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Realistic estimate of water hold-up, circulation and consumption in solar concentrating thermal power plants

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This paper presents a comprehensive analysis of water utilization in concentrating solar thermal (CST) thermal power stations (TPS) keeping in mind the experience of operating coal plants. The water utilization is divided into three modes: water hold-up, water circulation and water consumption. The water hold-up and circulation represent the minimum quantity of water required for running a power plant with a few days autonomy. The water consumption represents the extent of replenishment required on a continuous basis. On the basis of quality, the consumption can be classified into: raw water, soft water and demineralized (DM) water. The reserve hold-up in a CST station of 1 GW is around 0.95 to 1.05 million m^3 per GW which corresponds to 9-10 days consumption. The working hold-up inside the plant is 0.27 million m^3 per GW. The water circulation rate for a 1 GW CST station is 7500 m^3/h or 0.18 million m^3/day. The major water consumption which is not generally tracked or measured is conveyance loss between the raw water intake source and the power station intake point which can be as high as 30 %. Loss of DM water directly affects the energy efficiency as it mostly represents the high quality steam lost from the system and has a high cost of production.

Keywords: *Water consumption, water hold-up, circulation flow, specific water consumption, conveyance loss.*

1.0 INTRODUCTION

An Water is the primary working fluid in the Rankine cycle CST power plants (also called as concentrating solar power) (CSP). It is the universal cooling media for transfer and dispensing of the unconverted energy in the turbine cycle and in the heat generating components like bearings, casing jackets, etc. It is specially used for reflector cleaning, general services, etc. in CST plants. In coal fired plants is used as a medium for flue gas handling, fuel oil handling, ash handling, dust suppression, conveying of residual solid particles, tempering, scrubbing of flue gas, etc.

Water consumption for Rankine cycle CST power plants is essentially the same as of coal units except the following significant differences:

- Steam temperatures and pressures in CST plants are lower than in coal units at present but in due course of development, parity would be reached.
- The plant load factor or capacity factor in coal units is 80-95 % whereas in CST plants it is around 19-23 %
- Auxiliary power in coal plants varies from 5 % of gross generation to 8 % depending on the type of fuel used. In CST plants it varies

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between 5.5 % to 6.5 %. Water requirement for cooling of bearings of rotating auxiliary equipment is lower in CST plants.

- CST plants are sometimes operated in the mixed mode with natural gas firing for load stabilization and operation during the no-solar period.
- Coal units have water requirement for handling of fuel, its combustion products and its residue like ash, etc., which are totally absent in CST plants.

Baring these differences the major water consuming component, viz., water for cooling of steam condensed, is essentially the same for CST plants as in coal plants.

Although water-energy interrelationship or interdependence or nexus (as it is popularly called) is clearly seen in TPS, energy efficiency has been given a higher level of importance than water consumption. Over the last 70 years, the water consumption in TPS has considerably reduced due to energy efficiency and water conservation practices [1]. The water withdrawal has been reduced from 238 m^3/MW in 1950s down to 80 m^3/MW in 2000 [1]. However, new amendments to the coal TPS such as flue gas desulphurization (FGD), carbon capture and storage (CCS) are leading to almost doubling of the specific water consumption or circulation (SWC) due to increase in auxiliary power. In CST plants, there is no water consumption on account of fuel, flue gas and ash handling or its associated activities.

Nearly two thirds of the energy input (fuel) to thermal plants is dissipated as thermal energy into the environment. Coal plants account for nearly 40-50 % of the total national water withdrawal and 20-25 % of the total national waste water generated in many countries [3,4].

CST plants are on the verge of making an inroad into the generation scenario and there is likely to be a demand on water for operation of these plants (Figures 1 and 2). In this paper the approach is based on the scenario that CST plants are ultimately going to be on par with coal fired units in their steam conditions and unit sizes. The data available on water consumption in CST TPS is rather scanty and not fully authenticated through metering. Though the water consumption gets recorded it is not treated as a key performance index (KPI).

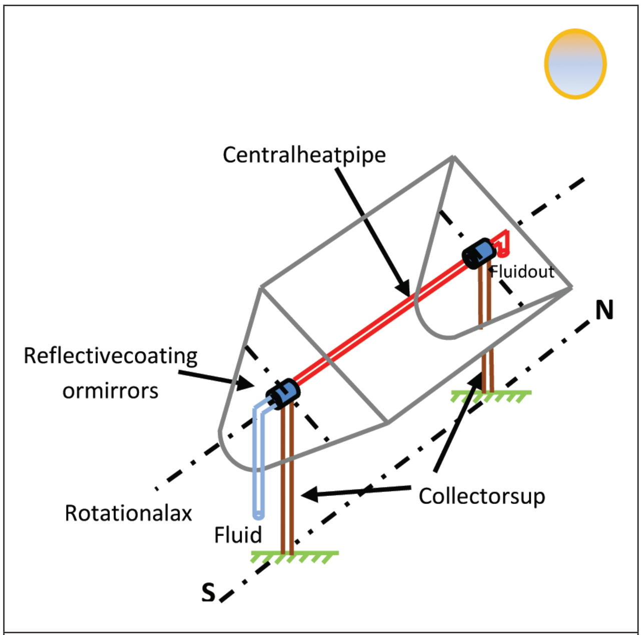

FIG. 1 VIEW OF A SINGLE PARABOLIC TROUGH COLLECTOR OF A CST PLANT

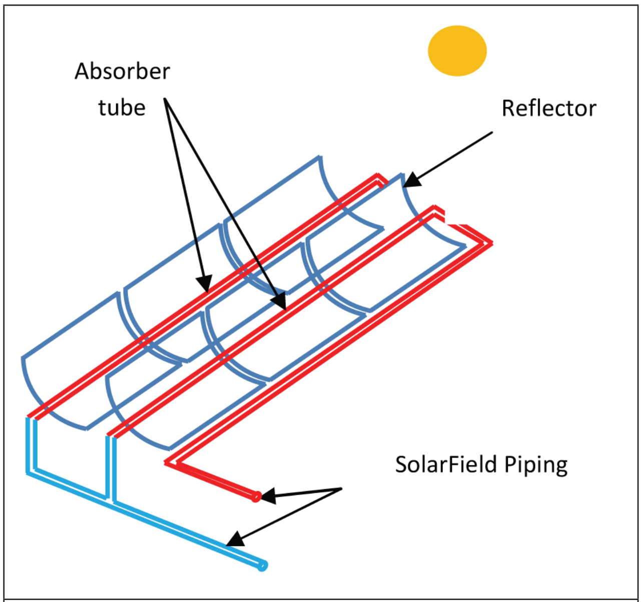

FIG. 2 VIEW OF A CST BOILER FOR STEAM GENERATION

There are two terms associated with raw or fresh water usage- water withdrawal which is the water drawn from the source for the TPS application, and water consumption which is the water consumed by the TPS. Water withdrawal is substantially larger than water consumption. Majority of the water withdrawal is either recycled or returned but water consumption has to be replenished with new water. Few stations are following the principle of zero discharge.

The primary supply of water for both CST and coal units is raw water which is directly used for certain applications, purified as soft water for low pressure applications and converted in demineralized water (DM) for high temperature and pressure applications in the boiler and turbine circuits. The water used as a working fluid in the Rankine cycle is very high quality demineralized water meeting stringent requirement of pH, dissolved solids, electrical conductivity, etc. The cost of the DM water is the highest and also it has a high impact on the energy efficiency of the plant as the DM make up represents the high quality steam lost from the system. The other water streams like raw water and soft water only affect the auxiliary power of the plant but do not directly affect the energy efficiency of the plant.

The water requirement of a CST TPS can be segregated into three components:

(i) Dead volume or hold-up in different components of stored water at different levels of purity represented by m^3/MW of installed capacity of the system or number of seconds/minutes/hours/days of autonomy. This will have to be replenished on operations under unsteady conditions.

(ii) Circulation flow volumes of water in the various circuits such as: raw water intake flow, boiler main steam flow, condenser cooling water flow, soft water flow. This is a nearly constant amount of water which is required for cooling, conveying of energy, etc.

(iii) Replenishment of water of different levels of purity to compensate for water permanently lost from the power plant or process through evaporation, percolation, discharge, etc.. This is the consumption which will have to be replenished on a steady state basis.

For simplification of calculations, water consumption of CST plants can be divided into:

- In-house or in-plant water consumption such as boiler make-up, in-plant equipment cooling water, etc.
- Water consumption for outlying activities such as, raw water tank, water treatment plant, cooling tower, etc.

Equipment centric classification of water in CST is as follows:

(i) Cooling tower make up to account for cooling tower evaporation, draft and blow down.

(ii) DM water make up in the turbine cycle to compensate for blow down and auxiliary steam use.

(iii) Soft water make up in heat exchangers of bearing cooling and auxiliary cooling systems.

(iv) Raw water consumption at the water intake and water treatment plant.

CST plants are characterized by total absence of fuel handling related water consumption. In coal plants, ash handling is by used water from cooling tower blow down, blow down of water treatment plant or boiler blow down. Also, in coal plants the auxiliary cooling requirements are much higher than in CST plants, e.g., for fans, pumps and their bearings associated with flue gases transfer, flue gas purification, flue gas discharge, fuel handling, fuel preparation and ash handling.

Based on the final water quality, CST consumption is classified into:

(i) Raw water

(ii) Soft or clarified water

(iii) Demineralized (DM) water

The raw, soft and DM water are all not added to obtain total water because raw water is converted into soft and DM water. Raw water consumption includes soft and DM water.

The water consumption of CST plants is dependent on some of the following factors:

- Type of Rankine cycle in use (turbo-generator efficiency).
- Type of cooling system adopted-river water cooling, sea water cooling, natural draft cooling towers, forced draft cooling towers.
- Quantum of auxiliary power.

The purpose of this paper is to provide a comprehensive, realistic and holistic picture of water consumption in CST plants based on the coal plant experience and to point towards bench marks for minimum water consumption based on theoretical design criteria.

A typical index for water consumption is specific water consumption or specific water circulation (as the case may be) denoted by SWC on the basis of water per kWh or per MW of energy generated (as litres/h per kW or litre/kWh= m^3/h per MW= m^3/MWh). DM is usually denoted by ml/kWh. The very rough thumb rule is that the circulating steam-water in the boiler turbine circuits (specific steam consumption) is 3 litres/h per kW of power generated at the generator terminal. Theoretically for every litre of steam circulated in the boiler-turbine-condenser circuit 40.69 litres of water is required to cool the latent heat in the steam.

A review of literature [5-20] indicates that water consumption varies over a wide range. Table 1 gives typical SWC in coal and nuclear TPS [1-12]. Table 2 gives similar data for CST plants [13-20]. Table 3 gives the break-up of typical SWC for a single unit of 500 MW and for a station of 1 GW. It can be seen that the nominal SWC for CST is in the range of 3.5-4.1 m^3/MWh of which 50 % is accounted for by cooling towers. This must not be confused with the similar number of 3 t/MWh of specific steam consumption in the turbine given above.

TABLE 1

TYPICAL STEADY SPECIFIC WATER CONSUMPTION IN COAL/ NUCLEAR (SPECIFICALLY INDICTED) FIRED THERMAL POWER STATIONS

Sl. No.	Particular	SWC (m^3/MWh)	Ref-er-ence
	Once through cooling		
1	US sub-critical	0.38	[9]
2	US sub-critical	1.14	[1]
3	US sub-critical	0.52	[8]
4	US sub-critical	1.51	[11]
5	Indian sub-critical- once through sea water cooling	0.40	[6]
6	US sub-critical	0.40	[8]
7	US sub-critical , wet flue gas de-sulfurization	0.52	[8]
8	US super-critical , wet flue gas de-sulfurization	0.47	[8]
9	US sub-critical , nuclear	0.52	[8]
10	US sub-critical	0.38	[1]
11	UK sub-critical	0.38	[10]
12	India sub-critical	3.0-4.0	[3]
	Wet cooling towers		
13	US sub-critical	4.16	[9]
14	US sub-critical power	4.11-4.62	[5]
15	US sub-critical	1.82	[1]
16	US sub-critical	3.0	[8]
17	US sub-critical	0.75-4.5	[12]
18	US sub-critical	4.2	18
19	US super critical	3.86-4.11	[8]
20	US sub-critical mechanical draft cooling towers	2.5	[8]
21	US sub-critical –normative value	2.9	[8]
22	Indian 500 MW	4.0-5.0	[7]
23	Indian sub-critical	3.5-4.0	[6]
24	All India sub-critical	3.5-8.0	[3]
25	Indian 2 x 500 MW	3.0	[7]
26	Indian sub-critical	3.0	[6]

27	US sub-critical , wet flue gas de-sulfurization	1.75	[8]
28	US super-critical , wet flue gas de-sulfurization	1.96	[8]
29	US sub-critical , nuclear	2.36	[8]
30	UK sub-critical	4.2	[10]
	UK sub-critical, nuclear	5.7	[10]
31	US sub-critical without carbon capture and storage	2.0	[5]
32	US super-critical without carbon capture and storage	1.7	[5]
33	US sub-critical with carbon capture and storage	3.7	[5]
34	US super-critical with carbon capture and storage	3.2	[5]
35	India sub-critical	3.5-4.5	[3]
Dry cooling			
36	Indian sub-critical	0.55	[6]
37	US sub-critical	0.106-0.136	[4]

TABLE 2

WATER CONSUMPTION OF DIFFERENT CST PLANTS

Sl. No.	Once Through	Wet cool-ing	Dry cool-ing	Hybrid	Other require-ments	Total	Reference
m^3/MWh							
Parabolic Trough							
1	-	3.48	-	-	0.30	3.78	[13]
2	-	-	0.30	-	0.30	0.6	[13]
3	102.18	-	-	-	0.30	102.48*	[15]
4	-	3.48	0.30	-	0.30	4.08	[13]
5	-	3.02	0.29	1.70	0.30	5.31	[13]
6	-	4	-	-	0.30	4.3	[15]
7	-	-	0.2	-	0.30	0.5	[15]
Parabolic dish- Engine							
8	-	0.1	-	-	0.30	0.4	[15]
9	-	-	0.1	-	0.30	0.4	[15]
10	-	-	-	-	0.75	0.75	[17]
Linear Fresnel systems							
11	-	4	-	-	0.30	4.3	[15]
12	-	-	0.2	-	0.30	0.5	[15]
13	-	0.37	-	-	0.30	0.67	[15]
Towers (central receiver systems)							
14	-	2.88	-		0.30	3.18	[15]
15	-	2.83	0.34	0.94	0.30	4.41	[15]
16	-	4	-	-	0.30	4.3	[15]
17	-	-	0.2	-	0.30	0.5	[15]

* Refers to water drawl and not actual consumption.

TABLE 3

COMPARATIVE SWC IN CST AND COAL TPS

Sl. No.	Particulars of plant	Units	Unit of 500 MW		Station of 1 GW	
			Coal	CST	Coal	CST
1	Station/unit capacity	MW	500	500	1000	1000
2	Boiler make up	m^3/h	65	40	85	80
3	Cooling tower make up	m^3/h	940	940	2550	2550
4	Potable water	m^3/h	21	21	52	52
5	Service water	m^3/h	170	150	200	150
6	Losses etc.	m^3/h	550	547	1202	1202
7	Total	m^3/h	2246	2198	5089	5034
1	Boiler make up	%	2.89	1.82	1.67	1.59
2	Cooling tower make up	%	41.85	42.77	50.11	50.66
3	Potable water	%	0.93	0.96	1.02	1.03
4	Service water	%	7.57	6.82	3.93	2.98
5	Losses etc.	%	24.49	24.89	23.62	23.88
6	Total	%	100.00	100	100	100
1	Boiler make up	m^3/MWh	0.13	0.08	0.09	0.08
2	Cooling tower make up	m^3/MWh	1.88	1.88	2.55	2.55
3	Potable water	m^3/MWh	0.04	0.04	0.05	0.05
4	Service water	m^3/MWh	0.34	0.30	0.20	0.15
5	Losses etc.	m^3/MWh	1.10	1.09	1.20	1.20
6	Total	m^3/MWh	3.49	3.40	4.09	4.03

*Exclusive of conveyance losses in the raw water line

The raw water consumption report by a TPS is normally taken at the discharge of the raw water plant. Water losses are also present between the source end discharge and raw water intake. These losses are not normally reported as litres/kWh and are generally considered as commercial losses (unlike in Table 3). This paper also tries to estimate the losses not normally included in the reporting so as to obtain a holistic picture closer to the real water consumption.

2.0 ESTIMATION OF WATER CONSUMPTION IN SUB-SYSTEMS

A few models for water consumption have been developed but these are based only on cooling. The percentage of heat rate (kcal/kWh) which goes into cooling is estimated and the heat rate is converted into SWC (m^3/MWh) by estimating the quantity of water needed to provide a certain quantum of cooling. But these models do not account for water use in direct steam loss and cooling rotating machines for auxiliary applications. The conveyance efficiency between the water withdrawal point and the TPS affect the total consumption.

- The methodology is to accurately compute:
- Sending end transmission efficiency.
- Hold-up or dead volume of water stored in a number of stations.
- Circulation flows.

- Fresh water make-up consumption.
- Recycling of used water to minimize fresh water make up.

The theoretical basis for computing the water consumption are:

2.1 Hold-up quantity

Hold-up or dead volume of storage can be classified into that of in-plant and out-lying areas. In the out-lying areas raw water intake system, water treatment plant and cooling water system are the main storage volumes. In the in-plant boiler and turbine circuit and heat exchangers for bearing, coupling, generator cooling, etc., account for the hold-up volumes.

Security storage level in a TPS is given by number of days of water autonomy which is normally taken as 9-10 days. If the security storage level is increased then the losses will increase and if it is reduced it can result in disruption of the power generation. The optimal storage level is given by a degree of water autonomy of 10 days.

2.2 Circulation flow quantity

The major circulation water quantities can also be classified into that of in-plant and out-lying areas. In the out-lying areas raw water intake system and cooling water system are the main circulating volumes. In the in-plant boiler and turbine circuit account for the circulating volumes.

2.2.1 Cooling tower circulation

The circulation qantities are normally linked to the power generation process. In the case of the condenser cooling water, the heat generated in the condenser is given by,

$$Q_{CC} = \frac{P_O(1-\eta_T)}{\eta_T} \quad ....(1)$$

Where Q_{cc} is the heat dissipated in the condenser cooling (MW). P_o is the power output of the unit (MW) and η_T is the turbo-generator efficiency (dimensionless). A decrease in turbine efficiency increases the cooling load on the condenser thereby necessitating higher quantity of cooling water and consequent higher level of make up.

The circulation flow cooling water ($V_{MS,C}$) as a function of the volume of the main steam flow ($V_{MS,C}$) is given by,

$$V_{CW,C} = V_{MS,C} \times f_{cond} \times f_{dryness} \times f_{SH} \quad ....(2)$$

Where f_{cond} is the fraction of main steam flow going into the condenser (normally 0.78-0.79 in most modern turbines). $f_{dryness}$ is the dryness fraction of the bulk of fluid (normally 0.90-0.92), f_{SH} is the fraction of superheat (1.02 to 1.03).

Circulation ratio of litres of cooling water per litre of steam condenser (CR) is given by,

$$CR = \frac{hfg+hsup}{Cp\Delta T} \quad ....(3)$$

Where h_{fg} is the latent heat of vaporization (kJ/kg), h_{sup} is the superheat (kJ/kg), C_p is the specific heat of water (kJ/kg°C) and ΔT is the rise in the cooling water temperature in the condenser (°C). By using a first order approximation of 3 kg/kWh (=t/MWh), the circulation for cooling water is 122 m^3/h per MW.

2.2.2 Cooling of in-plant heat dissipation

The in-plant heat dissipation is on account of friction in rotating elements such as generator cooling, bearing cooling, cooling of shaft coupling fluids. The main bearings are generator and turbine bearings. In additional there are nearly 100 bearings of high tension motors and their fluid elements in a typical CST plant. Besides, there is also some cooling load due to jacket cooling, seal cooling, etc.

The heat generated in the generator (stator and rotor) is given by,

$$Q_G = \frac{P_O(1-\eta_G)}{\eta_G} \quad ....(4)$$

Where Q_g is the heat dissipated in the generator (MW). P_o is the power output of the unit (MW) and η_G is the generator efficiency (dimensionless) (normally 0.986-0.988).

The circulation quantities in the bearings are dependent on the heat generated in the bearings (Q) (W) as given by,

$$Q = M\omega = \mu F\left(\frac{d}{2}\right)\omega \quad ....(5)$$

Where μ is the coefficient of friction, M is the friction moment (Nm), F is the bearing load (N), d is the bearing diameter (m), ω is the angular velocity (1/s). Normally the heat generated in motor bearings are 12-20 % of the full load losses. High tension motors with efficiency of in the range of 87.33-95.02 % with a normative value of 94 % have a bearing loss of 7.2-12 kW/MW of motor capacity. The heat generated in turbine and generator bearings are calculated based on the above relationship.

The total heat transferred in auxiliary cooling water (Q_{AC}) is given by,

$$Q_{AC} = (Q_A + Q_G) \quad ....(6)$$

The auxiliary power accounts for 4-9 % of the generated power. Of this the motor loads which need water cooling are around 6-7 % of the gross generation.

The circulation water quantity for removal of heat is given by,

$$\dot{m} = \frac{Q_{AC}}{C_{pw}\Delta T} \quad ....(7)$$

Where C_{pw} is the specific heat of water (4.186 kJ/kg°C) and ΔT is permissible rise in water temperature which is normally 10 ºC.

2.3 Steady and intermittent consumption

The major consumption can again be classified into that of in-plant and out-lying areas.

In the out-lying areas like raw water intake system, cooling water system where water is in open tanks, closed tanks and channels the consumption is quantified as:

- Evaporation from open surfaces considering solar radiation, wind and isothermal evaporation.
- Evaporation from indoor surfaces through isothermal evaporation
- Blow down in cooling towers, water treatment plants, recycling plants, etc.
- In the case of coal plants ash ponds are also included for open evaporation.
- In the in-plant areas the water consumption is mainly on account of:
- DM water make up for steam used and lost in the process: This is composed of auxiliary steam consumption for boiler, turbine and supply to external systems like tracking lines, etc..
- Water lost in the heat exchangers for cooling of in-plant equipment like generator, bearings, couplings, etc. of major motors, etc.

Some of the major causes of consumption of water are given as follows.

2.3.1 Transmission efficiency in between sending end and raw water receipt point

The overall water conveying cum storage efficiency (η_C) can be defined as the ratio of the mass of water utilized/consumed ($m_{utilized}$) to the mass of water purchased/withdrawal ($m_{purchased}$),

$$\eta_C = \frac{m_{utilized}}{m_{purchased}} \quad ....(8)$$

The distribution efficiency varies between 60-90 % for most systems, which implies that 10-40 % of the water is not utilized [21].

2.3.2 Storage cum handling efficiency after water is received at raw water plant

2.3.2.1 Evaporation in free surfaces

The standard unit for evaporation in free surfaces is mm/day or m/year. The volume of water evaporated over a period of time is determined by multiplying the evaporation rate with the free surface area (m^2). The water evaporation (also known as pan evaporation or evaporation from an open pan) is given by,

$$m_e = h_{fg}^* \, A(\emptyset_{sat} - \emptyset) \quad ....(9)$$

Where h^*_{fg}= evaporation rate (kg/m^2h), A is the exposed horizontal surface area of water (m^2) , Φ is the specific humidity at the ambient condition and Φ_{sat} is the saturation specific humidity at the atmospheric condition.

$$h_{fg}^* = 25 + 19\,v \quad ....(10)$$

Where ν is the wind velocity (m/s).

In pan evaporation the effect of net solar radiation (influx minus the ground absorption) is not considered. If these are considered then the water evaporation rate is given by the celebrated modified Penman equation [22] which is,

$$E_O = \left\{\left[\left(\frac{\Delta}{\Delta+\gamma}\right)\left\{\left(\frac{R}{h_{fg}}\right) - \left[Q_{ground}\right]\right\}\right] + \left[\left(\frac{\gamma}{\Delta+\gamma}\right)\{(25+19v)(\phi_{sat}-\phi)\}\right]\right\} \quad ....(11)$$

Where E_o is the overall evaporation from an open surface (kg/m^2s), Δ is the slope of the vapor pressure versus temperature curve (saturated vapor pressure line) at the ambient temperature (Pa/°C), γ is the psychrometric constant (≈ 66.8 Pa/°C), R is the incident solar radiation (W/m^2), Q_{ground} is the solar radiation absorbed by the ground, h_{fg} is the latent heat of vaporization (J/kg) at the ambient temperature.

The overall annual evaporation loss can be computed by simulating the performance for one year (8760 hourly readings). The evaporation loss can be converted from kg/m^2s to mm/day through multiplying by 86400 (i.e. s/day).

National Institute of Hydrology (NIH), Roorke India [23] has extensively studied all year round water evaporation from free water surfaces in the presence of solar radiation and wind for a period of 9 years. Based on the experimentally measured pan evaporation values, the monthly and annual values are computed. They have concluded that Penmann and Van Ravel [24] methods grossly under predict the evaporation while Kohler [25] and Morten [26] methods are better. The evaporation values for the present study are estimated based on the NIH studies. Another study which has estimated evaporation from free surfaces all over India is by the Basin Management Organization under Central Water Commission, New Delhi [27]. The experimental data is provided for each month as well as annual data all over India based on 72 evaporimeter stations located all over India, for the time period 1959 to 2006 [27]. The evaporation varies between 1 to 9 mm/day.

2.3.2.2 Evaporation from indoor water pools and tanks

For indoor pools, Shah's correlation gives good representative values [28] when the air velocity is below 9 m/min and density difference lies below 0.0043 kg/m^3. In the case of range of variations the average value has been computed as 0.24 mm/day (1 kg/m^2/h= 24 mm/day). The volume of water evaporated over a period of time is determined by multiplying the evaporation rate with the water surface area (m^2) and time period.

2.3.2.3 Percolation

Percolation occurs in raw water system. The percolation rate based on experimentally data [27] is in the range of 3 mm/day for clayey soils and 14 mm/day for sandy soils. For clay loam soils it can be taken as 7 mm/day. The volume of water evaporated over a period of time is determined by multiplying the evaporation rate with the water surface area (m^2) and the time period.

2.3.2.4 Evapro-transpiration and lateral seepage

The two other sources of water losses are evapro-transpiration caused by transpiration from plants and lateral seepage [29]. Evapro-transpiration varies in the range of 5 mm/day to 10 mm/day and a representative value can be taken as 6 mm/day. Lateral transpiration can be taken as 1 mm/day based on planar area of the water body. The total volume of water loss can be determined by multiplying the evapro-transpiration and lateral seepage with the water surface area (m^2) and the time period.

2.3.3 Cooling water make up

The main cooling tower losses resulting in make-up are windage, evaporation and blow down. A 3 % loss of water in the cooling tower is typical, which includes drift, evaporation and blow down works out to 2.6 litres/kWh [30]. Kairouani et al. (2004) [30] have validated the data in a semi-arid climate for a cross forced draft cooling tower to 4 % of the total water flow rate of 3.4 litres/kWh considering 70 % evaporative heat removal and 30 % sensible cooling. This is on the higher side for forced draft cooling towers.

2.3.4 DM water make up

The main losses are auxiliary steam consumption in the boiler, turbine and outlying areas; blow down and steam leakages in the system. The unsteady loss occurs when the unit boiler safety values open venting out major quantities of steam into the atmosphere. The water lost in the system which is represented by the demineralized water make up represents the main steam lost in the system.

The main steam make up is given by,

$$V_{MS,MU} = V_{MS} \times f_{DM} \qquad ....(12)$$

Where V_{MS} is the main steam flow and f_{DM} is the DM water make up. DM water make up has been brought down from 0.9 to 2.0 % of the main steam flow to 0.5 to 0.7 % through reduction in sampling flow, valve passing, blow down and vacuum pump overflows, etc.

2.3.5 Soft water make up (in plant cooling of heat exchangers)

Soft water make up can be normally taken as 2-5 % of the circulating water flow quantity. In a few rare cases where contamination is expected, the entire water is withdrawn and used for tasks requiring lower level of water quality.

2.3.6 Miscellaneous consumption- drinking water, etc.

The human drinking and cleaning water can be considered on the basis of manpower. The Indian average manpower is 1.8 persons/MW which excludes contract staff. If contract staff is included it is around 3.0 persons/MW. Considering a water requirement of 50 litres/person/day with a utilization efficiency of 80 %, the water requirement is 8 m^3/h. The gardening water requirement is taken as 1 m^3/h. The miscellaneous consumption is 10 m^3/h for a 1 GW plant.

3. Results and discussions

The water consumption is considered for a typical station of 1 GW. The data is fitted to a linear fit as follows:

$$Y = A_0 + A_1X + A_2X^2 + A_3X^3 \qquad ....(13)$$

3.1 Hold-up quantities

Table 4 gives the reserve hold-up volumes for the TPS. The reserve hold-up is in the range of 9-10 days. The raw water reservoir is designed based on 10 days consumption plus but the in-plant one day raw water storage is nearly 10 times higher than the actual daily consumption to take care of refilling in the event of plant tripping causing steam venting and water loss.

TABLE 4			
COMPARATIVE RESERVE HOLD-UP VOLUME OF WATER FOR COAL AND CST STATIONS OF 1 GW			
Sl. No.	**Particulars of hold-up before the station**	**Storage capacity million m^3 per GW Coal**	**Storage capacity million m^3 per GW CST**
1	Raw water reservoir (before raw water pumps) {9 to 10 days storage}(*)	0.9-1.0	0.6 to 0.7
2	In plant raw water storage {1 day storage} (**)	0.35	0.35
3	Total reserve hold-up	1.25-1.35	0.95-1.05

*This is ~10 day consumption plus ; **This is not a daily consumption

Table 5 gives the working hold-up volumes of the plant areas. The working hold up for CST units is 0.27 million m^3 per GW. The working hold up varies between 10-15 seconds for the boiler (solar collectors) to few minutes for cooling towers. Table 6 gives the sensitivity of specific water quantity to unit size.

TABLE 5				
COMPARATIVE WORKING HOLD-UP VOLUME OF WATER FOR COAL AND CST STATIONS OF 1 GW				
Sl. No.		**Particulars of hold-up in a station of 1 GW**	**Storage capacity (m^3)**	**Storage capacity (m^3)**
			Coal	**CST**
1		Water treatment plant		
	1.1	Water treatment plant storage	54000	54000
	1.2	DM storage tank	3800	3800
	1.3	Gravity filters, clarifiers	2000	2000
	1.4	Clear water tanks	3000	3000
	1.5	Soft water tanks	2000	2000
2		Condenser cooling water		
	2.1	Natural draft cooling tower and its pond	198000	198000
	2.2	Piping and open channel between cooling and condenser	1200	1200
	2.3	Condenser water side volume	320	320
3		Boiler and turbine		
	3.1	Boiler volume	1800	1800
	3.2	Boiler drum	225	225
	3.3	Boiler bottom seal	30	30
	3.4	Condensate make up tank	100	100
	3.5	Condenser hot well	90	90
	3.6	Deaerator	400	400
	3.7	Water volume of turbine side steam	300	300
	4.1	Heat exchangers and pipe line	500	500
	4.2	Auxiliary and bearing water seal	400	400
5		Ash handling plant- applicable only to coal units (not applicable to CST plants)		
	5.1	Slurry tank	500	
	5.2	Mixer tank	140	
	5.3	Ash pipe line	3500	
	5.4	Boiler bottom water seal	50	
		In-house		
6		Total working hold-up in the TPS		
	6.1	Coal	272355	
	6.2	CST		268165

TABLE 6			
CURVE FITS FOR THE SENSITIVITY OF THE SPECIFIC WATER QUANTITIES TO STATION SIZE			
Sl. No.	**Particulars of variables**	A_0	A_1
X: Station capacity [100-1500 MW]			
01	Y:Raw water storage requirement of a CST plant (m^3/MW)	139.56	+0.2097
02	Y:DM water storage requirement of both coal & CST plants (m^3/MW)	5.664	-0.001
03	Y: Raw water requirement in a coal plant (m^3/h per MW)	5.5717	-0.0003
04	Y: Raw water requirement in a CST plant (m^3/h per MW)	4.3529	-0.0002
05	Y: Total hold up in the boiler of a coal plant (m^3)	91.098	1.2695
06	Y: Total hold up in the heater of a CST plant (m^3)	59.661	0.5964

3.2.1 Condenser cooling water and Auxiliary cooling water

Table 7 gives the cooling loads of coolers for a 1 GW plant. The total cooling requirement of 38 MW per GW for CST units (46.53 MW_t per GW for coal for comparison) which corresponds to a cooling flow rate of 4100 m^3/h per GW.

For a 1 GW unit (of CST or coal) the heat generated in a generator is around 12.2 MW_t (excluding H_2 cooler which is covered in the above table) which corresponds to a circulating water flow of 1000 m^3/h for CST units and (1220 m^3/h for coal units for comparison).

TABLE 7			
COMPARATIVE CAPACITY OF COOLERS AND HEATERS OF 1 GW COAL AND CST STATIONS			
Sl. No.	**Description**	**Thermal load (kW)**	
		Coal unit	**CST unit**
01	H_2 Cooler	2000	2000
02	Seal Oil Cooler	130	130
03	Main Oil Cooler	3400	3400
04	BFP Main Oil Cooler	7200	7200
05	BFP Working Oil Cooler	500	500
06	Bearing oil coolers	7000	7000
07	Lube oil coolers	7600	7600
08	Primary water coolers	7000	7000
09	Control fluid (fluid coupling) coolers	600	600
10	Pump jacket coolers	400	400
11	Pump seal water coolers	600	600
12	Exciter air coolers	400	400
13	Water sampler coolers	600	600
14	Motor starter coolers	200	200
15	Compressor coolers	400	400
16	Ash slurry pump coolers	300	-
17	Electrostatic precipitator control room coolers	8000	-
18	Total cooling requirement	46330	38030

Table 8 gives the auxiliary power for which bearing cooling is involved. Considering a 6 % heat generation in the auxiliary motors of which bearings form 20 %, the 12 MW which corresponds to 1100 m^3/h per GW.

TABLE 8

COMPARATIVE AUXILIARY POWER EQUIPMENT WHERE HEAT IS GENERATED FOR 1 GW COAL AND CST STATIONS

Sl. No.	**Particulars**	**Actual measured value (% of gross generation)**	
		Coal	**CST**
01	Condensate extraction pumps	0.40	0.40
02	Induced draft fans	1.43	-
03	Forced draft fans	0.46	-
04	Primary air Fans	0.89	-
05	Raymond bowl mills	0.55	-
06	Bearing cooling pumps	0.13	0.13
07	In-house Aux.	3.86	0.53

Table 9 gives the circulation quantities in the TPS. The circulation rates for a 1 GW station are 7548 m^3/h for CST plants and 16045 m^3/h for coal (for comparison).

3.3 Steady and intermittent consumption

The steady and intermittent consumption for CST and coal stations are given in Table 10. The water consumption works out to 4.70 litres/kWh with natural draft cooling towers and 0.98 litres/kWh without natural draft cooling tower (once through cooling).

Table 11 gives the curve fits for variation of SWC with temperature gain across the condenser water side, circulation ratio (CR), energy efficiency [represented by the unit heat rate (UHR) and station heat rate (SHR) in units of kcal/kWh] and station size.

In natural draft cooling towers 80-83 % of the water loss is due to evaporation, 2-2.5 % by drift and the balance of 14.5-18 % is through blow down [6]. There is a possibility for recovery of 10 % of the evaporated water by mechanical extractors. Forced draft or mechanical draft cooling towers consume 1-1.2 % of the total generated power. Air cooled condensers (dry cooling systems) cost almost 50 % higher than forced draft cooling towers. Indirect dry cooling systems cost almost 150 % more than forced draft cooling systems [8].

The soft water make up is in the range of 2-5 % of the circulating flow quantity. DM water make up which varies between 2-5 % (≈60-150 ml/kWh) of the main steam flow can be brought down to 0.5-0.7 % (≈15-21 ml/kWh) [31].

TABLE 9

COMPARATIVE CIRCULATING WATER QUANTITIES FOR 1 GW COAL AND CST STATIONS

Sl. No.	**Particulars**	**Circulating quantity per GW (m^3/h)**	
		Coal unit	**CST unit**
01	Natural draft cooling water circulation for heat withdrawal from condenser	3662	3662
02	Soft water circulation for heat withdrawal from coolers	6083	4988
03	DM water circulation in the boiler-turbine circuit	3100	3100
04	Raw water circulation	3200	2560
05	Total circulating quantities	16045	7548

TABLE 10

COMPARATIVE STEADY CONSUMPTION OF WATER FOR COAL AND CST STATIONS OF 1 GW

Sl. No.	Particulars for 1 GW plant		Consumption (m^3/h) Min	Consumption (m^3/h) Max	Consumption (m^3/h) Average	SWC (litres/kWh) Min	SWC (litres/kWh) Max	SWC (litres/kWh) Average
1	Raw water transport and storage							
	1.1	Evapro-transpiration	6	20	12	0.006	0.02	0.012
	1.2	Tank evaporation	4	12	10	0.004	0.012	0.01
	1.3	Seepage	10	12	11	0.01	0.012	0.011
	1.4	Spillage and overflow	20	30	25	0.02	0.03	0.025
	1.5	Conveyance loss from intake power house	300	1500	600	0.3	1.5	0.6
	1.6	Blow down	50	110	60	0.05	0.11	0.06
	Subtotal of raw water		390	1684	718	0.39	1.68	0.72
2	Condenser cooling water							
	2.1	Blow down	500	600	550	0.5	0.6	0.55
	2.2	Evaporation	2700	2900	2800	2.7	2.9	2.8
	2.3	Drift and windage	350	400	370	0.35	0.4	0.37
	Subtotal of condenser cooling water		3550	3900	3720	3.55	3.9	3.72
3	Soft are clarified water							
	3.1	Soft water make up	50	150	115	0.05	0.15	0.115
	3.2	Water for cleaning and garden	8	20	10	0.008	0.02	0.01
	3.3	Drinking water	10	20	12	0.01	0.02	0.012
	Subtotal of soft water		68	190	137	0.068	0.19	0.137
4	DM water							
	4.1	Production and conveyance loss	50	80	60	0.05	0.08	0.06
	4.2	DM make up	50	80	60	0.05	0.08	0.06
	Sub-total of DM water		100	160	120	0.1	0.16	0.12
5	Ash conveying		2000	2400	2200	2	2.4	2.2
6	Total water consumption							
	6.1 Coal*		6108	8334	6895	6.11	8.33	6.90
	6.2 CST*		4108	5934	4695	4.11	5.93	4.70

*Inclusive of conveyance losses in the raw water circuit.

TABLE 11

THE CURVE FITS FOR THE SENSITIVITY OF SWC OF COOLING WATER SYSTEM WITH THE OPERATING VARIABLES- APPLICABLE TO BOTH COAL AND CST UNITS

Sl. No.	Particulars of variables	A_0	A_1
01	X: Temperature gain across condenser (°C) Y: SWC (m^3/h per MW)	263.39	-14.174
02	X: Temperature gain across condenser (°C) Y: CR (dimensionless)	87.798	-4.727
03	X: Station capacity (MW) Y: Condenser SWC (m^3/h per MW)	157.62	-0.0424
04	X: Design turbine heat rate (kcal/kWh) Y: SWC (m^3/h per MW)	-2.580	+0.003
05	X: Operating turbine heat rate (kcal/kWh) Y: SWC (m^3/h per MW)	-2.309	+0.003

3.4 Overall water indices

3.4.1 Water consumption indices

The major index of water consumption in a TPS is raw water consumption (m^3/h per MW = litres/kWh). Table 12 gives the experimental data from the 41 coal stations and 8 CST stations on of the raw water, soft water and DM water consumption. The station can be divided into three categories with consumption:

- Once through cooling systems: Below 0.5 litres/kWh
- Wet cooling towers: 2 to 5 litres/kWh
- Wet cooling towers: Over 5 litres/kWh.

NA: Not available

The average water consumption works out to 4.2 litres/kWh for CST stations and 2.772 litres/kWh for coal stations (for comparison).

TABLE 12

COMPARATIVE SWC OF RAW WATER FOR COAL AND CST UNITS

Sl. No.	Particulars	Raw water (litres/ kWh)	Soft water (litres/ kWh)	DM water (ml/ kWh)	Raw water (liters/ kWh)	Soft water (liters/ kWh)	DM water (ml/ kWh)
		Coal	Coal	Coal	CST	CST	CST
01	Average value	2.772	2.09	90.40	4.1	0.52	100
02	Maximum value	7.400	2.50	214.10	5.3	2.0	NA
03	Minimum value	0.140	1.40	6.70	0.6	NA	NA
04	Standard deviation	2.262	0.25	48.55	-	-	-
05	Average value below: 0.5 litres/kWh for raw water 15 ml/kWh for DM water	0.238	-	8.30	-	-	-
06	Average value between: 2 to 5 litres/kWh for raw water 15 to 100 ml/kWh for DM water	3.680	-	72.80	-	-	-
07	Average value above: 5 litres/kWh 100 ml/kWh for DM water	6.740	-	142.42	-	-	-

The detailed computation of water consumption for CST stations indicates 4.70 litres/kWh with natural draft cooling towers and 0.98 litres/kWh without natural draft cooling tower (once through cooling). The difference between the data in Table 10 and Table 12 is because losses associated with raw water transport (0.72 litres/kWh) and internal conveyance losses are not recorded while declaring the raw water consumption by many stations leading to lower than actual values.

3.4.2 Water circulation indices

The water circulation rate for a 1 GW station is 7548 m^3/h per GW or 0.18 million m^3/day per GW for CST for 16045 m^3/h per GW or 0.38 million m^3/day per GW for coal (for comparison).

3.4.3 Water hold-up indices

The reserve hold-up in a CST station of 1 GW is around 0.6 to 10.7 million m^3 per GW which corresponds to 9-10 days consumption. The raw water storage inside the plant is 0.35 million m^3 per GW and the working hold-up is 0.27 million m^3 per GW.

3.5 Impact on energy efficiency

The major impact on energy efficiency is of DM water quantity. Energy efficiency also affects the quantity of condenser cooling water. The water consumption in other circuits such as in-plant soft water and soft water or raw water in the out-lying areas does not impact the energy efficiency except for increase in auxiliary power. There is no direct impact of soft or raw water on the energy efficiency. A curve fit of the data provided by Martin (2012) [4] indicates that the sensitivity of SWC (m^3/MWh) to Station heat rate (SHR) (kcal/kWh) is -0.0019 m^3/MWh per kcal/kWh.

The DM water make-up seriously impacts energy efficiency. The impact of DM water make-up as a function of the unit UHR. It can be seen that the impact on UHR is 24.783 kcal/kWh and THR is 21.71 kcal/kWh.

The pumping and handling power (auxiliary power required for various water handling processes) as a percentage of gross energy generation is given in Table 13. Pumping power for CST plants is accounting for 1.86 MW per GW.

TABLE 13

COMPARATIVE PUMPING POWER FOR 1 GW COAL AND CST STATIONS

Sl. No.	Particulars	Actual measured value, % of gross gen.	
		Coal	CST
01	Cooling water pumps and cooling towers	1.51	1.47
02	General service pumps \and auxiliary cooling water pumps	0.27	0.2
03	Bearing cooling pumps	0.13	0.1
04	Water treatment plant pumps	0.09	0.09
05	Ash handling plant	0.3	-
06	Total	2.30	1.86

4.0 CONCLUSIONS

i. The reserve hold-up in a CST station of 1 GW is around 0.6 to 0.7 million m^3 which corresponds to 9-10 days consumption. The raw water storage inside the plant is 0.35 million m^3 per GW and the working hold-up is 0.27 million m^3 per GW.

ii. The water circulation rate for a 1 GW station is 7548 m^3/h or 0.18 million m^3/day for CST plants and for comparison it is 16045 m^3/h or 0.38 million m^3/day for coal. The circulation water rate impacts the pumping power positively.

iii. The water consumption (inclusive of conveyance loss) works out to 4.70 litres/kWh (=m^3/MWh) with natural draft cooling towers. With once through cooling, i.e., without natural draft cooling towers it is 0.98 litres/kWh. One of the major water consumption which is not tracked and measured in many reports is the conveyance loss between the raw water intake source and the power station intake point. This is quite significant and cannot be ignored in reporting of water consumption. In some cases the conveyance loss is as high as 30 % of the total raw water consumption.

iv. The DM water consumption varies between 90 ml/kWh to 214 ml/kWh (=litres/MWh) CST plants. Loss of DM water besides its high cost of production, directly affects the energy efficiency as it mostly represents the high quality steam lost from the system.

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