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Thermal and Economic analysis of Solar Organic Rankine Cycle

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ABSTRACT

The use of solar thermal energy for electricity generation is a clean and sustainable way to cover the increasing energy needs of our society. The most mature technology for capturing solar energy in high temperature levels is the Parabolic Trough Collector. In this study, an Organic Rankine Cycle coupled with Parabolic Trough Collector is analysed for two approaches. First is to develop a hybrid cycle in which the Parabolic Trough Collector field is combined with Traditional Steam Rankine Cycle without storage tank having boiler as a heat exchanger for 25MW power generation at GNFC, Bharuch. And the second approach is to develop an Organic Rankine cycle coupled with Concentrated Solar collector field (Parabolic Trough Collector Field) without storage tank and water is used as a working fluid in both the systems. Economic analysis is also reported to assess the performance and commercial viability of the system.
Keywords: Organic Rankine Cycle, Solar Thermal Collector, Concentrated Solar Power System, Solar-Coal based Hybrid System.

I. INTRODUCTION

1.1 Basics of ORC, Solar Thermal Collector and CSP and Hybrid System

- ORC: This cycle is similar to the Conventional Rankine Cycle. Organic Rankine Cycle (ORC) technology can generate electric power efficiently by heat sources of the middle low temperature.
- It is capable to utilize low grade heat sources such as waste heat from industries, solar energy, geothermal energy, biomass etc. In Organic Rankine Cycle system, Organic Fluids are used as working fluids but sometimes water is also used as a working fluid.
- Now a day's ORC is a well-known and widely spread form of energy production, mostly in biomass and geothermal, but great rises in solar and heat recovery applications are also expected.

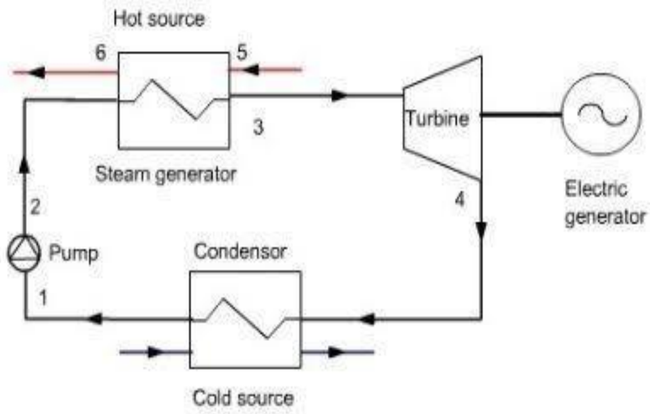

Fig1: - Organic Rankine Cycle

CSP: Concentrated Solar Power Technology(CSP) use mirrors to concentrate sun's radiation and convert it into heat to create steam to drive a turbine that generate electric power.CSP can be integrated with thermal storage systems to generate electricity during cloudy weather. This ability to store solar energy

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makes CSP a flexible and dispatchable source of renewable energy.

There are 4 types of CSP technologies in which parabolic trough collector system and power tower system are most efficient technologies.

1. Parabolic Trough System: -In a parabolic trough CSP system, the sun's energy is concentrated by parabolically curved, trough-shaped reflectors onto a receiver pipe – the heat absorber tube – running along about a meter above the curved surface of the mirrors. The temperature of the heat transfer fluid flowing through the pipe, usually thermal oil, is increased from 293ºC to 393ºC, and the heat energy is then used in the thermal power block to generate electricity in a conventional steam generator.

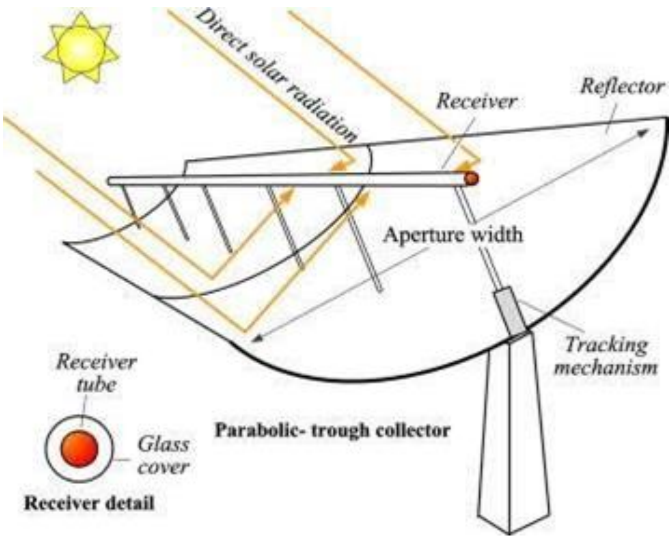


Fig 2: - Parabolic Trough Collector

2. Power Tower System: -Power tower or central receiver systems utilize sun- tracking mirrors called heliostats to focus sunlight onto a receiver at the top of a tower. A heat transfer fluid heated in the receiver up to around 600ºC is used to generate steam, which, in turn, is used in a conventional turbine-generator to produce electricity. 300 to 2000°C temperatures can be achieved by this system.

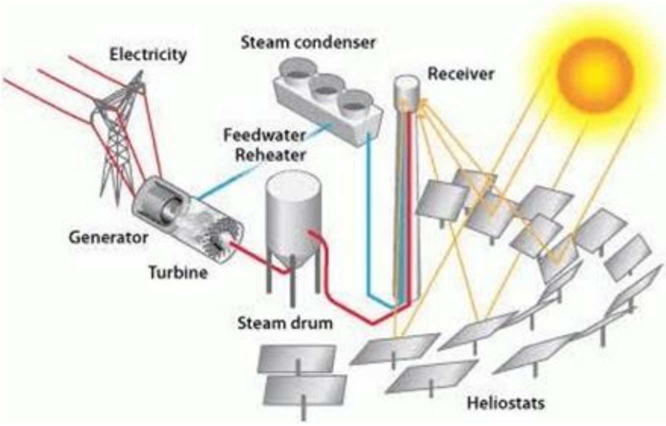


Fig 3: -Solar Power Tower

3. Linear Fresnel System: - Similar to the long arrays of a parabolic trough CSP system, a Linear concentrating collector field consists of a large number of collectors in parallel rows. These are typically aligned in a north-south orientation to maximize annual and summer energy collection. The mirrors are laid flat on the ground and reflect the sunlight to the pipe above.

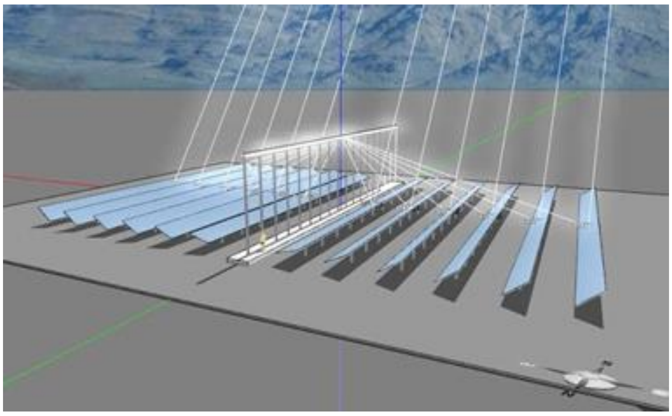


Fig 4: -Linear Fresnel Collector

4. Parabolic Dish System: - A Parabolic dish system consists of a parabolic-shaped point focus concentrator in the form of a dish that reflects solar radiation onto a receiver mounted at the focal point. These concentrators are mounted on a structure with a two-axis tracking system to follow the sun. The collected heat is typically utilized directly by a heat engine mounted on the receiver moving with the dish structure. Dish can attain extremely high temperatures, and holds promise for use in solar

reactors for making solar fuels which require very high temperatures.

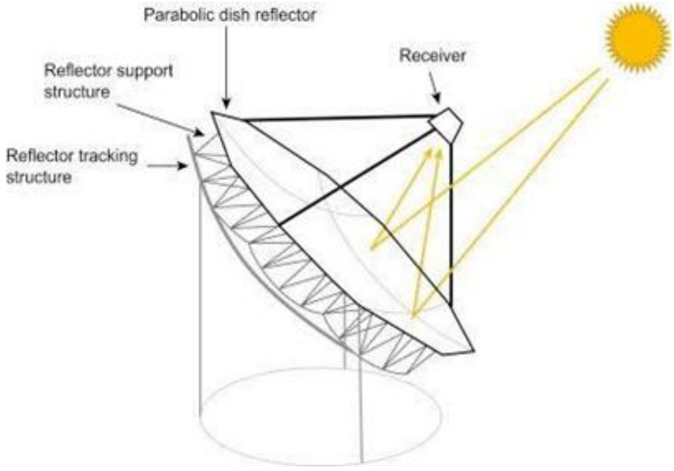
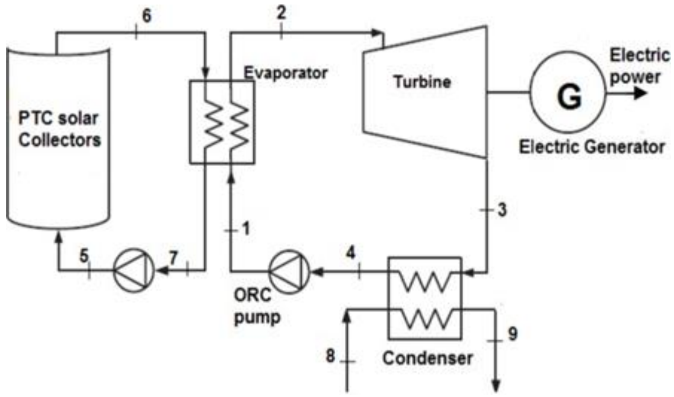


Fig 5: - Paraboloid Dish Collector

Hybrid System: CSP system can also be combined with combined cycle power plants resulting in hybrid power plants which provide high value, dispatchable power. They can also be integrated into existing thermal fired power plants that use a power block like CSP such as coal, natural gas, biofuel or geothermal plants. It can also use to fossil fuel to supplement the solar output during periods of low solar radiation. In that case coal fired or natural gas fired boiler or reheater is used.



District	Month	Monthly Average Solar Radiation (KWh/m2/day)
Bharuch	Jan	6.38
	Feb	7.10
	Mar	7.06
	Apr	7.00
	May	6.71
	Jun	4.11
	Jul	2.44
	Aug	2.23
	Sep	4.25
	Oct	6.36
	Nov	6.13
	Dec	5.94
Average annual solar irradiation		5.46

Table -1- Average Solar Irradiation (Source : NREL)

1. Solar Power and its Technology: Environment Friendly and Cost Effective

• Every energy generation and transmission method affects the environment. As it is obvious conventional generating options can damage air, climate, water, land and wildlife, landscape, as well as raise the levels of harmful radiation. Solar power technologies are substantially safer offering a solution to many environmental and social problems associated with fossil and nuclear fuels.

• Solar power technologies provide obvious environmental advantages in comparison to the conventional energy sources, thus contributing to the sustainable development of human activities not counting the depletion of the exhausted natural resources, their main advantage is related to the reduced CO2 emissions and, normally, absence of any air emissions or waste products during their operation.

- It reduces of the emissions of the green house gases (mainly CO2, NOx), and also prevents toxic gas emissions (SO2, particulates).
- It helps in reclamation of degraded land.
- It reduces the required transmission lines of the electricity grids.
- It also helps in improvement of the quality of water resources.

Table -2- Emission Reduction by CSP Plants (Source : Solar Task Force Report, Western Governor's Association

Pollutant	Proxy Fossil Plant Emissions Rate (Kg/KWH)	CSP plant capacity		
		100 MW (tons/year)	2100 MW (tons/year)	4000 MW (tons/year)
NOx	9.286	7.4	156	297
CO	5.572	4.5	96	181
VOC	3.250	2.6	54	103
CO2	238349	191,000	4,000,000	7,600,000

II. DESIGN

In this report 2 approaches are discussed in which hybrid system with solar – coal based power plant and another system is CSP with ORC is considered.

Three systems are described below which are current system, Hybrid system according to first approach and CSP coupled ORC system according to second approach.

In current system steam is superheated at 510 C and 96 Kg/cm2.

Description of Current system:

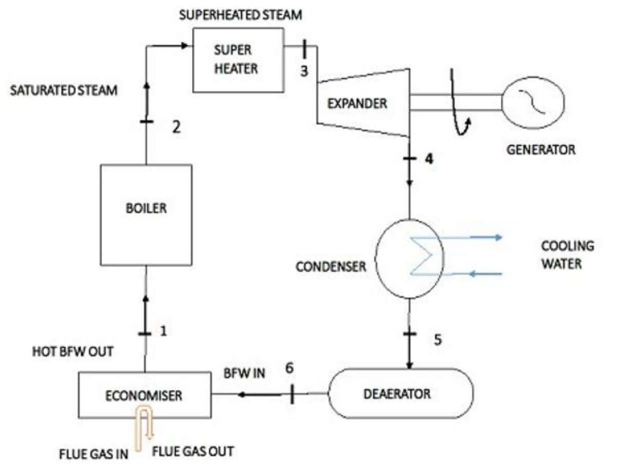


Fig 6: - Schematic Diagram of Current System

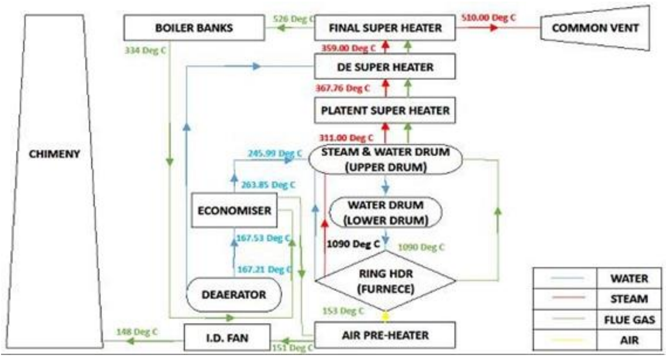


Fig 7: - Schematic Diagram of Boiler Plant

•Fig. 6 shows the current system diagram of the plant and Fig. 7 shows the flow and temperature of Boiler feed water, steam and flue gases.

•In this system heat is supplied to the water in boiler and thus saturated steam is generated then this steam is superheated in superheater. The superheated steam enters into the turbine where it expands and work produced by turbine is rotary work and is used to drive a generator. Then low pressure low temperature steam is condensed into the condenser attached at the exit of the turbine and this condensate is passing through the deaerator where dissolved oxygen is removed from it and then moving to the economiser where BFW is preheated by flue gases.

•Temperature of inlet and outlet at each stage is given in the table.

Feed Water Temperature	**Inlet temp**	**Outlet temp**
Deaerator	**-**	**167.21˚**
Economiser	**167.53˚c**	**236.85˚**
Upper Drum	**245.99˚c**	**-**
Steam Temperature		
Upper Drum	**-**	**311.00˚ c**
Platent Superheater	**311.00˚c**	**367.76˚ c**
De superheater	**367.76˚c**	**359.00˚ c**
Final superheater	**359.00˚c**	**510.00˚ c**
Common vent	**510.00˚c**	**-**
Flue Gas Temperature		
Final Superheater	**-**	**526.00˚ c**
Boiler Banks	**526.00˚c**	**334.00˚ c**
Economiser	334.00˚c	**153.00˚ c**
Air Pre heater	153.00˚c	**151.00˚**

		c
I.D. fan	151.00°c	**148.00° c**
Chimney	148.00°c	**148.00° c**

Table – 3 – Inlet and Outlet Temperature at each stage

Description of Hybrid system:

•The schematic diagram of solar-coal based hybrid system is shown below in fig. 8

•In this system solar Thermal collector (PTC) is parallely combined with boiler.

•The temperature generated in furnace is obtained by solar thermal collectors which is 49C.

•During day time operation, feed water from economiser is passing through solar collector and converted into saturated steam by using solar energy from sun's radiation. After leaving from collector saturated steam is entered into superheater and the same process is occurs as per traditional cycle.

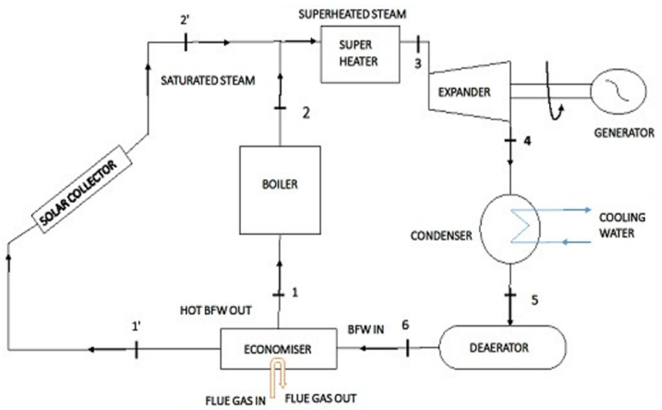


Fig 8: - Schematic Diagram of Hybrid System

Description of Solar based ORC system:

•Schematic diagram of solar thermal Organic Rankine Cycle is shown as below.

•In this system Parabolic Trough Collectors are used as solar energy concentrator.

•Working of this system is same as the traditional cycle but the main difference is that in ORC used low grade heat sources to generate electricity. In some systems water is also used as a working fluid.

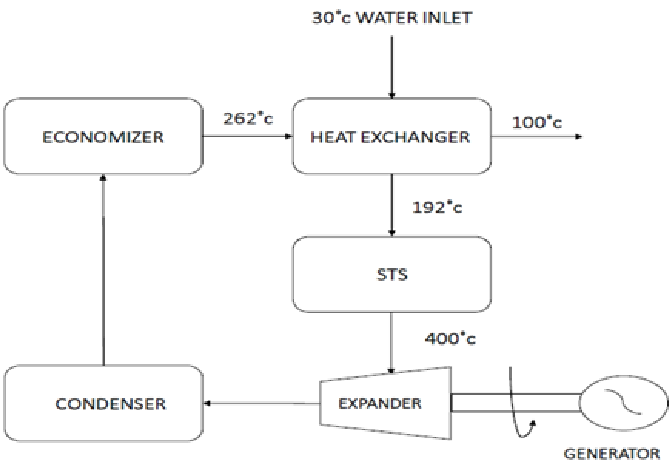


Fig 9: - Schematic Diagram of Solar based ORC

•In this system 208 C temperature is increased by solar thermal system which is parabolic trough collector field.

•As shown in the fig:- 9, from economizer water is entering into heat exchanger with 262 C and leaves from heat exchanger at 100 C. This water heats the water entering into solar thermal system and convert it into saturated steam at 192 C and solar thermal system convert it into superheated steam which is coming out from solar thermal system at 400 C.

•In this system, assuming some parameters and then finding the electricity generation which is 12 MW.

•Temperature, pressure and mass flow at inlet and outlet of the turbine is given below.

	Inlet Steam	**Outlet Steam**
Pressure(Kg/cm2)	24.6	0.98
Temperature(°C)	400	125.5
Mass flow(T/H)	93.4	93.4

Table – 4 – Temp., Pressure and Mass flow of Turbine (12)

III. Calculation PROCEDURE

3.1 Collection of Data

First of all, data should be collected from the GNFC steam and power generation department. The important data of boiler and solar thermal collectors for calculation are given below in the table.

Quantity of steam generated per hour	180 MTPH
Fuel consumption per hour	700 MTPH/DAY = 29.167 MTPH/HOUR
Boiler feed water temperature	170 C
Gross CFV of Indian coal	4220 KCal/KG
Gross CFV of Imported coal	6600 KCal/KG
Enthalpy of saturated steam at 60 kg/cm2	2785.00 KJ/KG
Enthalpy of Boiler feed water	719.10 KJ/KG
Mass flow rate	47.222 KG/S
Specific heat	4.186 KJ/KG C
Outlet temperature	311 °C
Inlet temperature	262 °C

Table – 5– Data of Boiler (From GNFC, Bharuch)

Parameters	**PTC**	**LFR**	**PDS**
No (Optical Efficiency)	0.7	0.65	0.65
ID(W/m2)	800	800	800
Ul1(Heat Transfer Coefficient(W/m2K))	0.1	0.1	0.35
Ul2(W/m2K2)	0	0	0.00002
Tin(°C)	262	262	262
Tout(°C)	311	311	311
To	28	28	28

Table –6 – Data of Solar Collector [10]

Losses	**Percentage (%)**
Heat loss in dry flue gas	4.93%
Heat loss due to formation of H2O from H2 in fuel	3.59%
Heat loss due to moisture in fuel	1.44%
Heat loss due to moisture in air	0.26%
Radiation loss	0.29%
Heat loss due to solid combustible in ash	3.49%
Total	14.00%

Table – 7 – Data for finding Boiler Efficiency by Indirect Method

3.2 Thermal Analysis of System

For thermal analysis of the system we need to find the efficiency and also heat transfer rate of boiler. The efficiency of boiler can be calculated by two methods such as direct method and indirect method.

BOILER CALCULATION: -

BOILER EFFICIENCY: -

- First we need to calculate boiler efficiency.
- Two methods for calculate boiler efficiency, Direct method Indirect method

DIRECT METHOD: -

$\boldsymbol{\eta} = \mathbf{Q} \times (\mathbf{H} - \mathbf{h}) \times \mathbf{100}\ (\boldsymbol{q} \times \boldsymbol{GCV})$

Q= Quantity of steam generated (kg/hr) H= Enthalpy of steam (Kcal/kg)

h= Enthalpy of water (kcal/kg)

GCV= Gross calorific value of the fuel.

q= Quantity of fuel use per hour (kg/hr)

INDIRECT METHOD: -

100 – (i +ii + iii + iv + v + vi)

i. Percentage heat loss due to dry flue gas

ii. Percentage heat loss due to evaporation of water formed due to H2 in fuel

iii. Percentage heat loss due to evaporation of moisture present in fuel

iv. Percentage heat loss due to moisture present in air.

v. Percentage heat loss due to radiation and other unaccounted loss Vi. Percentage heat loss due to solid combustible in ash

Q OF BOILER: -

First we calculate the Q (heat transfer) of boiler for find out the solar thermal area and efficiency.

q = (m / t) cp dT

q = heat transfer (kJ/s, kW) m / t (ṁ) = mass flow (kg/s) m = mass (kg)

t = time (s)

Cp = specific heat (kJ/kg C)

dT = temperature difference between inlet and outlet of the boiler (C)

SOLAR THERMAL CALCULATION: -

As shown in Table no. 3, different parameters for the calculation of solar thermal collector efficiency and area are given.

For finding efficiency of solar thermal collector some important parameters such as altitude and latitude of the particular location (GNFC, Bharuch), declination angle, direct normal irradiation of that location.

Direct Normal Irradiation – DNI is the amount solar radiation received per unit area by a surface that is always held perpendicular or normal to the rays that come in straight line from the direction of the sun at current position in the sky. It is also defined as the rate at which solar energy falls onto a surface.

EFFICIENCY OF THE SOLAR COLLECTOR FIELD: -

Equation as shown below is used to find the efficiency of different type of concentrated solar thermal collectors.

$$\eta_{CL,D} = \eta_{o,CL} - U_{l1} \cdot \left(\frac{T_{m,CL} - T_0}{I_D} \right) - U_{l2} \cdot \left(\frac{(T_{m,CL} - T_0)^2}{I_D} \right)$$

ηCL = efficiency of the solar collector field

Ul1-Ul2= Heat loss co-efficient based on aperture area of solar field (W/m2-K) ηo = Optical efficiency of the solar field

ID = Aperture effective design DNI (W/m2) Tm,CL = mean temperature of collector field To = ambient temperature

AREA OF SOLAR COLLECTOR FIELD: -

Then calculate the area of concentrated solar thermal collectors and choose the appropriate collector.

$$A_{p,CL} = \frac{Q_{CL,D}}{\eta_{CL,D} \cdot I_D}$$

AP,CL = aperture area of the solar collector field ηCL = efficiency of the solar collector field
ID = Aperture effective design DNI (W/m2) QCL,D = solar collector heat gain

Then we are calculating useful energy gain by the solar thermal collector

$$Q_{CL,D} = \eta_{o,CL} \cdot I_D \cdot A_{p,CL} - U_{l1} \cdot (T_{m,CL} - T_0) \cdot A_{p,CL} - U_{l2} \cdot (T_{m,CL} - T_0)^2 \cdot A_{p,CL}$$

QCLD = efficiency of the solar collector field

Ul1-Ul2= Heat loss co-efficient based on aperture area of solar field (W/m2-K) ηoCL = Optical efficiency of the solar field

ID = Aperture effective design DNI (W/m2) Tm,CL = mean temperature of collector field To = ambient temperature

3.3 Economic Analysis of Proposed System

FOR 1^{ST} CASE

The necessity for economic analysis of solar system is obvious when assessing their feasibility vis-a-vis conventional alternative systems. For economic analysis of the system, taking into account the fuel costs, operation costs and the maintenance costs for both the solar system and its conventional alternative.

The saving produced by installation is obtained by taking the difference between the total expenditures of the conventional and solar system, accumulated during their foreseen lifetimes.

The economic model for proposed hybrid solar thermal system included Cost of hybrid solar thermal system, CRF(capital recovery factor), Operation and maintenance cost of hybrid system and current system, LCOE(levelized cost of energy) and SPP(simple payback period).

The capital cost of system could be calculated by:

$$C_{sys} = C_{sl} * A_p$$

Overall cost of hybrid system per year can be calculated as below:

$AC_{sys} = (C_{sys} * CRF) + C1 + C2$ C1= Operation Cost and Maintenance Cost of Solar System

C2= Operation Cost and Maintenance Cost of boiler

Capital Recovery Factor – It is the ratio used to determine the present value of theseries of equal annual cash payments.

$CRF = d((1+d)^k) /((1+d)^k-1)$

d=Discount rate K= Life cycle years

LCOE – The levelized cost of energy (LCOE) was expressed as the total value of plant from the day of installation to the project economic life time expressed in ₹/kWh of energy produced over the project life time. The levelized cost of energyLCOE was calculated by using annual project cost for project capitalized.

$$LCOE = AC_{sys}/Q_{kWth/y}$$

SPP – Simple Payback period was the time in which the initial cash outflow of an investment was expected to be recovered from the cash inflows generated by the investment.

SPP = Total Investment/ Total Savings

This economic analysis had been done by using MATLAB.

Data for economic analysis of the first case is given below.

	180MT/HR	**103.3MT/HR**
Mass of fuel per year in RS	1344075708	770459520
Aperture area of solar thermal collector for 1 M2	17418	9996
Cost of solar thermal collector for 1 M2	25000	25000
Heat energy generated by solar thermal collector	557.9	557.9
Filtered 8 hours per day	2920	2920
Operation and maintenance cost of solar 10% of systemcost	43545000	24990000
Operation and maintenance cost of boiler	896050472	513639680
Discount rate	0.1	0.1
Life cycle years	25	25
Subsidy as per govt 30% of system cost	130635000	74970000

Table – 8 – Data for economic analysis of the first case

FOR 2ND CASE

For an Economic analysis of 2nd case we need to calculate fuel consumption ofboiler.

Equation for finding fuel consumption of boiler is given below.

$$\text{Fuel consumption of Boiler} = \frac{Qcld}{\text{Efficiency of Boiler} * \text{CV of Coal}}$$

Fuel consumption of boiler/year = Fuel consumption of boiler/hr*Filtered 8 hrs/daySavings = (Fuel consumption of boiler/year)*(Price of coal)

- Payback Period :

$$\text{Without Subsidy} = \frac{\text{System cost}}{\text{Savings}}$$

$$\text{With Subsidy} = \frac{\text{System cost} - \text{Subsidy}}{\text{Saving}}$$

Data for economic analysis of the second case is given below.

Steam Generation	93.44 MT/HR
Qcld	11356550.4
Efficiency of boiler	88%
CV of coal	17656.48
Filtered 8 hours per day	2920
price of coal/KG in rupees	6
aperture area of solar thermal collector for 1 M2	21299
cost of solar thermal collector for 1 M2	25000

Table – 9 – Data for economic analysis of the second case

CALCULATION OF CO2 EMISSION :-

Implementation of this system can reduce the use of coal and it can produce the heat without adding any carbon emission.

The amount of coal saved and is shown in table no. 10

	1ST CASE		**2ND CASE**
	ṁ = 180 MTPH	**ṁ = 103.3 MTPH**	**ṁ = 93.44 MTPH**
COAL SAVED(T/YEAR)	**67014**	**38427.2**	**2349.68**

Table – 10 – Amount of coal saved

IV.RESULTS

A. Results of Thermal Analysis

Boiler	**ṁ = 180.0 MTPH**	**ṁ = 103.3 MTPH**
Boiler efficiency by direct method	72%	
Boiler efficiency by indirect method	86%	
Q of boiler	9685483.08 W	5339117.42 W

Table – 11 – Results of boiler calculations

FOR 1ST CASE : ṁ = 180 MTPH & 103.3 MTPH

Solar thermal collector	**ṁ = 180.0 MTPH**	**ṁ = 103.3 MTPH**
Parabolic through collector		
Efficiency	66.768%	
Area	17,418 m^2	9996 m^2
Paraboloid dish collector		
Efficiency	53.280%	
Area	21,728 m^2	12526 m^2
Linear fresnel reflector		
Efficiency	61.768%	
Area	19600 m^2	10805 m^2

Table – 12 – Results of solar thermal collector for 1st case

Parabolic through collector has minimum area and maximum efficiency for this system.

FOR 2ND CASE : ṁ = 93.44 MTPH

Boiler	**Tin – 192 °C** **Tout – 400 °C**
PARABOLIC THROUGH COLLECTOR	
Efficiency	66.65%
Area	21,299 m2
Q cld	11391560.96 KW

Table – 13 – Results of solar thermal collector for 2nd case

Results of Economic Analysis –

FOR 1ST CASE

	ṁ= 180MT/HR	ṁ = 103.3MT/HR
Annual Heat energy generated by solar thermalcollector	1629068	1629068
System cost	435450000	249900000
CRF	0.1102	0.1102
Total cost	987570000	566160000
LCOE	606.2167	347.5366
Total cost after subsidy	304815000	174930000
Savings	448025236	256819840
Payback Period with subsidy	0.6804	0.6811
Payback Period without subsidy	0.9719	0.9731

Table – 14 – Result of Economic Analysis for 1st case

FOR 2ND CASE

	ṁ = 93.44 MT/HR
Fule consumption of boiler/ hr in KG	730
Fule consumption of boiler/ year in KG	2131600
Savings in RS	12789600
Solar sytem cost	532475000
Payback with subsidy	29.24
Payback without subsidy	41.63

Table – 15 – Result of Economic Analysis for 2nd case

REDUCTION IN CO2 EMISSION

	1ST CASE		2ND CASE
	$\dot{m}$ = 180 MTPH	$\dot{m}$ = 103.3 MTPH	$\dot{m}$ = 93.44 MTPH
CO EMISSION (T/YEAR)	**180,000**	**103,000**	**6297.14**

Table – 16 – Reduction of CO2 Emission (13)

V. CONCLUSION

From this study, it is conclude that parabolic trough solar thermal collector system is capable of producing high temperature steam efficiently. Proposed Hybrid System can replace a portion of coal demand by substituting its energy contribution via input from a solar field. During day time operation, solar energy can be used to reduce coal consumption. As solar radiation decreases during latter part of the day, the coal contribution can be increased, allowing the plant's boiler always operate at full load. When solar radiation increases again, the process is reversed, with solar input gradually reducing that of coal. Alternatively, input from solar field can be used to produced additional steam that can be fed through the turbine, increases electricity output. This form of hybrid technology can be applied to any form of conventional thermal power plant. In this approach, calculations shows that the area of solar field is 17,418 m2 for generating the steam of 180 MTPH and increases its temperature by 49 °C. It can save 67014 T/YEAR of coal and also reduce the emission of carbon dioxide up to 180,000 T/YEAR. Same as for generating 103.3 MTPH of steam the area required is 9996 m2. It can save 38427.2 T/YEAR of coal and also reduce the emission of carbon dioxide up to 103,000 T/YEAR.

Second system shows the Organic rankine cycle coupled with parabolic trough collector field which increases the temperature of steam up to 208 °C and steam comes out from STS at 400 °C. Area required for this system is 21,299 m2 for steam generation of 93.44 MTPH. It can save 2349.68 T/YEAR of coal and reduce the emission of carbon dioxide up to 6297.14 T/YEAR.

As shown in the results, the payback period of the 1st system is low than the 2nd system which is 0.9739 year. So according to this result, it is conclude that solar – coal based hybrid system is more economical than the 2nd system.

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