridisation of CSP plants

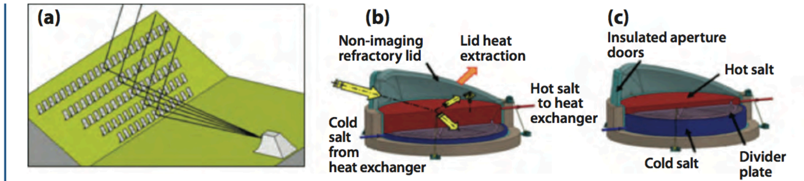
Novel and advanced hybrid systems

- Air Brayton cycle*
  - more efficient than current power cycles, does not use water, can be directly combined with natural gas combustion
  - High temperature molten salt drives a combined open-air Brayton cycle with natural gas peaking capability. Since T is above the auto-ignition temperature of natural gas, natural gas could be injected directly into the last stage of the turbine. This would allow variable power output from the system. In addition, natural gas can provide backup in this hybrid system.
  - A hybrid solar– gas turbine system was demonstrated in 2002.
- Supercritical CO2 Brayton cycle
  - due to the fact that CO2 at supercritical conditions (approximately 31°C and 70 atmospheres) is almost twice as dense as steam, which allows for the use of smaller
  - A supercritical CO2 Brayton cycle is of particular interest because of its higher efficiency (near 60%) and smaller volume relative to current Rankine cycles.
  - generators with higher power densities. The other advantage of a supercritical CO2 Brayton cycle is that it can be utilized in directly heated power cycles, in which a fuel such as natural gas is burned in a mixture of CO2 and oxygen. The combustion process increases the temperature of the working fluid (in this case CO2) while producing only water and additional CO2.
    The produced water is separated and removed, and the CO2 from combustion is also removed from the cycle.

- Direct solar-to-salt
  - Variation of central receiver design
  - Receiver is replaced by tank containing molten salt
  - Materials design issues for the receiver surface are avoided (solar energy is absorbed through several meters of penetration in the salt bath)
  - Simple integration with storage and operation at much higher temperatures than traditional receivers.
  - Does not require flat terrain

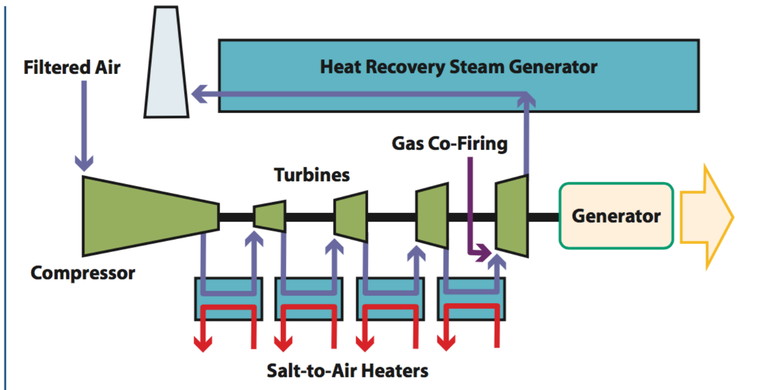
- 'Solar fuels',
  - Cleaner fuel is produced by decorbonisation of fossil fuels via decomposition, steam reforming or gasification

Figure 3.12 Direct Solar-to-Salt Design



Note: (a) Heliostat arrangement. (b) During the daytime, solar energy is absorbed and the volume of hot fluid in the tank increases. (c) At night, hot fluid is withdrawn to produce electricity.[22]

Figure 3.13 Combined Open-Air Brayton Cycle with Natural Gas Peaking Capability[23]



*Conventional Brayton cycle: used in gas turbines and jet engines.
Air is compressed, heated, and then expanded in a turbine. Generally, the Brayton cycle is capable of operating at much higher temperatures and therefore delivering higher efficiencies.

Source: Lovegrove & Stein, 2012, *Concentrating Solar Power Technology* Massachusetts Institute of Technology, May 2015, *The Future of Solar Energy,*

Thank you for your attention!