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1. Modeling of Combined Steam Power Plant and Water-LiBr Absorption Refrigeration Systems for Both Electric Power and Cooling

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Abstract:

A boiler where superheated steam at 300oC, 25 bar is produced by combustion of municipal solid waste (MSW) of composition: carbon-25%, hydrogen-3%, oxygen-20%, sulphur0.3%, nitrogen-0.5%, ash-25%, moisture -25% based on an ultimate analysis. The heat rate to the boiler is 1MW and for that combustion of 84.305 kg/s of MSW is required and 0.355 kg/s of steam is produced. Some amount of the steam is extracted from steam turbine at 10 bars, 190.619oC and pumped to the boiler at 25 bar at 179.91oC where this steam heat is utilized by a generator of water-LiBr absorption refrigeration system. The remaining steam after meeting the generator heat load is sent through a condenser at 0.1 bar and pumped back to the boiler at 25 bars. The present study is done for January and May for Kolkata city, India. The temperature of the evaporator considered is 15oC, generator temperature is 80oC and for the absorber and condenser, an ambient temperature of January and May with cooling load of 350 kW. In May the generator load is more hence more steam is extracted and the turbine work is less than January. The net pumping power required is more for January than May. The power required for pumps in steam power plant and refrigeration is supplied by 2 Central Electronics Limited Make PM 150 solar photovoltaic modules in series and 28 in parallel with 383.538 Ah as battery backup. The discharging and charging amount by the battery in January and May are 71.714Ah, 532.917 Ah; 71.431Ah, 860.519 Ah respectively.

Keywords:

Boiler, Battery, Generator, Municipal solid waste, Solar photovoltaic.

1.1 Introduction:

Presently demand for electrical power and cooling are in an increasing trend. If power or cooling is extracted from a single plant then there is a considerable loss of energy, greater emission of pollutants and an investment cost. But if simultaneous power and cooling is obtained in a combined mode it leads to a better cycle efficiency, a lower emission level and a lower investment cost.

Researchers have used various combinations of power and cooling plants for obtaining both power and cooling at a same time. Martin and Goswami, 2006 investigated the combination of a power and cooling production by using an ammonia–water-based cycle. Ayou *et al*., 2013 gave a summary of the absorption cycles in the literature for obtaining both power and cooling. Goswami, 1999 proposed a combination of a thermal driven power and cooling cycle which combined the Rankine and ammonia water absorption refrigeration systems where Rankine cycle plant was heated by using a low-cost concentrating collector.

Nondy and Gogoi, 2020 compared the results of four simultaneous power and cooling cycles in which the exhaust heat of a topping plant of a gas turbine plant is utilized for further simultaneous power and cooling production. Tamm and Goswami, 2003 did an intensive investigation both in theory and experiments for a combination of thermal power and cooling cycle proposed by Goswami. Ravelli *et al.*, 2018 dealt with the performance prediction of Concentrated Solar Power plants integrated with cooling energy production for Saudi desert region.

1.2 System Layout:

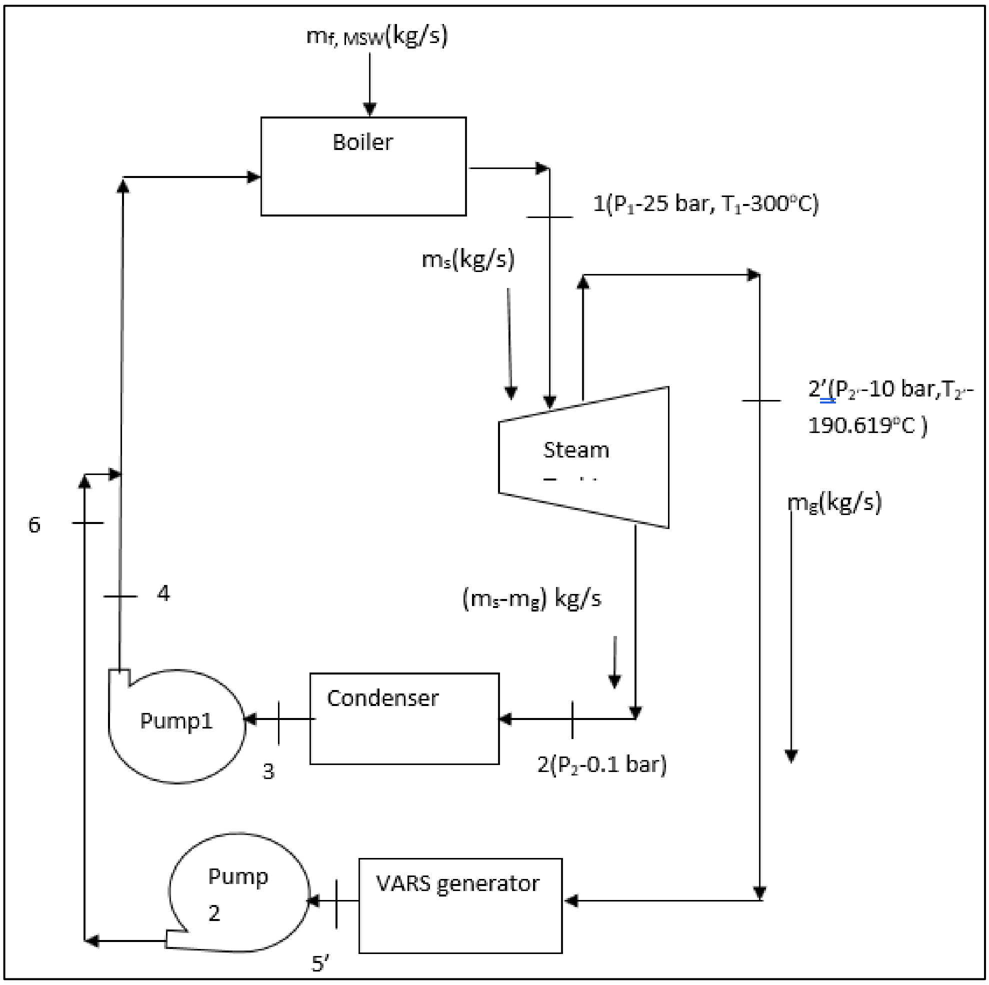

Figure 1.1: Schematic view of steam power plant acting as topping cycle

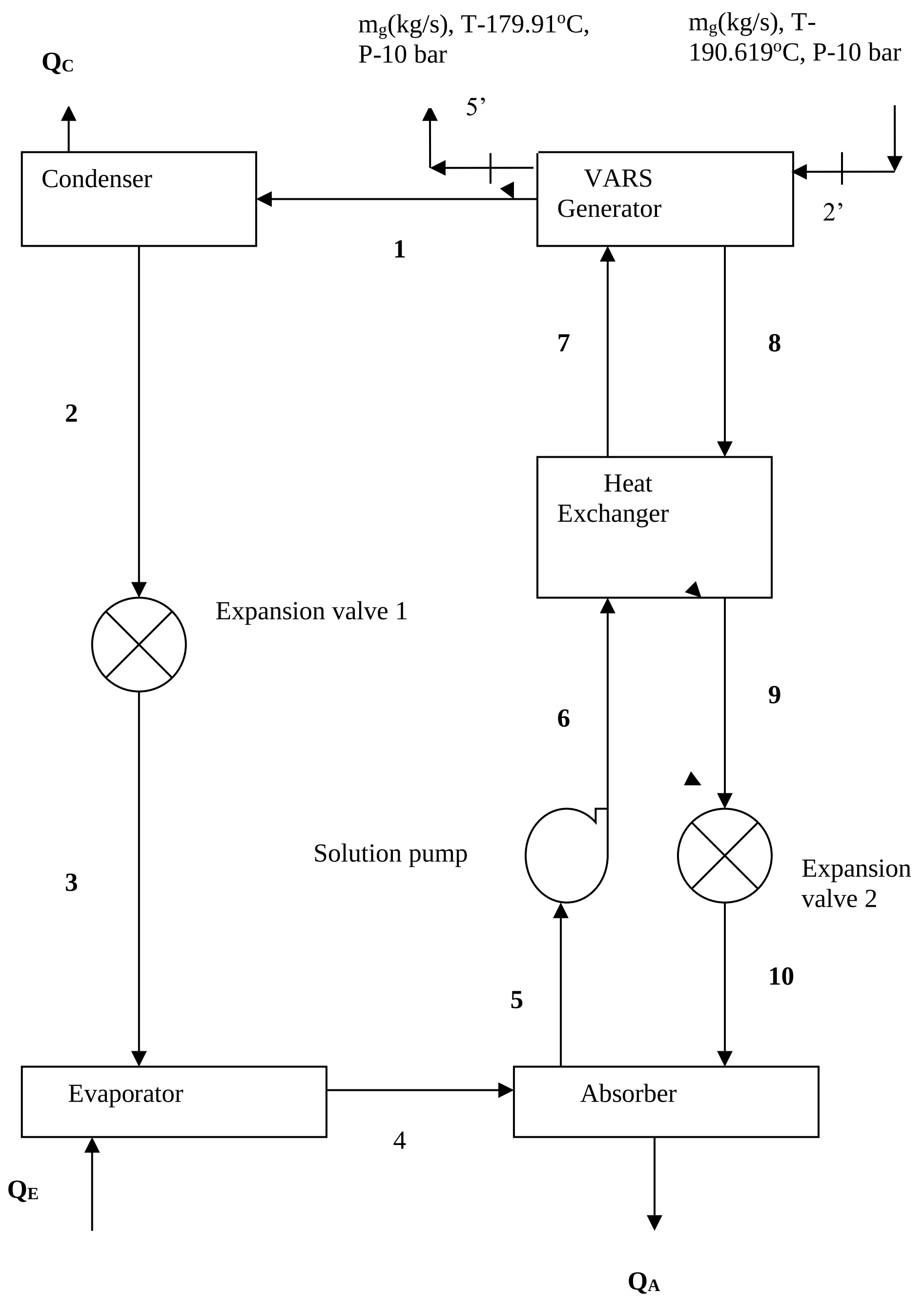

Figure 1.2: Schematic view of water-LiBr absorption refrigeration system utilizing steam heat by generator

The present paper deals with supplying heat to a steam power plant by burning MSW (municipal solid waste) and extracting some amount of steam from a turbine for supplying heat to the generator of water-LiBr absorption refrigeration system producing both power and cooling. The steam power plant acts as a topping cycle and water-LiBr absorption refrigeration system as a bottoming cycle. Figure 1.1 shows a steam power plant where heat to a boiler of 1MW is supplied by burning MSW of composition: carbon-25%, hydrogen-3%, oxygen-20%, sulphur0.3%, nitrogen-0.5%, ash-25%, moisture -25% based on an ultimate analysis (Becidan, 2007) and its calorific value is found from (Kaushik and Singh, 2013). Steam is superheated to 300° C at 25 bars. The steam produced by boiler (m_s) is passed through a turbine. An amount of m_g quantity of steam is extracted from the turbine for heating the generator of water-LiBr absorption refrigeration system and the steam(m_g) exits from generator at 5' after rejecting heat to the generator which is pumped back to the boiler. The remaining steam (m_s-m_g) is passed through a steam condenser at 0.1 bar and pumped back to the boiler.

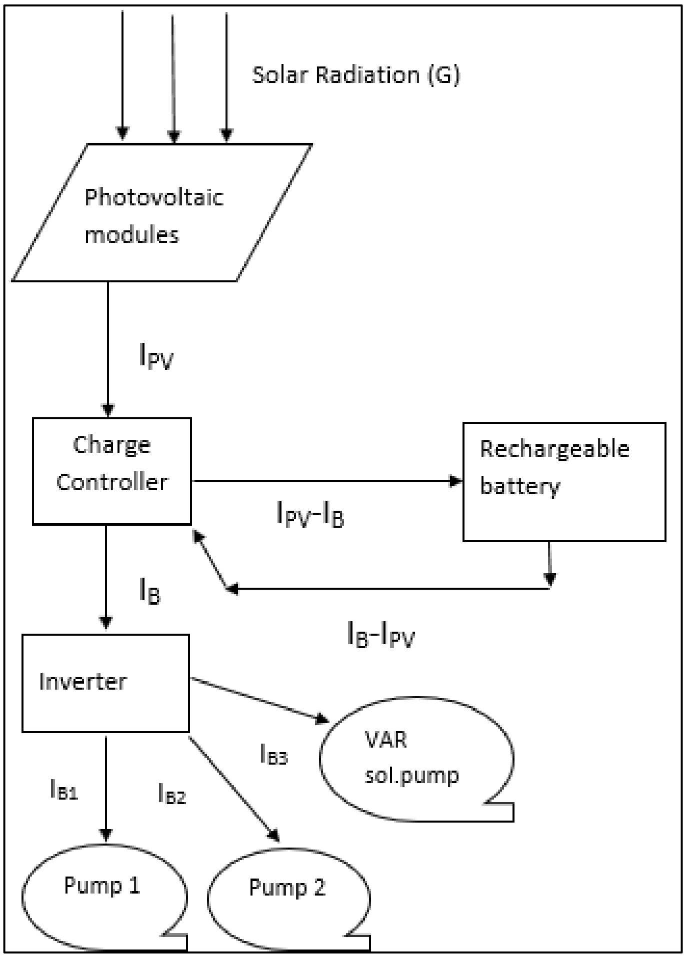

Figure 1.3: Schematic view of solar photovoltaic system for powering pumps in steam power plant and VARS solution pump.

Figure 1.2 shows a water-LiBrVARS (vapour absorption refrigeration system) where the evaporator temperature, generator temperature are maintained at 15°C, 80°C respectively and along with absorber and condenser temperature at ambient temperatures for city of Kolkata, India (Tiwari, 2004) for January and May. The quantity of steam extracted (m_g)

from the turbine at 190.619^{o}C, 10 bar is allowed to flow through the generator and exits at 179.91^{o}C,10 bar from the generator after rejecting the required heat in the generator.

The heating load of the generator is determined for 100 TOR (ton of refrigeration) (350 kW) for January and May with a heat exchanger effectiveness for counter flow flat plate heat exchanger as 0.8 (Flat plate heat exchanger…2023).

Solar radiation falling on the photovoltaic modules generates current I_{PV}. This current is passed through a charge controller where the current required by pumps I_B (I_{B1}+I_{B2}+I_{B3}) is sent through an inverter.

The excess currents (I_{PV}-I_B) after meeting the pumps' current are sent to the rechargeable battery from the charge controller to be utilized during non-sunshine hours/night time.

1.3 Modeling of Combined Steam Power Plant and Absorption Refrigeration Plant:

In the boiler 1MW quantity of heat is supplied by burning MSW at a rate of 84.305 kg/s. The efficiency of turbine and pumps as 90% (Steam turbine efficiency…2023) and 80% (Pump efficiency…2023) respectively are considered. The amount of steam produced due to 1 MW heat to bolier(m_s) as shown in fig.1 is obtained by:

$$m_s = \frac{1000}{(h_1 - h_4)} \tag{1}$$

Where, 1000-kilowatt amount of heat given to boiler by burning 84.305 kg/s MSW; h_1-3008.8 k J/kg at 25 bar, 300^{o}C; h_4-194.953 k J/kg at 25 bar, 46.558^{o}C.

The quantity of steam flow rate needed to be extracted from the steam turbine at 10 bars, 190.619^{o}C for meeting generator heating load (Q_g) as shown in fig.1and 2 is:

$$m_g = \frac{Q_g}{h_{2'} - h_{5'}} \tag{2}$$

Where, m_g-mass flow rate of steam needed to be extracted from steam turbine for generator heat load(kg/s); $h_{2'}$-2804.646 k J/kg at 10 bar, 190.619^{o}C extracted from turbine; $h_{5'}$-762.79 k J/kg at 10 bar,179.91^{o}C (saturated liquid state) at exit from generator.

The pumping power for the pump 1(W_{p1}):

$$W_{p1} = \frac{(m_s - m_g) \times (h_4 - h_3)}{0.8} \tag{3}$$

Where, h_4-194.953 k J/kg at 25 bar, 46.558°C; h_3-191.81 k J/kg at 0.1 bar, 45.81°C (saturated liquid state); 0.8-efficiency of pump (Pump efficiency…2023).

The pumping power for the pump 2 (W_{p2}):

$$W_{P2} = \frac{m_g \times (h_6 - h_{5'})}{0.8} \quad (4)$$

Where, h_6-764.480 k J/kg at 25 bar, 180.312 °C; $h_{5'}$-762.79 k J/kg at 10 bar,179.91°C (saturated liquid state), 0.8-efficiency of pump(Pump efficiency…2023).

The solution pumping power of VARS(W_{ps})(k W) is:

$$W_{ps} = \frac{m_{ss} \times (P_{condenser} - P_{evaporator})}{\rho_{ss}} \quad (5)$$

Where, m_{ss}-mass flow rate of strong solution(kg/s) in VARS; $P_{condenser}$-pressure of condenser (kPa); $P_{evaporator}$-pressure of evaporator(kPa); ρ_{ss} -density of strong solution(kg/m^3)

The turbine work output (W_T)(kW) is given by:

$$W_T = (0.9 \times m_s \times (h_1 - h_{2'})) + (0.9 \times (m_s - m_g) \times (h_{2'} - h_2)) \quad (6)$$

Where, 0.9-efficiency of turbine (Steam turbine efficiency…2023); h_2-2106.05 k J/kg (considering 80 % dryness fraction of steam).

The amount of current required from solar photovoltaic modules (I_{SPV}) for whole day is given by:

$$I_{SPV} = \frac{(\sum W_{p1} + \sum W_{p2} + \sum W_{ps}) \times 1.25 \times 1000}{48 \times 0.85 \times 7 \times 0.85 \times 0.85} \quad (7)$$

Where, 1.25-derating factor (Telecommunication Engineering Centre. 2012); 48-system voltage; 0.85-power factor; 7-sunshine hours in Kolkata city (Patra and Datta, 2012); 0.85-inverter efficiency, 0.85- charge controller efficiency.

The photovoltaic modules(number) required in parallel (N_p) is: $N_p = \frac{I_{SPV}}{4.8}$ (8)

Where, 4.8-maximum module current (Solar photovoltaic….2021)

The photovoltaic modules(number) required in series (N_s) is: $$N_s = \frac{48}{34} \qquad (9)$$

Where, 48-system voltage, 34- maximum module voltage (Solar photovoltaic….2021)

The solar radiation data and temperature for January and May for Kolkata city are obtained from (Tiwari, 2004). Wind speed for January and May for Kolkata city is obtained from (Wind speed in Kolkata…2012).

1.4 Results and Discussions:

From equation 1, the steam flow rate quantity produced is found to be 0.355 kg/s throughout the day.

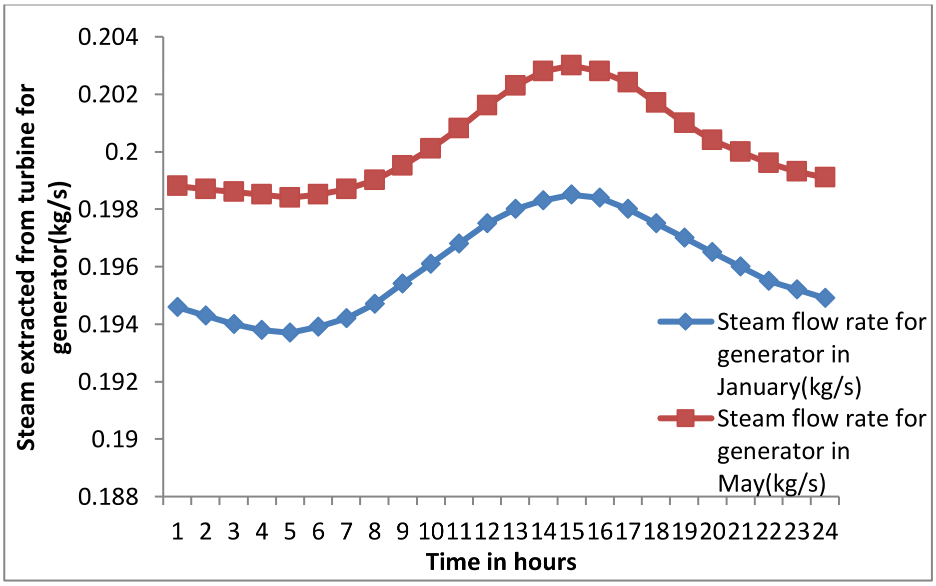

Figure 1.4: Variation of extraction rate of steam from turbine for VARS generator heating.

From figure 1.4 it is seen that the steam extraction(m_g) gives a decreasing trend from 1:00 to 5:00 hours, an increasing trend from 6:00 hours to 15:00 hours and again a decreasing trend from 16:00 hours to 24:00 hours as heating load of generator (Q_g) shows a decreasing trend from 1:00 to 5:00 hours, an increasing trend from 6:00 hours to 15:00 hours and again a decreasing trend from 16:00 hours to 24:00 hours respectively accordingly to equation 2. In May (m_g) is more than January due to greater generator heating load.

In figure 1.5 it is seen that pumping power by the pump1 shows an increasing trend from 1:00 to 5:00 hours, a decreasing trend from 6:00 hours to 15:00 hours and again an increasing trend from 16:00 hours to 24:00 hours as m_g gives a decreasing trend from 1:00 to 5:00 hours, an increasing trend from 6:00 hours to 15:00 hours and again a decreasing trend from 16:00 hours to 24:00 hours resulting in term (m_s-m_g) to show an increasing trend from 1:00 to 5:00 hours, a decreasing trend from 6:00 hours to 15:00 hours and again an increasing trend from 16:00 hours to 24:00 hours in equation 3. However, h_3 and h_4 remains constant.

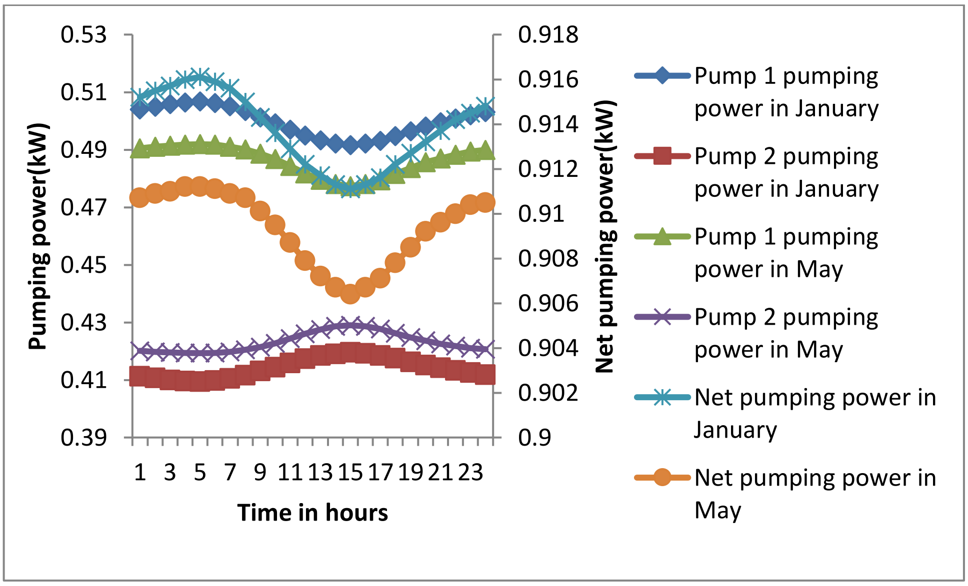

Figure 1.5: Variation of pumping power by pump 1 and 2

In figure 1.5, pumping power by the pump1 in January is more than May because in May, m_g is more in May resulting the term (m_s-m_g) in equation 3 being less which results in the lower pumping power in May.

Again, in figure 1.5, pumping power by pump 2 shows a decreasing trend from 1:00 to 5:00 hours, an increasing trend from 6:00 hours to 15:00 hours and again a decreasing trend from 16:00 hours to 24:00 hours because m_g gives a decreasing trend from 1:00 to 5:00 hours, an increasing trend from 6:00 hours to 15:00 hours and again a decreasing trend from 16:00 hours to 24:00 hours in equation 4. However, h_6 and $h_{5'}$ remains constant.

In figure 1.5, pumping power by the pump 2 in May is more than January because in May, m_g is more in May in equation 3 resulting in more pumping power in May than January.

The solution pumping power of VARS varies in the same trend as heating load of generator and is very small and after adding it to W_{p1} and W_{p2}, the net pumping power is similar to as shown to figure 1.5.

It is seen that the net pumping power of January is more than May as magnitude of W_{p1} variation in January is more than May with little variation effects of W_{p2} for the net pumping power.

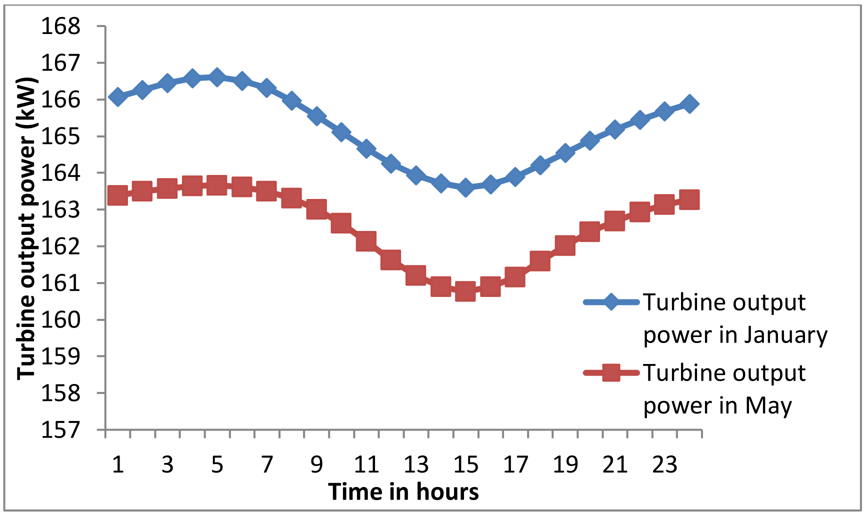

Figure 1.6: Variation of turbine power

In figure 1.6, it is seen that the turbine power shows an increasing trend from 1:00 to 5:00 hours, a decreasing trend from 6:00 hours to 15:00 hours and again an increasing trend from 16:00 hours to 24:00 hours as the term (m_s-m_g) in equation 6 shows an increasing trend from 1:00 to 5:00 hours, a decreasing trend from 6:00 hours to 15:00 hours and again an increasing trend from 16:00 hours to 24:00 hours as explained for the pump 1 in figure 1.5. The variation of m_g is shown in figure 4. However, h_1, $h_{2'}$, h_2 in figure 1.1 remains constant.

The turbine output for January is more than May due to lesser value of term (m_s-m_g) in May than January.

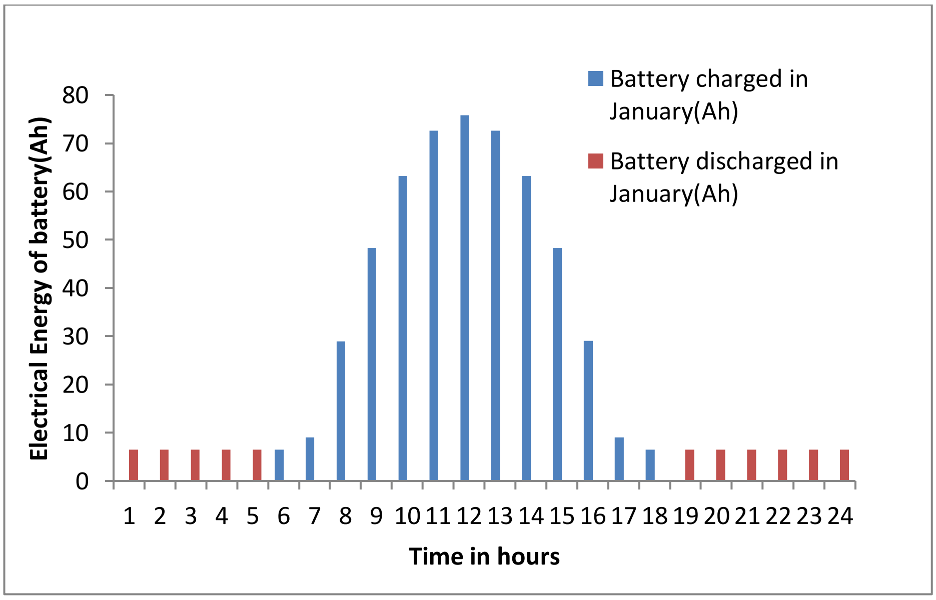

Figure 1.7: Variation of battery charging and discharging in January

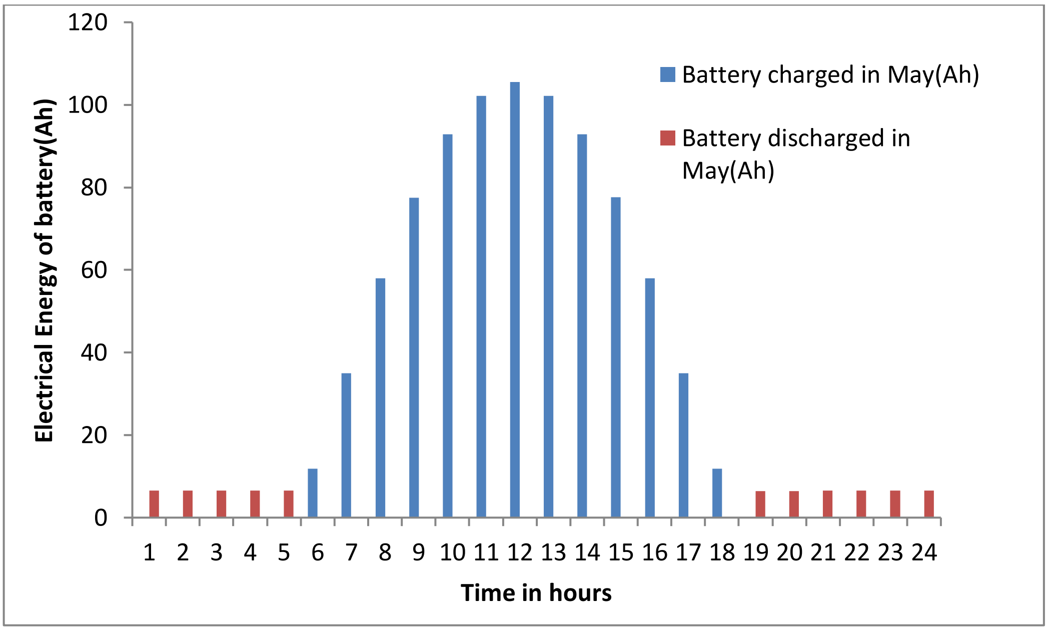

Figure 1.8: Variation of battery charging and discharging in May

Figure 1.7 and 1.8 illustrates the charging and discharging pattern of the rechargeable battery in January and May. As seen in the figure's battery discharging increases from 1:00 to 5:00 hours and again increases from 19:00 hours to 24:00 hours as net pumping power increases from 1:00 to 5:00 hours and again increases from 19:00 hours to 24: hours. Battery charging increases from 6:00 hours to 12:00 hours and again decreases to 18:00 hours as solar radiation increases from 6:00 hours to 12:00 hours and again decreases to 18:00 hours.

Also from the figures, battery discharging is more in January due to greater net pumping work than May. Also, battery charging is more in May as it has greater solar radiation than January.

The quantity of charge discharged and charged by the battery in January and May are 71.714Ah, 532.917 Ah; 71.431Ah, 860.519 Ah respectively.

The requirement of the photovoltaic modules of Central Electronics Limited Make PM 150 in parallel and series as calculated from equation 8 and 9 are found to be 28 and 2 respectively.

1.5 Conclusions:

Based on consideration as 15°C evaporator temperature, 80°C generator temperature, ambient temperature of Kolkata city in January, May as absorber and condenser temperature of water-LiBr absorption refrigeration, 350 kW cooling load can be obtained by using steam extraction from a turbine of a steam power plant where 1 MW of boiler heat is obtained by combustion of 84.305 kg/s of MSW of composition mentioned in text. The requirement of photovoltaic modules of Central Electronics Limited Make PM 150 in parallel and series are found to be 28 and 2 respectively for powering pump1, pump 2 and absorption pump. The study is made for January and May because January and May have minimum solar radiation, temperature and maximum solar radiation, temperature respectively and if it works well in minimum and maximum conditions the combined system will work well throughout the year in Kolkata city, India.

The limitation of the study is that COP (coefficient of performance) is low for the single stage water-LiBr absorption refrigeration. Two stage or three stage water-LiBr absorption refrigeration can be used for improving the COP which will require a greater generator heating load resulting in more amount of MSW combustion in the boiler.

Use of solar concentrators/ a greater amount of MSW combustion can be used in a boiler for higher steam production and higher cooling load to be used by a generator of absorption refrigeration system. Also, solar collectors can be used for heating generator of a higher stage absorption refrigeration system.

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