Solar Storage Technology

Use of Molten Salt

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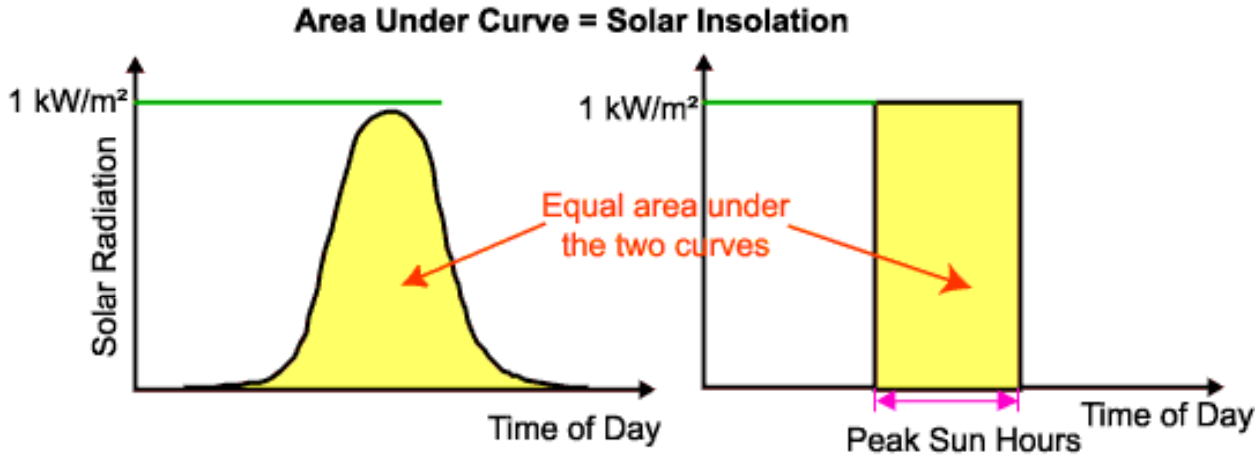
ECE 4833

Need for Solar Storage



[1]

- Power is produced only while sunlight is available.
- Need to store energy for later use
- Storage beneficial in grid connected or hybrid systems (Photovoltaic + other source /the power grid)
- Benefits of Storage:
  - High Reliability
  - Peak Shifting
  - Buffering During Periods of Low Insolation (including passing cloud cover)
  - In hybrid/grid connect systems for Load Matching

[1] PVCDROM

Key Concepts About Storage Needs

- Buffering:

  Problem: Intermittent insoltaion ->
  Turbine-generator will operate at partial load & in transient mode -> Reduced efficiency of electrical production
  Solution: Buffer Smoothes Transients
  Storage Capacities: maximum 1 hour full load

- Delivery Period Displacement (Peak Shifting):

Shifts some or all of the energy collected during periods with sunshine to a later period with higher electricity demand

Size: 3 to 6 hours of full load operation.

- Delivery Period Extension:

The purpose is to extend the period of power plant operation with solar energy.

Size: 3 to 12 hours of full load

[2] Survey of Thermal Energy Storage for Parabolic Trough Power Plants Ulf Herrmann and David W. Kearney, J. Sol. Energy Eng. 124, 145 (2002), DOI:10.1115/1.1467601

METHODS OF STORAGE

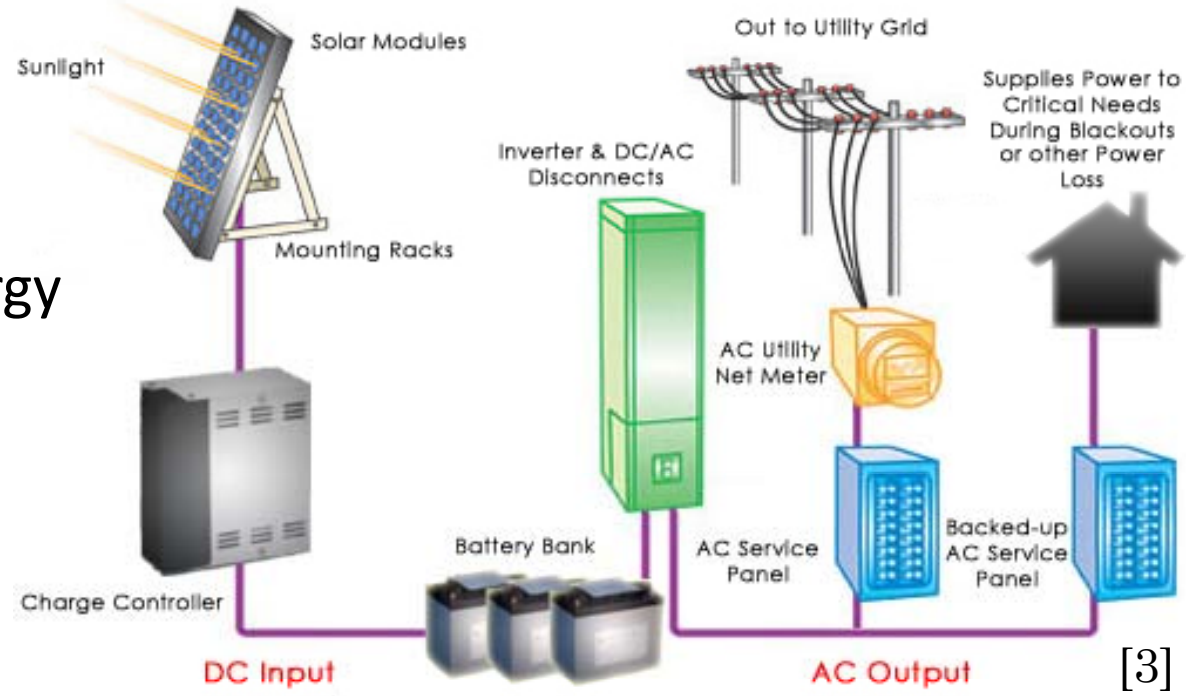
- Approaches:

1. Store Electrical Energy

Using: Batteries

(Example:

lead acid or alkaline)



[3]

2. Store Heat Energy

- For Heating purposes
- To convert to electricity by powering a steam generator

Using: Heat Transfer Fluids and/or Molten Salt

Thus, de-coupling the collection of solar energy from production of power

[3] http://solarbc.org/wp-content/uploads/2009/10/solar-2.jpg

STORING ELECTRICAL ENERGY

- Stores Energy in Chemical Redox (Reduction – Oxidation) Reactions
- Lead Acid Battery:

Negative terminal: $Pb + SO_4^{2-} \underset{charge}{\overset{discharge}{\rightleftharpoons}} PbSO_4 + 2e^-$

Positive terminal: $PbO_2 + SO_4^{2-} + 4H^+ + 2e^- \underset{charge}{\overset{discharge}{\rightleftharpoons}} PbSO_4 + 2H_2O$

Overall : $PbO_2 + Pb + 2H_2SO_4 \underset{charge}{\overset{discharge}{\rightleftharpoons}} 2PbSO_4 + 2H_2O$

Lead acid battery bank. [1]

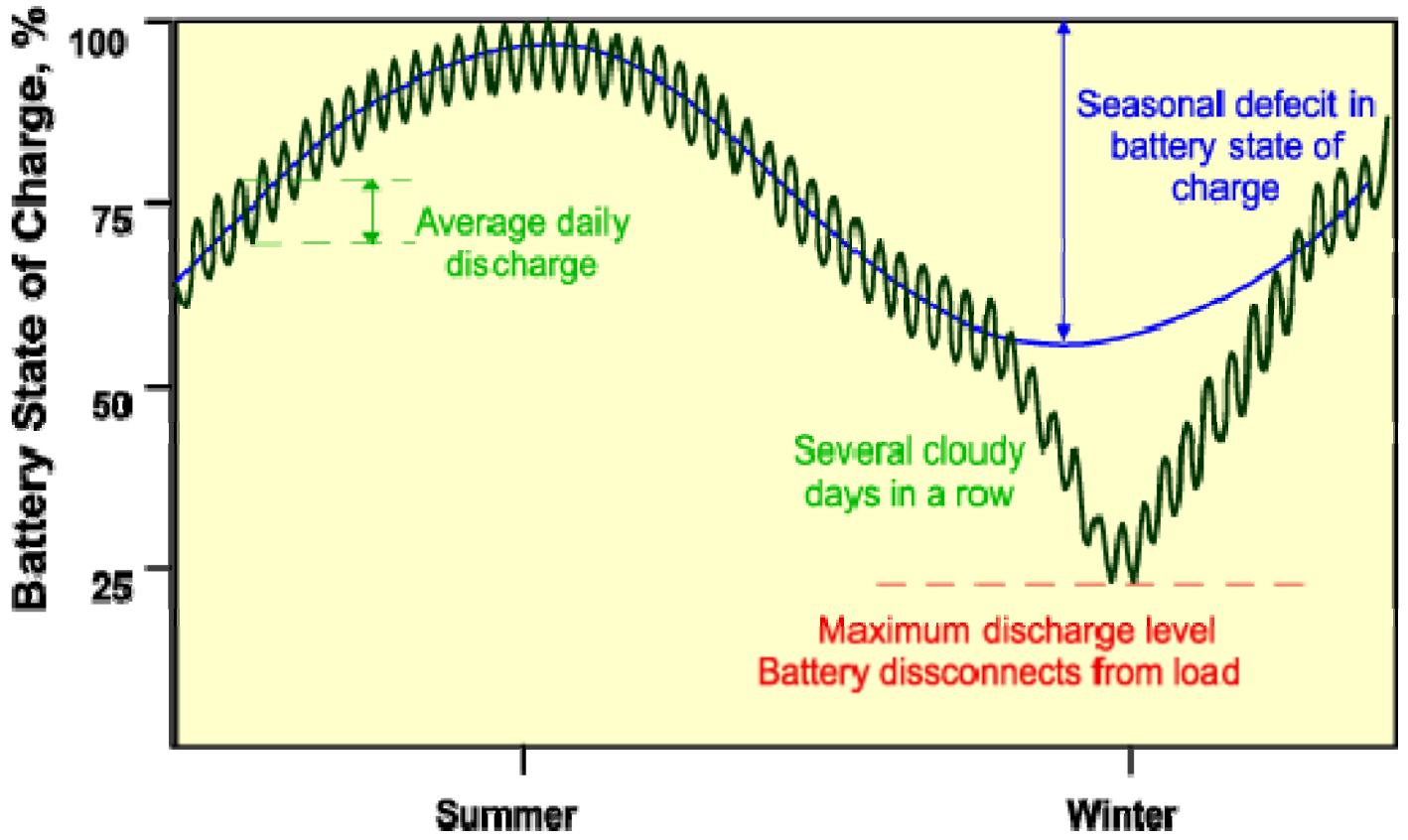
Lead Acid Batteries

Advantages: Long lifetime, low costs, mature technology base

Disadvantages: low energy density, moderate efficiency and high maintenance requirements

[1] PVCDROM

YEARLY BATTERY STATE OF CHARGE



[1]

Battery state of charge over a year showing the battery discharge overnight, during cloudy weather and seasonal variations.

[1] PVCDROM

Storing Heat Energy

Thermal Energy Storage Systems:

- Use different heat transfer fluids to store energy
- Use stored Heat Energy at a later time to convert to Electrical Energy

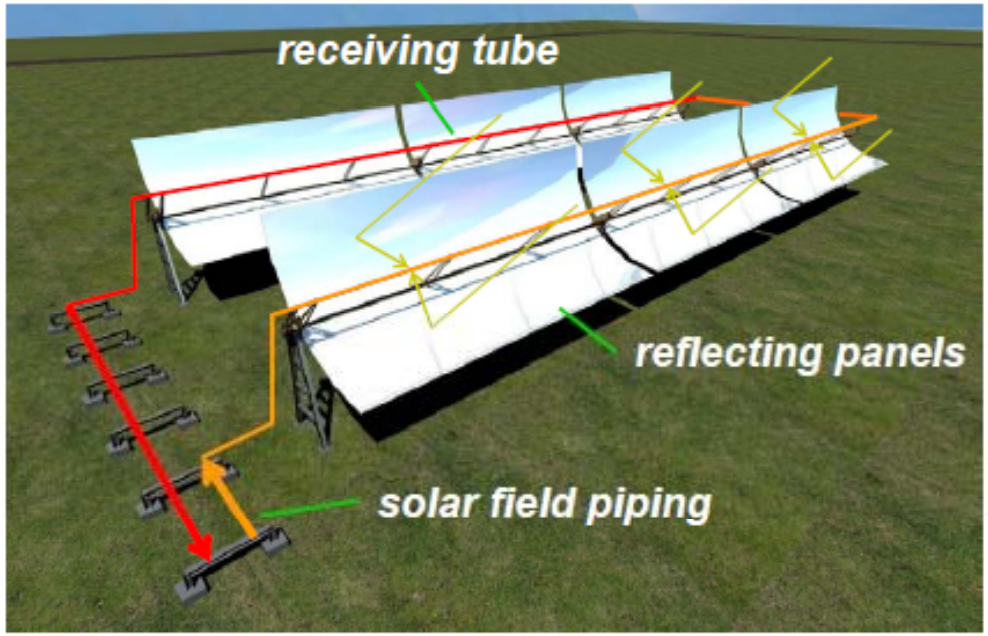
Types of Thermal Energy Storage Systems:

- Two-tank Direct:
  - Two tanks containing hot and cold liquid.
  - Same fluid circulated in Solar Field and Storage Medium
- Two-Tank Indirect
  - Two tanks containing hot and cold liquid respectively.
  - Different fluid in storage medium and solar field.
- Single-Tank Thermocline:
  - Single Tank containing fluid with a temperature gradient

Example of a Solar Collector

Parabolic Trough Solar Collector

- The sunlight is concentrated by reflecting panels onto a receiving tube running along the focus of the parabolic surface
- This concentrated energy heats a fluid (oil or molten salts) flowing into the tube
- The heat is then used to generate steam in a conventional steam generator



Solar Field

- The Solar Field comprises many Solar Collectors connected in strings of 6 elements deployed in parallel rows, usually aligned on a North-to-South axis.
- This configuration enables the rotating mirrors to track the sun from East to West during the day, to always focus the sunlight on the receiving tubes [4]

Example of a Direct Thermal Energy Storage System on the collection end

[4] Data from Italian company Tecnik which is part of Solare XXI consortium of Italy

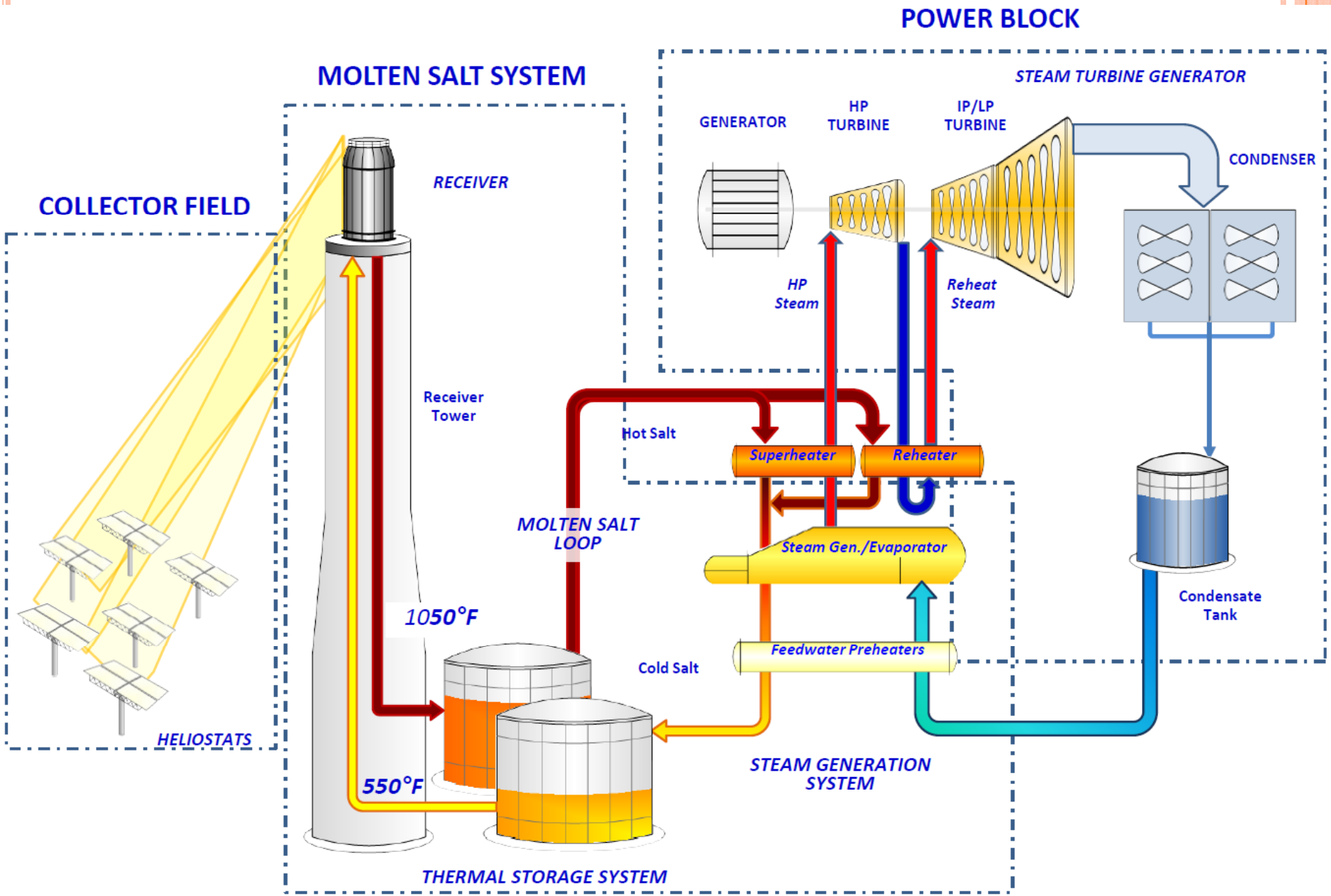
Molten Salt

- A look at the properties of molten salt which is used for heat storage
- Composition:
  - Mixture of 60 % $NaNO_3$ (sodium nitrate) & 40 % KNO_3 (potassium-nitrate), commonly called *saltpeter*.
- Properties:
  - Liquid at Atmosphere Pressure
  - Non-toxic & non-flammable compared with oil

Freezing point, C	220
Upper temperature, C	600
Density @ 300C, kg/m^3	1899
Viscosity @ 300C, cp	3.26
Heat capacity @ 300C, J/kg-K	1495

[5] Assessment of a Molten Salt Heat Transfer Fluid in a Parabolic Trough Solar Field D. Kearney, U. Herrmann, P. Nava, B. Kelly, R. Mahoney, J. Pacheco, R. Cable, N. Potrovitza, D. Blake, and H. Price, J. Sol. Energy Eng. 125, 170 (2003), DOI:10.1115/1.1565087

Two Tank Direct Storage



[6] Solar Reserve: http://www.solar-reserve.com/technology/ProcessFlowDiagram.pdf

Two Tank Direct Storage

Steps:

1) Liquid kept at *550 F* in an insulated cold storage tank
2) The salt is pumped to the top of the tower, where concentrated sunlight heats it in a receiver to *1050 F*. (The receiver is a series of thin-walled stainless steel tubes)
3) The heated salt then flows back down to a second insulated hot storage tank (The size of this tank depends on the requirements of the utility; tanks can be designed with enough capacity to power a turbine from two to twelve hours.)
4) When electricity is needed from the plant, the hot salt is pumped to a conventional steam-generating system to produce superheated steam for a turbine/generator.

[7] http://www.sandia.gov/Renewable_Energy/solarthermal/NSTTF/salt.htm

[8]

Tank Size: Tanks that provide enough thermal storage to power a 100-MW turbine for four hours would be about 30 feet tall and 80 feet in diameter.

Studies show that the two-tank storage system could have an annual efficiency of about 99%.

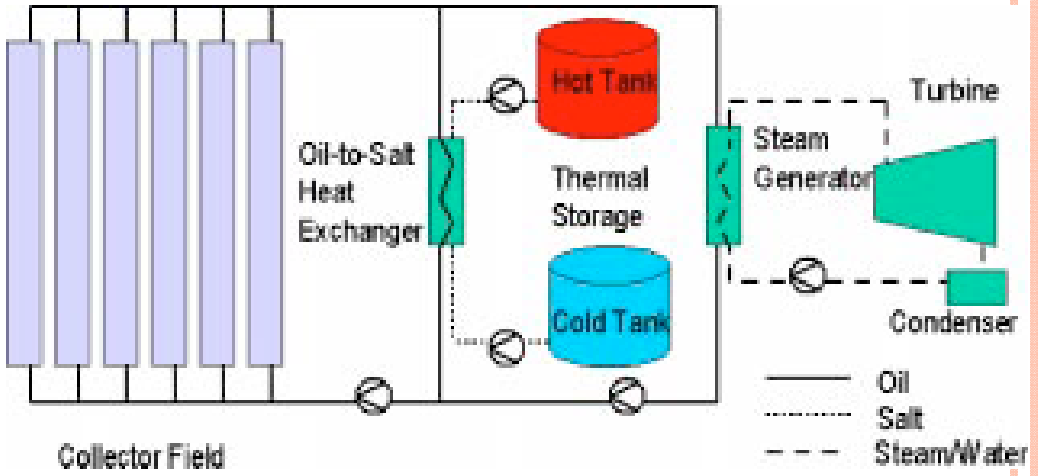
[9]

[8]http://renewable.typepad.com/photos/uncategorized/2008/01/15/solarsalt3.jpg
[9]http://www.groovygreen.com/groove/wp-content/uploads/2008/01/solarsalt.jpg

Two Tank Indirect Storage System

Components

- A cold storage tank, operating at a nominal temperature of 290 °C
- Hot storage tank, operating at a nominal temperature of 385 °C
- A storage inventory of a mixture of binary nitrate salts
- An oil-to-salt heat exchanger
- Nitrate salt circulation pumps
- Can use Molten Salt as the storage medium



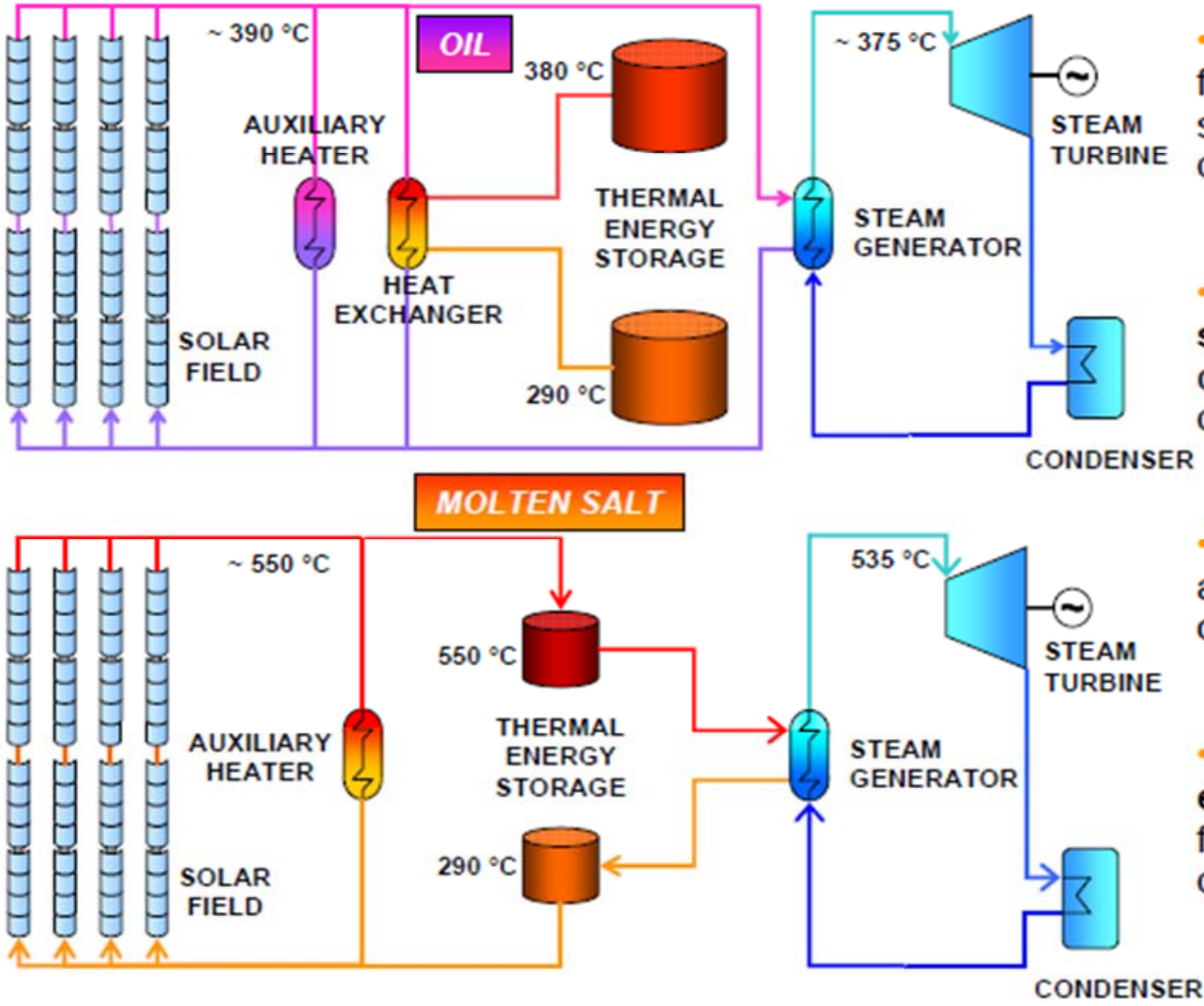
[10] Kearney, D, Kelly, B., and Price, H., 2002, "Thermal Storage Commercial Plant Design Study for a 2-Tank Indirect Molten Salt System," Final Report, NREL Contract No. AAA-2-32432-01, October 25, 2002.

Two Tank Indirect Storage System

- Thermal Storage Charge Cycle:
  - At oil-to-salt heat exchanger: Heat is transferred from collector field heat transport fluid to Molten Salt.
  - A portion of the oil from the collector field is directed to the oil-to-salt heat exchanger, where the oil cools from a nominal inlet temperature of 391 °C to an outlet temperature of about 298 °C.
  - Nitrate salt from the cold storage tank flows in a countercurrent arrangement through the heat exchanger.
  - The salt is heated from an inlet temperature of 291 °C to an outlet temperature of 384 °C, and then stored in the hot storage tank.
- Thermal Storage Discharge Cycle:
  - The fluid flows are reversed, and heat is transferred from the nitrate salt to the oil through the same heat exchanger to provide the thermal energy for the steam generator.

[10] Kearney, D, Kelly, B., and Price, H., 2002

Two Tank Indirect To Direct Storage



- Molten salts work as **sole fluid** for both heat absorption and storage allowing a simplified design of the plant
- Compared to traditional plants **a smaller thermal storage** fully compensate for solar discontinuities
- **Standard turbines** parameters are matched by a higher operating temperature
- Unlike oil, molten salts are an **environmentally friendly**, non-flammable, stable fluid, with no degradation of the receiving tube

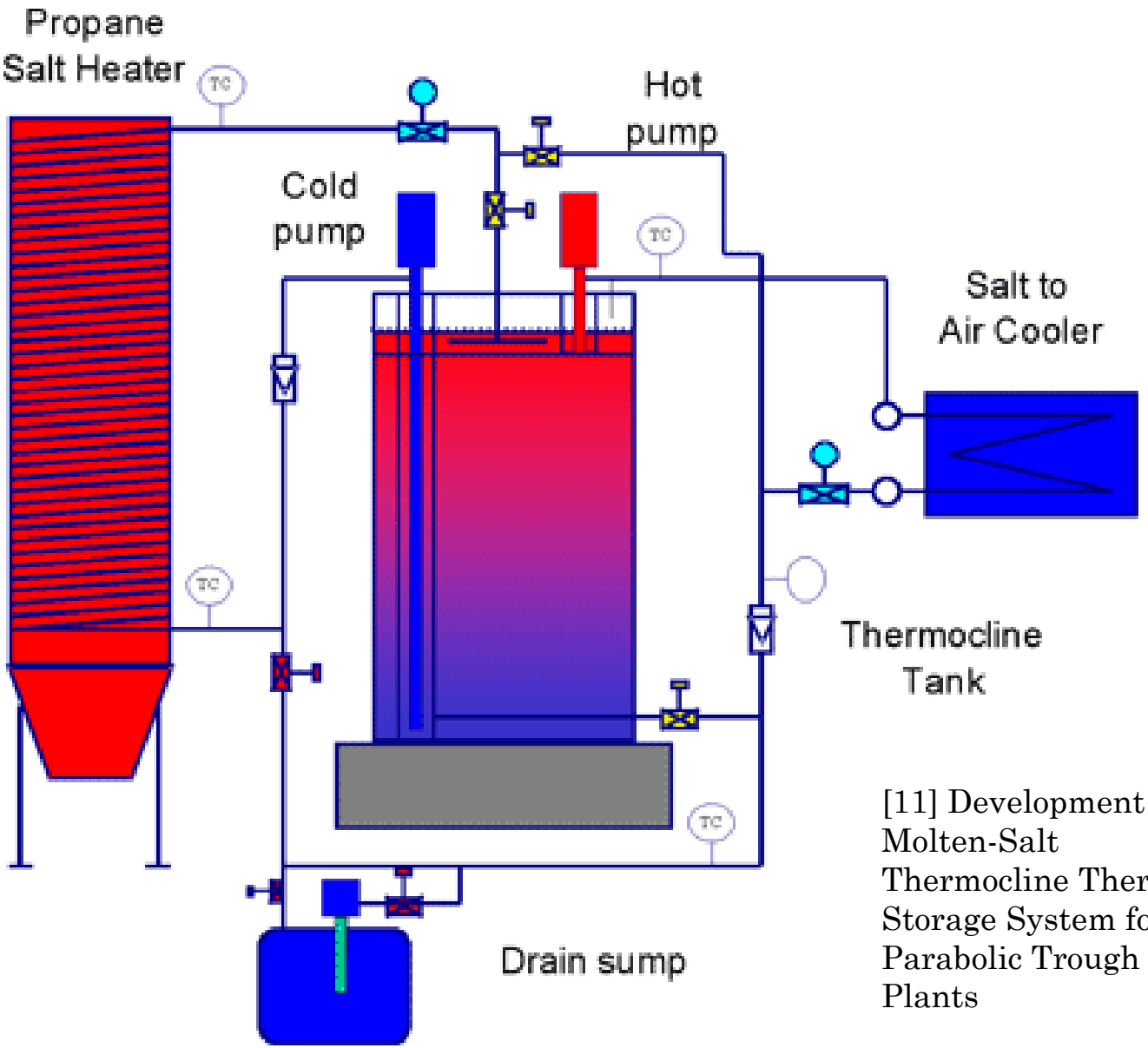
[4] Data from Italian company Tecnik which is part of Solare XXI consortium of Italy

Single-Tank Thermocline

- Fluid with a thermal gradient running vertically through the tank
  - Hotter fluid (lower density) is at the top of the tank
  - Colder fluid is at the base of the tank
  - The zone between the hot and cold fluids is called the thermocline.
- A low-cost filler material is mixed in the fluid in tank to:
  - Provides the bulk of the thermal capacitance of the thermal storage
  - Prevent convective mixing
  - Reduce the amount of fluid required

[11] Development of a Molten-Salt Thermocline Thermal Storage System for Parabolic Trough Plants James E. Pacheco, Steven K. Showalter, and William J. Kolb, J. Sol. Energy Eng. 124, 153 (2002), DOI:10.1115/1.1464123

SINGLE-TANK THERMOCLINE



[11] Development of a Molten-Salt Thermocline Thermal Storage System for Parabolic Trough Plants

Propane heater to simulate the heat input from oil-to-salt heat exchanger

SINGLE-TANK THERMOCLINE

Operation

- When the system is charged, cold fluid is drawn from the bottom, heated as it passes through a heat exchanger (heated with the receiver heat transfer fluid) and returned to the top of the tank.

- When the tank is discharged, hot fluid is drawn from the top, cooled as it passes through a heat exchanger (to transfer heat for steam generation) and returned to the bottom of the tank.

- Thermocline system can dispatch thermal energy at nearly a constant temperature over most of its discharge cycle.

[11] Development of a Molten-Salt Thermocline Thermal Storage System for Parabolic Trough Plants

Thermal Efficiency

$$\eta = \frac{Q_F + Q_L}{Q_{th}}$$

Qth = Energy which is theoretically available from the system

QF = heat losses through the walls of the storage vessel.
In many practical situations heat is transferred to the same space as that serviced by the HTF.

$$Q_F = \sum_{j=1}^{n} \dot{M}_d C_{pd} (T_0 - T_i) \Delta t_j$$

Ma, To and Ti are the arithmetic averages at the beginning and end of each interval of the HTF mass flow rate

QL = energy carried by the heat transfer fluid

$$Q_L = \sum_{j=1}^{n} U_w \cdot \pi DH (T_c - T_r) \Delta t_j$$

D and H are the inside diameter and height of the storage vessel, Tc is the continuous phase temperature and Tr is the room temperature

[12] A.E. Fouda, G.J.G. Despault, J.B. Taylor, C.E. Capes, Solar storage systems using salt hydrate latent heat and direct contact heat exchange--II Characteristics of pilot system operating with sodium sulphate solution, Solar Energy, Volume 32, Issue 1, 1984, Pages 57-65, ISSN 0038-092X, DOI: 10.1016/0038-092X(84)90049-5.

Technical Requirements for a Thermal Energy Storage System

- High energy density (per-unit mass or per-unit volume) in the storage material
- Good heat transfer between heat transfer fluid (HTF) and the storage medium
- Mechanical and chemical stability of storage material
- Compatibility between HTF, heat exchanger and/or storage medium
- Complete reversibility for a large number of charging/discharging cycles
- Ease of control

[2] Survey of Thermal Energy Storage for Parabolic Trough Power Plants Ulf Herrmann and David W. Kearney, J. Sol. Energy Eng. 124, 145 (2002), DOI:10.1115/1.1467601

Cost Issues

The cost of a TES system mainly depends on the following items:

- The storage material itself
- The heat exchanger for charging and discharging the system
- The cost for the space and/or enclosure for the TES

[2] Survey of Thermal Energy Storage for Parabolic Trough Power Plants Ulf Herrmann and David W. Kearney, J. Sol. Energy Eng. 124, 145 (2002), DOI:10.1115/1.1467601

Advantages of Using Molten Salt

- The molten salt medium is in comparison to oil:
  - much cheaper
  - more environment-friendly
  - non-toxic
  - non-flammable

- The mass flow in the solar field is considerably lower with molten salt, which leads to a lower pressure loss in the piping. Both effects combined—low mass flow and low pressure loss—lead to relatively low pumping parasitics [5]

[5] Assessment of a Molten Salt Heat Transfer Fluid in a Parabolic Trough Solar Field D. Kearney, U. Herrmann, P. Nava, B. Kelly, R. Mahoney, J. Pacheco, R. Cable, N. Potrovitza, D. Blake, and H. Price, J. Sol. Energy Eng. 125, 170 (2003), DOI:10.1115/1.1565087

Effect on Efficiency

Quantity	Molten Salt	High Temperature Oil
Solar Field Output Temperature	450– 500°C	393°C
Rankine cycle efficiency of the power block steam turbine	40% range	37.6%

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Cost Effectiveness of Molten Salt

Table 3 Effective storage fluid cost

Salt	Temperature Rise °C	Cost per Kg $/kg	Storage Cost $/kWh$_t$
Hitec[a] [142°C]	200	0.93	10.7
Solar Salt[b] [220°C]	200	0.49	5.8
Calcium Nitrate	200	1.19	15.2
[HitecXL][c] [120°C]	150	1.19	20.1
	100	1.19	30.0
Therminol VP-1[d]	100	2.2	57.5

Notes: a. 7:53 Na:K nitrate, 40 Na nitrite
b. 60:40 Na:K nitrate
c. 42:15:43 Ca:Na:K nitrate
d. biphenyl/diphenyl oxide

[5] Assessment of a Molten Salt Heat Transfer Fluid in a Parabolic Trough Solar Field D. Kearney, U. Herrmann, P. Nava, B. Kelly, R. Mahoney, J. Pacheco, R. Cable, N. Potrovitza, D. Blake, and H. Price, J. Sol. Energy Eng. 125, 170 (2003), DOI:10.1115/1.1565087

Cost Effectiveness of Molten Salt

- Possible use of Direct Storage: Eliminating heat exchangers and reducing costs
- A Single tank thermocline storage system can used: resulting in a substantially lower cost storage system.

Disadvantages of Using Molten Salt

- High freezing point of 120°C:
  - Complications related to freeze protection in the solar field
  - Solar field preheating
  - Collector loop maintenance
  - Selection of appropriate materials for piping and fittings
- At very high temperatures of around 600°C, the salt can decompose with a potential risk of corrosion in the system.

[5] Assessment of a Molten Salt Heat Transfer Fluid in a Parabolic Trough Solar Field D. Kearney, U. Herrmann, P. Nava, B. Kelly, R. Mahoney, J. Pacheco, R. Cable, N. Potrovitza, D. Blake, and H. Price, J. Sol. Energy Eng. 125, 170 (2003), DOI:10.1115/1.1565087

SUMMARY

- Solar Energy Storage can improve reliability of Solar Power Generation
- Different methods of the storage of heat energy can use Molten Salt as a storage medium and / or heat transfer fluid
- Molten salt provides a cheaper, more efficient, cleaner, non-toxic, non-flammable alternative to oil in heat storage systems