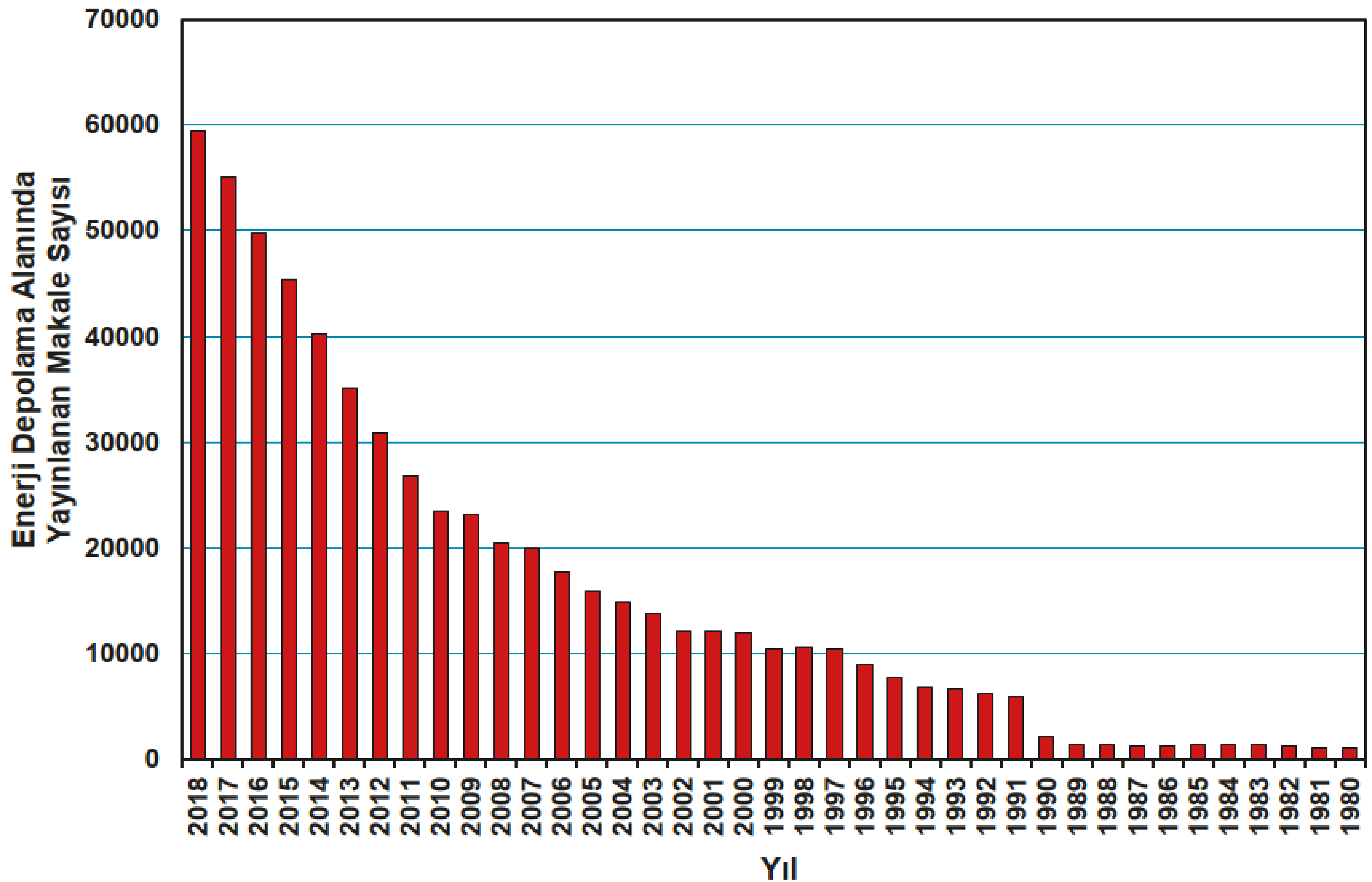

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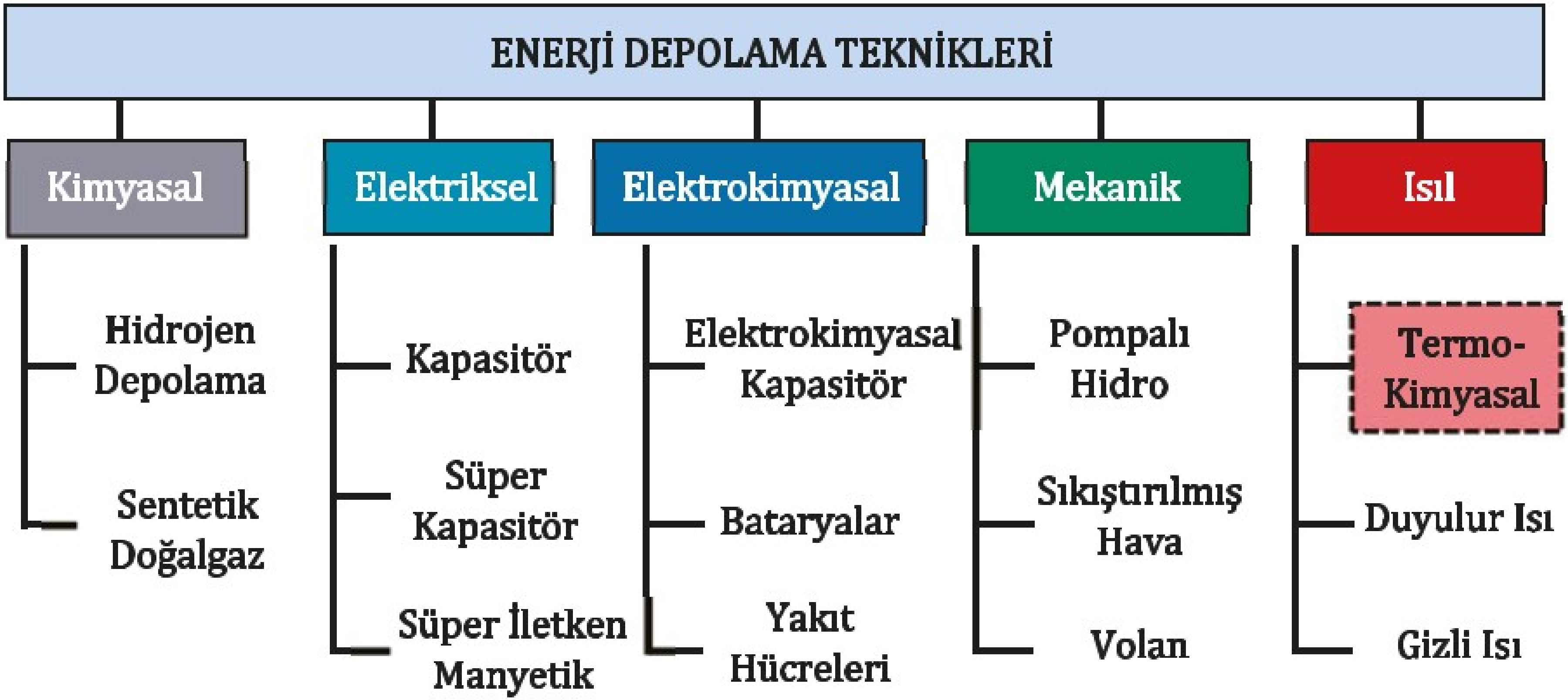

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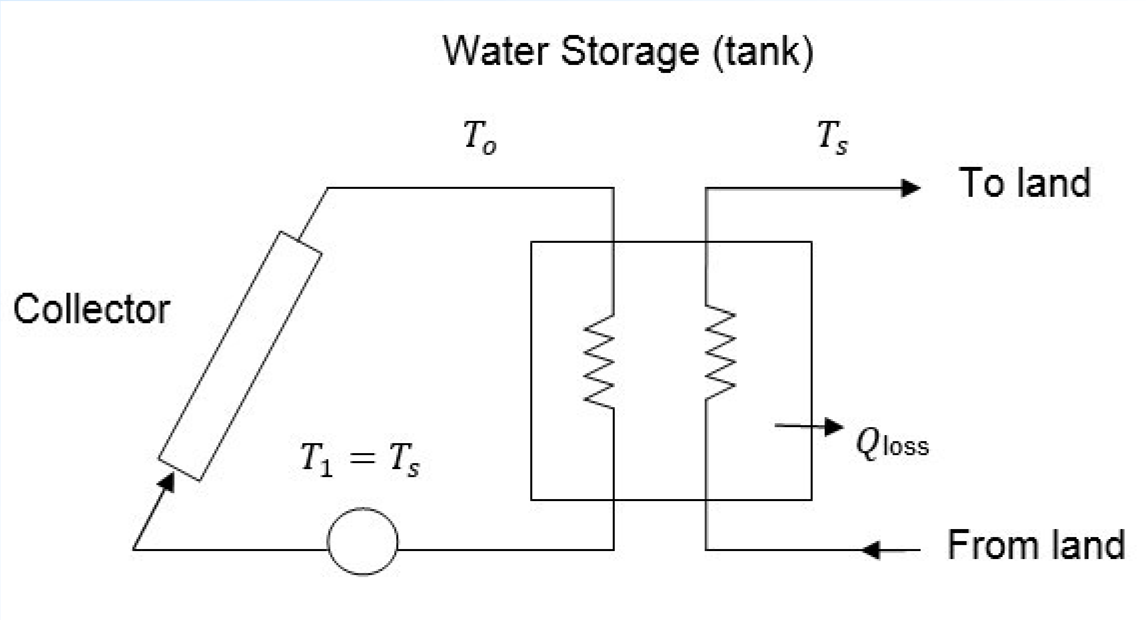
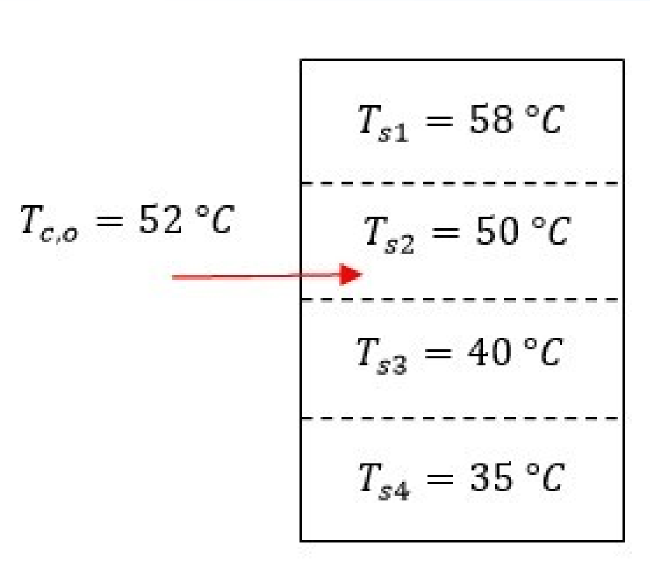
Read: https://en.wikipedia.org/wiki/Energy_storage

Thermal Energy Storage

1. Sensible Heat (Water tanks, Solar ponds)
2. Latent Heat (PCM – Phase Change Material)
3. Thermochemical Decomposition
4. Photochemical Decomposition

Water Storage

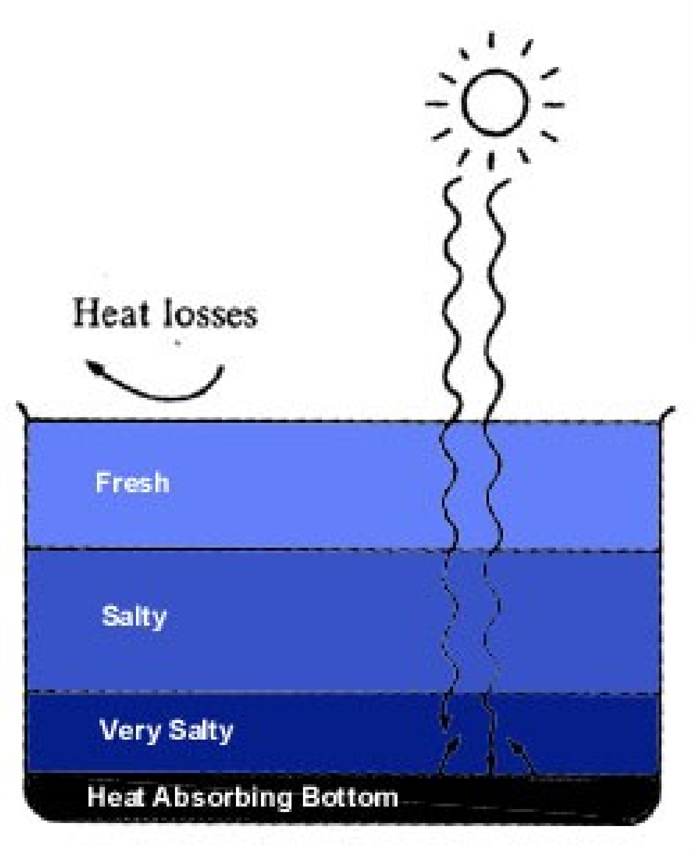




$$\dot{Q}_s = (\dot{m}\, c_p)_s\ \Delta T_s$$

- Top of the tank hotter than bottom
- Can allow for better thermal storage if properly designed

Solar Ponds



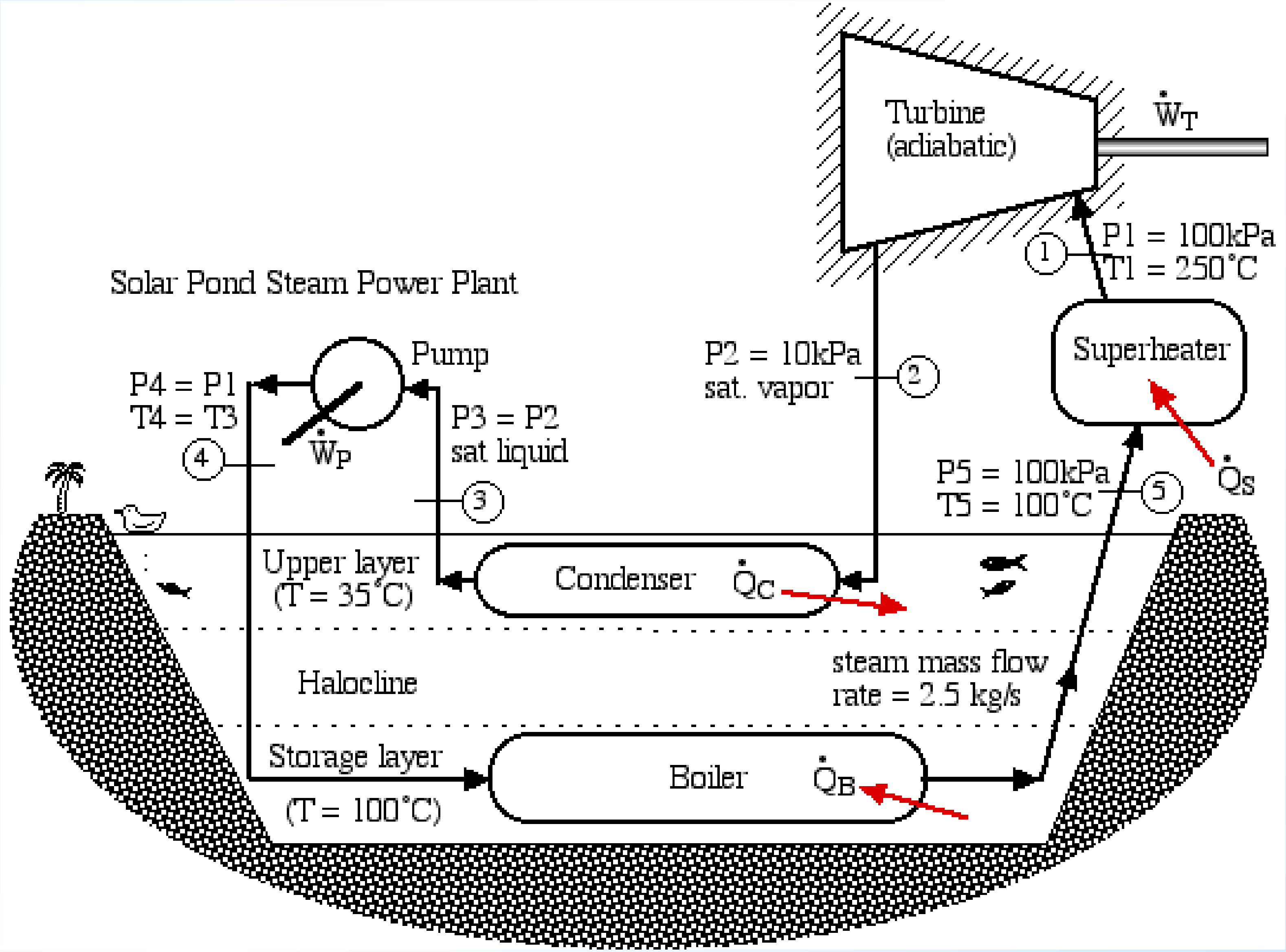
For normal bodies of water

- Large surface area
- Stratification due to buoyancy
- Warmer water at the surface

Some salt water lakes exhibit opposite behavior

- ΔT is reversed
- Greater concentration of salt (salinity) and higher temperature at bottom
- Solar energy absorbed at deeper layers remains there

Largest solar-pond power plant was built in Israel near Dead Sea, presently having a peak capacity of 5 MW.


Solar Pond Steam Power Plant
Turbine
(adiabatic)
$\dot{W}_T$
P1 = 100kPa
T1 = 250°C
1
Superheater
$\dot{Q}_S$
P2 = 10kPa
sat. vapor
2
Pump
$\dot{W}_P$
P4 = P1
T4 = T3
4
P3 = P2
sat liquid
3
P5 = 100kPa
T5 = 100°C
5
Upper layer
(T = 35°C)
Condenser
$\dot{Q}_C$
Halocline
steam mass flow
rate = 2.5 kg/s
Storage layer
(T = 100°C)
Boiler
$\dot{Q}_B$

Organic working fluid

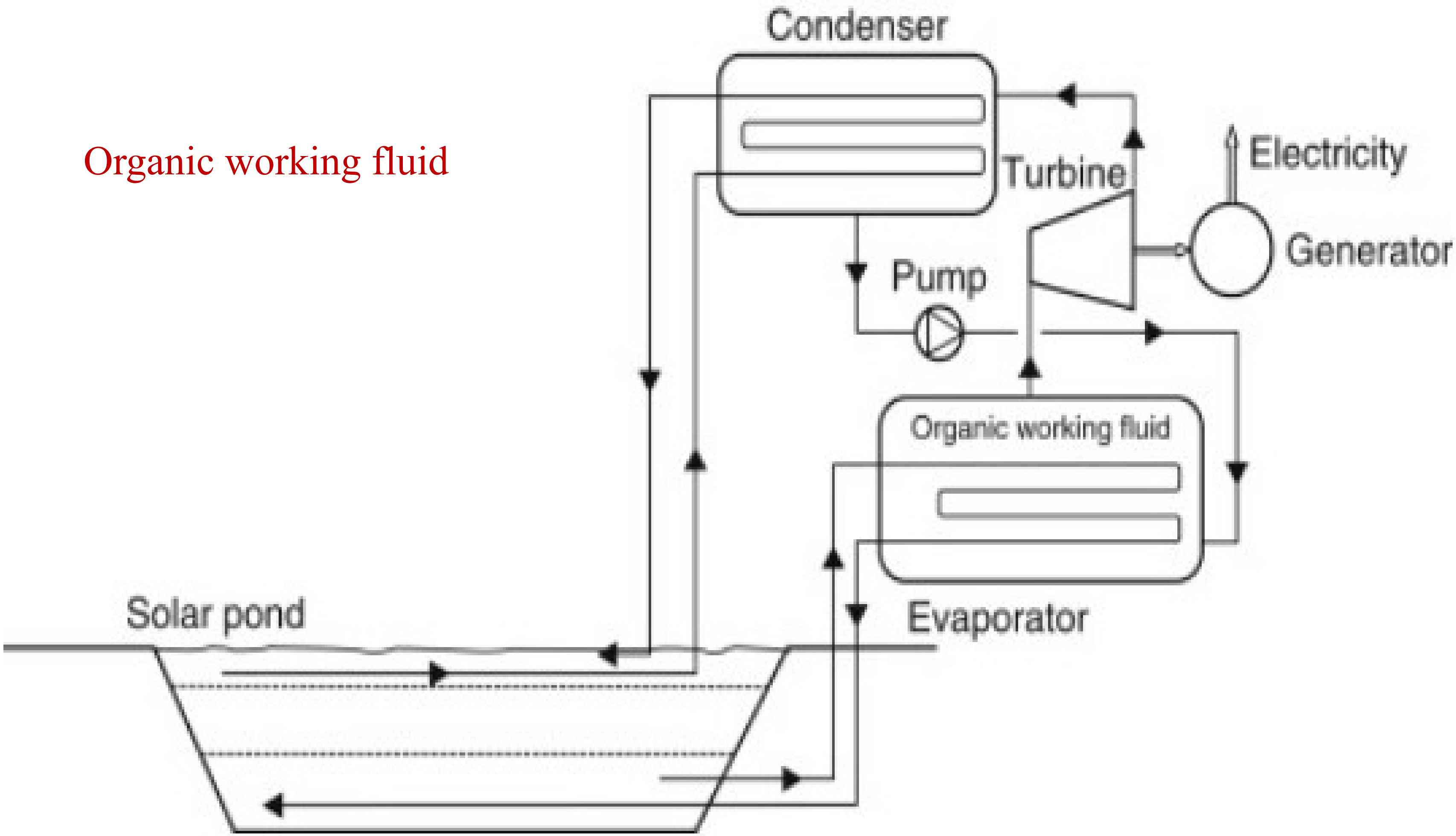


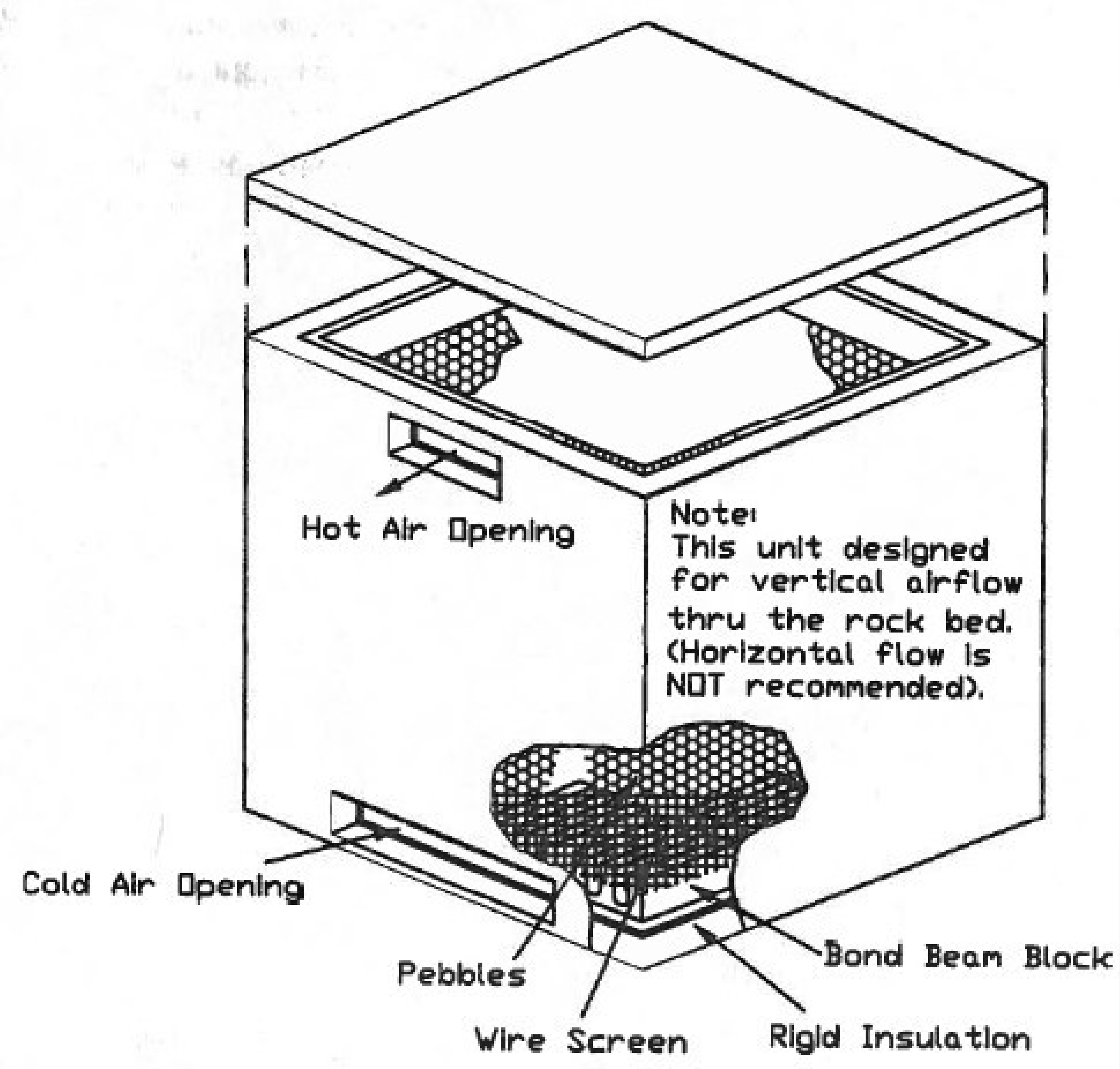
Table 4.1. Physical properties of some sensible heat storage materials

Storage Medium	Temperature Range, °C	Density (ρ), kg/m³	Specific Heat (C), J/kg K	Energy Density (ρC) kWh/m³ K	Thermal Conductivity (W/m K)
Water	0–100	1000	4190	1.16	0.63 at 38°C
Water (10 bar)	0–180	881	4190	1.03	—
50% ethylene glycol-50% water	0–100	1075	3480	0.98	—
Dowtherm A® (Dow Chemical, Co.)	12–260	867	2200	0.53	0.122 at 260°C
Therminol 66® (Monsanto Co.)	−9–343	750	2100	0.44	0.106 at 343°C
Draw salt ($50NaNO_3$-$50KNO_3$)[a]	220–540	1733	1550	0.75	0.57
Molten salt ($53KNO_3$/$40NaNO_3$/$7NaNO_3$)[a]	142–540	1680	1560	0.72	0.61
Liquid Sodium	100–760	750	1260	0.26	67.5
Cast iron	m.p. (1150–1300)	7200	540	1.08	42.0
Taconite	—	3200	800	0.71	—
Aluminum	m.p. 660	2700	920	0.69	200
Fireclay	—	2100–2600	1000	0.65	1.0–1.5
Rock	—	1600	880	0.39	—

[a] Composition in percent by weight.
Note: m.p. = melting point.

4

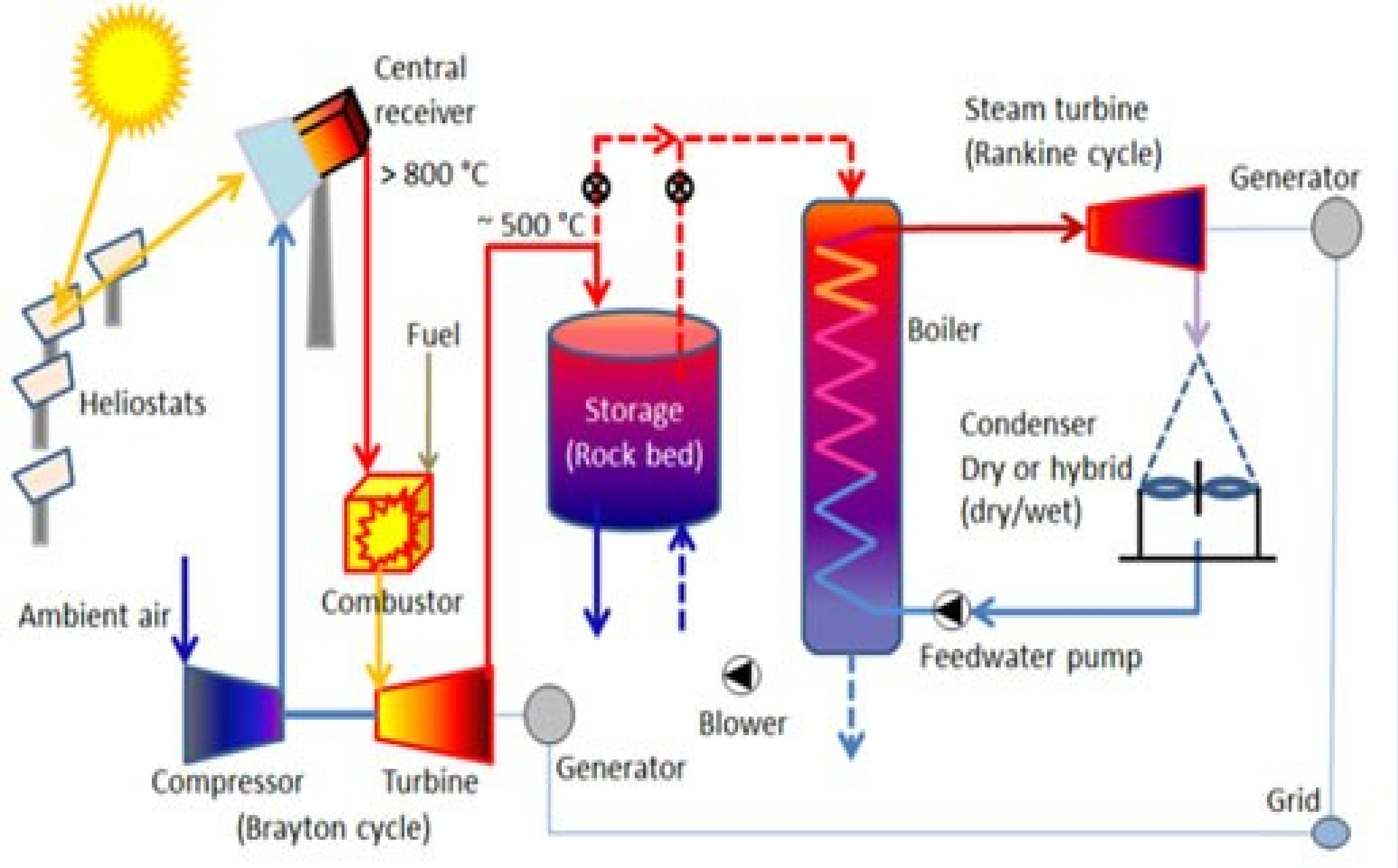
Goswami, Kreith, and Kreider



Packed-bed storage

- Pebble bed
- Rock pile

- Use heat capacity of bed material to store energy
- Usually air is the thermal transfer fluid


Central receiver
> 800 °C
~ 500 °C
Steam turbine (Rankine cycle)
Generator
Heliostats
Fuel
Storage (Rock bed)
Boiler
Condenser Dry or hybrid (dry/wet)
Ambient air
Combustor
Feedwater pump
Blower
Compressor
Turbine
(Brayton cycle)
Generator
Grid

PCMs Phase Change (or Latent Heat Storage) Material

$$\frac{\dot{Q}_s}{\dot{m}} = \dot{q}_s = c_s\ (T^* - T_1) + \lambda + c_l\ (T_2 - T^*)$$

sensible heat to meting point — latent heat of fusion — sensible heat from meting point

Glauber's salt $Na_2SO_4.10\ H_2O + Q \rightarrow Na_2SO_4 + 10\ H_2O$

$c_s \approx 1950$ J/kg.K

$c_l \approx 3550$ J/kg.K

$\lambda \approx 2.43\ 10^5$ J/kg at 34 °C

For 1 kg heated from 25 °C to 50 °C

$q_s = 315$ kJ/kg

$\lambda \approx 2.43\ 10^5$ J/kg at 34 °C

PCMs have a tendency to degrade with thermal cycling partially due to phase separation.

Table 4.3. Physical properties of latent heat storage materials or PCMs

Storage Medium	Melting Point °C	Latent Heat, kJ/kg	Specific Heat (kJ/kg °C)		Density (Kg/m³)		Energy Density (kWhr/m³K)	Thermal Conductivity (W/m K)
			Solid	Liquid	Solid	Liquid		
$LiClO_3 \cdot 3H_2O$	8.1	253	—	—	1720	1530	108	—
$Na_2SO_4 \cdot 10H_2O$ (Glauber's Salt)	32.4	251	1.76	3.32	1460	1330	92.7	2.25
$Na_2S_2O_3 \cdot 5H_2O$	48	200	1.47	2.39	1730	1665	92.5	0.57
$NaCH_3COO \cdot 3H_2O$	58	180	1.90	2.50	1450	1280	64	0.5
$Ba(OH)_2 \cdot 8H_2O$	78	301	0.67	1.26	2070	1937	162	0.653ℓ
$Mg(NO_3) \cdot 6H_2O$	90	163	1.56	3.68	1636	1550	70	0.611
$LiNO_3$	252	530	2.02	2.041	2310	1776	261	1.35
$LiCO_3/K_2CO_3$, (35:65)[a]	505	345	1.34	1.76	2265	1960	188	—
$LiCO_3/K_2CO_3/Na_2CO_3$ (32:35:33)[a]	397	277	1.68	1.63	2300	2140	165	—
n-Tetradecane	5.5	228	—	—	825	771	48	0.150
n-Octadecane	28	244	2.16	—	814	774	52.5	0.150
HDPE (cross-linked)	126	180	2.88	2.51	960	900	45	0.361
Steric acid	70	203	—	2.35	941	347	48	0.172ℓ

[a]Composition in percent by weight.
Note: ℓ = liquid.

Goswami, Kreith, and Kreider

Chemical Energy Storage

Decomposition of

- Metal hydrides
- Oxides
- Peroxides
- Ammoniated salts
- Carbonates
- Sulfur trioxide

Potassium oxide:

$$4\ KO_2 \rightarrow 2\ K_2O + 3\ O_2$$

Lead oxide:

$$4\ PbO_2 \rightarrow 2\ PbO + O_2$$

$$A + \Delta H_f \rightarrow B + C$$

Formation direction is endothermic

Reverse direction is exothermic

$$Q_s = a_{rm}\ \Delta H_f$$

Q_s : Amount of thermal energy stored

a_{rm} : fraction of mass reacted

Table 4.4. Properties of thermochemical storage media

Reaction	Condition of Reaction: Pressure, kPa	Condition of Reaction: Temperature, °C	Component (Phase)	Pressure, kPa	Temperature, °C	Density, kg/m³	Volumetric Storage Density, kWh/m³
$MgCO_3(s)$ + 1200 kJ/kg = $MgO(s) + CO_2(g)$	100	427–327	$MgCO_3(s)$	100	20	1500	187
			$CO_2(\ell)$	7400	31	465	
$Ca(OH)_2(s)$ + 1415 kJ/kg = $CaO(s) + H_2O(g)$	100	572–402	$Ca(OH)_2(s)$	100	20	1115	345
			$H_2O(\ell)$				
$SO_3(g)$ + 1235 kJ/kg = $SO_2(g) + \frac{1}{2}O_2(g)$	100	520–960	$SO_3(\ell)$	100	45	1900	280
			$SO_2(\ell)$	630	40	1320	
			$O_2(g)$	10000	20	130	

Note: s = solid; ℓ = liquid; g = gas

Goswami, Kreith, and Kreider

Facts, Advantages, Disadvantages

Solar Energy

Key Facts

1. Solar energy is converted to electricity by a photovoltaic cell in which an electron is dislodged to produce electrical currents.
2. We could meet all of the world's energy needs by constructing a solar facility 291 miles on each side (square) in a low latitude region. However, as of 1998, solar energy made up only 0.009% of global energy consumption.
3. It can be used in many ways, from heating to growing plants, and is currently one of the world's cleanest energy sources.

Solar Energy

Advantages

1. It is free, inexhaustible, versatile, produces no wastes, and has no moving parts.
2. Can be used anywhere, especially places with ample sunlight and poor agricultural conditions (e.g., many developing countries).

Disadvantages

1. It can be unreliable due to weather and time of day, time of year, location, etc.
2. It is very expensive (both to make the solar cells and build the facility)

(*Solar energy costs are about $0.20 per kWh compared with $0.04 per kWh for new conventional power plants)*