An Economic Examination of Solar Energy with Storage based Supply Options: Solar PV-Battery and CSP with Thermal-Storage

Arun Kumar V, Ashu Verma, Lavleen Singal

Abstract*: *Renewable energy is being promoted amidst rising environmental concerns associated with fossil-fuel usage for power generation. The stock of such fuels is also limited and is fast depleting. Renewable energy sources such as solar photovoltaic (PV) systems present a clean alternative that has become cost-competitive with conventional thermal power generation systems. However, to counter the intermittent nature of solar power and ensure firm power supply, energy storage is essential. This paper presents a comparative analysis of power supply options based on two solar energy technologies - PV and concentrated solar power (CSP). Energy storage in the form of battery and thermal energy respectively has been included and different combinations of supply options, along with utility grid, have been analyzed in terms of the levelized cost of electricity (LCOE). The LCOE values for supplying a particular substation load in India have been compared and it was found that CSP with thermal energy storage emerged to be the economically viable option for supplying the load.

Keywords* : *Energy Storage; Hybridized system; LCOE;Solar Energy; Thermal Storage; Utility Grid.

I. INTRODUCTION

The share of power from renewable energy sources is becoming increasingly significant in today's power system. Renewable energy accounted for 8.6% of global installed capacity in 2010 increasing to 18.2% in 2017 . Solar energy, especially in the form of Photovoltaic (PV), and wind energy are two foremost sources of electricity that are being increasingly integrated at the bulk power transmission level. Solar PV accounted for 5.89% of total installed generation capacity in the world in 2017 while wind energy had a share of 8.04% [1]. India has set an ambitious target of installing 175 GW [2] [3] of renewable energy based capacity in its power 10 system by 2022. Of this number, 100 GW and 60 GW have been kept for solar and wind energy respectively.

Power from solar PV has become commercially viable and cost-competitive with conventional fossil fuel based thermal power. This has been attributed to the steep fall in PV module prices globally, over the years, and which continues to reduce. According to a new cost analysis from the International Renewable Energy Agency (IRENA), Solar PV electricity costs have fallen 73% since 2010.

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Nomenclature

APPC	Average Power Purchase Cost	MNRE	Ministry of New And Renewable Energy
BESS	Battery energy storage system	NPV	Net Present Value
BOS	Balance of system	NREL	National Renewable Energy Laboratory
CAPEX	Capital cost	ORC	Organic Rankine cycle
CERC	Central Electricity Regulatory Commission	PCU	Power conditioning unit
CSP	Concentrated solar power DNI Direct normal irradiance (W/m2)	PPA	Power Purchase Agreement
DoD	Depth of discharge	PTC	Parabolic trough collector
EPC	Engineering, Procurement and Construction	PV	Photovoltaic
GHI	Global Horizontal Irradiance	SAM	System Advisory Model
HTF	Heat Transfer Fluid	SM	Solar Multiple
IRENA	International Renewable En-ergy Agency	TES	Thermal energy storage
LCOE	Levelized cost of energy ($/kWh)	TLCC	Total life cycle cost
		TMY	Typical meteorological year

Furthermore, solar PV costs are expected to reduce by 50% by 2020. According to estimates, the best solar PV projects could be delivering power at a tariff equivalent of 3 cents/ kWh or less within the next two years, compared to that from fossil fuel power ranging from 5 to 17 cents/kWh [4]. In India too, solar PV based electricity has achieved grid-parity and a large amount of bulk solar power has been integrated with the power grid from utility-scale power plants in the form of solar parks and solar farms. Solar energy can also be harnessed using Concentrated Solar Power (CSP) technologies [5] & [6]. For power generation, Parabolic through, Fresnel through and solar tower are the three forms of technology available for commercial use. Although the technology is well proven, the capital costs and operational costs are comparatively higher [7] than those for PV. However, when coupled with thermal energy storage, the financial viability becomes higher [8].

Even though solar PV and CSP provide clean power, their output power is inherently variable in nature. To address this issue, energy storage can play a vital role in power smoothening and in time-shifting the energy provided by solar power based technologies. Battery Energy Storage Systems (BESS) [9, 10, 11] can provide firm power, when coupled with bulk solar PV generators, and mitigate the fluctuations caused by them in the network [12]. Much has been documented about the need for storage in power transmission networks especially with increasing penetration of renewable energy based power sources [13], catering to both base- load and peak power demand. Similarly, Thermal Energy Storage (TES) [14, 15, 16] is essential to ensure continuity of supply during low insolation periods and during night time operation. It is also required to maintain the cycle efficiency of the CSP plant.

While much progress has been made at the solar power front, both in Photovoltaic (PV) [17] and Concentrated Solar Power (CSP) [18, 19, 20, 21] technologies, energy storage has not matured relatively. US DOE 'Global Energy Storage Database' is one of the most exhaustive energy storage databases available. Of the 1,600 storage projects installed globally with 200 GW cumulative capacity, about 630 projects with 2,300 MW capacity are battery storage based while 40 projects are of thermal storage, worth 2750 MW capacity, as shown in Table 1. According to this database, 463 battery storage projects may be operational, 288 of which have been confirmed by Sandia National Labs. The majority of the battery storage projects application is frequency regulation. The rated power ranges between 80 300 kW. Larger power rating battery storage projects of 500 1000 kW are for demand side management and 1 2 MW rated power projects are used for energy time shift. The storage duration for these projects is less than 2 hours. There are smaller projects also for supply reserve, microgrid capability, tertiary balancing and a host of other usages. The 41 thermal storage projects have the capability to meet all grid service requirements of transmission and distribution with a total installed capacity of 2750 MW, and with duration of storage ranging from 6 hours to 15 hours.

Table 1. Operational CSP projects worldwide

S.No.	Operational Project	Country	Capacity (MW)	Storage (hrs.)
1	Noor I	Morocco	160	3
2	KaXu	South Africa	100	2.5
3	Xina	South Africa	100	5.5
4	Bokspoot	South Africa	50	9.3
5	Khi	South Africa	50	2
6	Machsol I	Spain	50	7.5
7	Machasol II	Spain	50	7.5
8	Arcosol (Valle I)	Spain	50	7.5
9	Termosol (Valle II)	Spain	50	7.5
10	Andasol I	Spain	50	7.5
11	Andasol II	Spain	50	7.5
12	Andasol III	Spain	50	7.5
13	Extresol I	Spain	50	7.5
14	Extresol II	Spain	50	7.5
15	Extresol III	Spain	50	7.5
16	Axtesol	Spain	50	7.5
17	La Africana	Spain	50	7.5
18	Casablanca	Spain	50	7.5
19	La Florida	Spain	50	7.5
20	La Dehesa	Spain	50	7.5
21	Arenales	Spain	50	7
22	Aste 1A	Spain	50	8
23	Aste 1 B	Spain	50	8
24	Astexol II	Spain	50	8

25	Termosol I	Spain	50	9
26	Termosol II	Spain	50	9
27	Gemasolar	Spain	19.9	15
28	Crescent Dunes	USA	125	10
29	Solana	USA	280	6
30	Nevada Solar One	USA	72	0.50

On the other hand, CSP thermal storage costs of USD 30 per kWth to build large capacities are possible: the largest operational (demonstration) plants being 15 hours for a 17 MW (255 MWh) plant in operation since 2011. Operational thermal storage plants in Spain alone sum up to 9 GWh of storage. Also, 100 MW plus plants with 15 hours of storage (1.5 GWh) are the new norm. For example, the cost of thermal storage for a 100 MW parabolic trough plant with 6 hours storage would be in the range of 60 million USD [22]. Compared with battery storage, this cost in per kWh is about - of battery storage, not considering lifetime and other costs. However, when the lifetime and re-investment costs are accounted for, the scenario changes completely. For a suitable and proper comparison, the LCOE for each technology should be computed, rather than presenting upfront storage costs in kW or kWh basis.

Lithium-ion batteries and two-tank molten salt thermal storage are the most prominent and commercially viable forms of BESS and TES in use, respectively. This paper has therefore considered both in the analysis. Different supply options (based on solar PV and CSP) to cater to a given load, along with energy storage have been analyzed for economic viability. An attempt has been made to bench- mark the cost of power from CSP-TES and compare the relative cost with that from PV-BESS, for the Indian scenario. The study estimates the Levelized Cost of Energy (LCOE) for four types of power supply options: solar PV with battery storage, CSP with thermal storage, grid connected PV with battery storage and finally the hybrid option of using PV with CSP and thermal storage in tandem. The remaining sections of this paper are organized as follows: Section 2 describes the system model and assumptions considered. Detailed modeling of system operation and economic analysis is presented in Section 3. Results and discussions for different options are reported in Section 4. Finally, Section 5 concludes the paper.

II. SYSTEM DETAILS

This section describes the mathematical modelling associated with each solar energy and energy storage technology combination. Accordingly, system modeling details for CSP-TES, PV and BESS are given in subsections that follow.

1.1. Solar Systems Modelling

The Solar PV and CSP plants with respective storage technologies have been modelled in PVsyst, Ebsilon, and SAM for different types. The schematic of a CSP (Parabolic Trough) plant with thermal storage technologies is shown in Fig.1.

The schematic of a solar tower based CSP plant with thermal storage is shown in Fig.2. However, the tower technology is not much suitable for India because of the environmental conditions (especially dust) and Direct Normal Irradiance (DNI). The Solar PV with Battery system is shown in Fig. 3.

1.2. Mathematical modelling of CSP, PV, Thermal Storage and BESS

The heat and mass balance of CSP with TES is given in equation 1. The heat input (Q_e) into the fluid flow is given by

$$m_1(h_2 - h_1) = Q_e \qquad (1)$$

where, m_1 is mass flow rate, h_1 is enthalpy at input & h_2 is enthalpy at output.

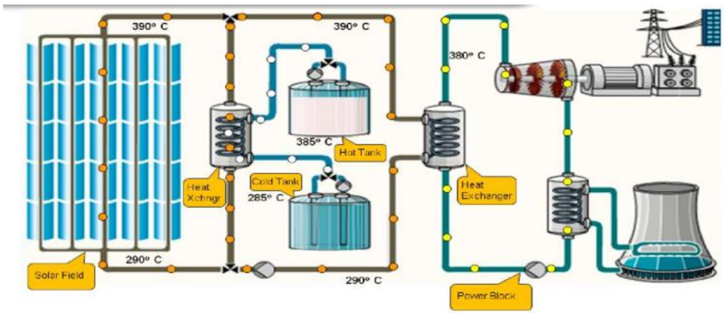

Figure 1: CSP (Parabolic) with Storage

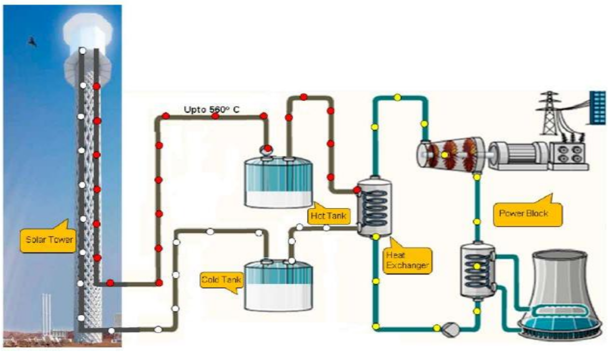

Figure 2: CSP (Tower) with Thermal Storage

The available heat input Q_A depends on the solar heat input Q_s and the thermal losses of the receivers Q_L and on the field piping Q_p. This is expressed in equation 2.

$$Q_A = Q_S - Q_L - Q_p \qquad (2)$$

The effective heat generated in the solar field is therefore reduced by the fraction R_F (actual focus state of collector) which is lost due to defocussed collectors as shown in equation 3.

$$Q_e = (Q_S R_F) - Q_L - Q_P \quad (3)$$

The solar input is determined by the equation 4.

$$Q_S = DNI * A_n * \eta_{m.o} * \theta_i * (\varpi * \Delta * \gamma) * \varepsilon * A_F \quad (4)$$

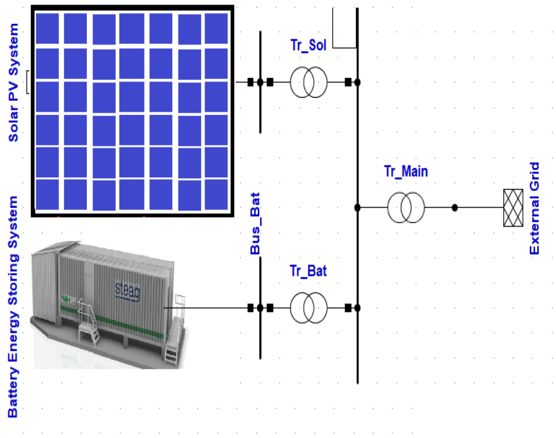

Figure 3: Solar PV with Battery Storage

Where, DNI is Direct normal irradiance, A_n is net aperture area, $\eta_{m.o}$ is Peak optical efficiency, θ_i is Incident angle correction (cosine losses already included), ϖ is a factor to include shading losses, Δ is a factor to correct end loss effects determined from the model, γ is a factor to include optical losses due to wind impact, ε is factor to correct for actual mirror cleanliness = cleanliness index ć and A_F is field availability. The heat loss of the collector is given in equation 5 which is dependent on length specific loss (q_L).

$$Q_L = q_L * L * N \quad (5)$$

Where, L and N are the length and number of collectors respectively. The optical efficiency η_o is defined as the ratio of irradiation after optical losses to the available solar irradiation as shown in equation 6.

$$\eta_o = R_F * \frac{Q_S}{DNI * A_n} \quad (6)$$

The thermal efficiency η_t and overall efficiency η_f are given in equation 7& 8 respectively.

$$\eta_t = Q_e / R_F * Q_S \quad (7)$$

$$\eta_f = Q_e / (DNI * L * W * N) = \eta_o * \eta_t \quad (8)$$

In the case of a storage tank, the mass balance and energy balance are given in equation 9 & 10 respectively. The mass flow of the integration of storage (both incoming and outgoing mass flow) is constant. The new mass in the storage is calculated using equation 9.

$$m_n = m_a + (m_{ld} * t) - (m_{uld} * t) \quad (9)$$

where, m_a is initial mass in storage, m_{ld} loading mass flow rate, m_{uld} is un-loading flow rate and t is mass flow duration. The energy flow is shown in the equations 10,11and 12. The energy flow equation has three parts, first part is the storage is loaded in hot tank, secondly heat loss to the atmosphere and finally the unload or discharge process.

$$H_a = (m_a * H_a + (m_{ld} * H_{ld} * t)) / (m_a + m_{ld} * t) \quad (10)$$

The heat loss is calculated as shown in equation 11.

$$Q_L = Q_{LR} * (0.5 * (T_s + T_n) - T_a m) * t \quad (11)$$

$$H_n = H_a * m_n - Q_L \quad (12)$$

The Solar PV system output P_{pv} is calculated based on the equation 13.

$$P_{pv} = R_{pv} * D_{pv} * \frac{G_T}{G_{T,STC}} (1 + \alpha_T (T_C - T_{C,STC}))$$

Here, R_{pv} is the rated capacity of solar PV, D_{pv} is the de-rating factor, G_T & $G_{T,STC}$ are the incident radiation during evaluation and at standard test condition respectively, α_T is temperature coefficient, T_c & $T_{c,stc}$ are the solar cell temperatures during evaluation and standard test condition respectively.

The BESS capacity P_{bess} is estimated based on the equation 14.

$$P_{BESS} = \frac{P_L * t_s}{\eta_{bess} * DOD} \quad (14)$$

Where P_L is the design load, t_s is the storage duration, η_{bess} is the overall efficiency of BESS system which is shown in equation 15 and *DOD* is depth of discharge of battery system.

$$\eta_{bess} = \eta_b * \eta_{in} * \eta_{t,c} \quad (15)$$

In this equation, η_b is efficiency of battery, η_{in} is the efficiency of inverter and $\eta_{t,c}$ is the efficiency of transformers, cables etc.

III. MODELING OF SYSTEM OPERATION

The study has tried to compare the economics of battery storage with thermal energy storage (both in coupling with solar PV and CSP respectively, and in hybrid mode also) for a sub-station in India whose 15% of the load is served from solar. One of the highlighting points of comparison between BESS and TES is the life of the storage technology relative to the life of the respective solar energy technology project. BESS of Li-ion based chemistry lasts for an average of 8 years of life-cycle (depending upon the number of cycles and the daily cycling operation) compared to 25 years of project life for a solar PV plant. In contrast, a TES lasts for 30 years, same as that for a CSP plant.

Accordingly, both cannot be compared on the basis of direct upfront costs of storage and hence a levelized cost approach has been presented in the paper. For BESS, important parameters like Depth of Discharge (DoD), number of charge-discharge cycles and battery efficiency at different DoD values have been appropriately assumed based on field experiences and manufacturers' recommendations. Accordingly, a battery bank with 20% DoD, 90% efficiency and 5,000 charge-discharge cycles with an average of 8 years life has been assumed. For TES, since many such plants are in operation for more than a decade, sufficient practical data is available and hence has been used in the study.

It has been assumed that the substation feeds an average of 9 million units per day (100 units per home for 90,000 homes) to its consumers through the grid. 15% of the energy has been assumed to be sourced from solar and the balance comes from the conventional coal based thermal power plant (referred to as utility grid here). Based on the technology considered, the thermal power plant has been assumed to operate between 60% and 100% of its capacity, scaling down generation gradually during night hours and scaling up at dawn. The general consumption pattern of the substation considered varies between 60% on the average generation at night with morning peaks at 130% and evening peak at 150%. Morning peak of roughly three hours and evening peak of four hours are met from solar with storage, obviating the need for buying costly power from the exchange. The model hardly meets typically fluctuating real-time demand but is a very simple generalization of the concept of using solar energy with storage. It was clearly foreseen that battery would provide for the intermittency of solar PV from infirm incident radiation while thermal storage, which requires the turbine operation to generate electricity, would provide for peak demand. This way the inherent advantages of both technologies could one day, not so far into the future, provide carbon-free energy, meeting the demand cost-effectively and without a burden on the Earth's depleting fuel resources. The model computes the incremental LCOE of solar plants in combinations with battery and thermal storage as described above. In one of the cases where the battery is being charged from the grid, the cost of electricity used for charging the battery has been accounted for in the calculations.

The load pattern was assumed based on the load profile typically observed in feeders in an Indian sub-station. The energy demand is low from 11 PM to 7 AM, peaking in the morning between 9 AM and 12 noon and again in the evening from 5 PM to 10 PM. Considering that energy from the coal plants have a time and cost limitation on reducing the supplies, a reduction up to 40% from peak generation is assumed appropriately. To meet the energy demand, the balance energy is supplied from the solar systems with storage, but not exceeding 15% of the total demand.

For comparison purposes we have assumed four different solar systems with storage, namely:

1. Standalone PV plant with battery bank, where the battery is not charged from the grid conventional energy but from the PV plant.
2. Solar PV plant with battery bank where the batteries are charged from the grid.
3. Standalone CSP with thermal energy storage.
4. Solar PV and CSP with thermal energy storage hybrid

The different supply options thus have been modeled in terms of various combinations of solar with storage, PV-Battery and CSP-Thermal storage.

3.1. Solar PV with battery bank, batteries charged from PV plants:

Based on the solar radiation data for a typical site (representative of the location considered), NRELs System Advisory Model (SAM) was used to compute the energy generated from the PV system. The size of the battery bank is based on the comparison with thermal storage. The total energy demand along with equals the energy available from conventional sources and the total sum of energy available from both conventional and solar plants. The excess energy is transferred to the battery bank for storage while the deficit is made up from the battery bank. This analysis determined the capacity of the PV plant to be 305 MWp and the battery bank to be 1,350 MWh to meet the hypothetical demand. The energy required from the conventional plant is 7,672,300 units per day.

3.2. PV with battery bank, batteries charged from conventional energy from the grid:

Instead of over-sizing the PV system to supply energy to the batteries, charging in this case is done from the grid (conventional). Computations show that the PV system would be required to have a capacity of 100 MWp with a battery bank of 400 MWh and energy required from the grid to charge the battery bank would be 16,150 units from a total of 8,588,450 units from the utility grid.

3.3. CSP with thermal energy storage; no energy required from the grid:

In this case the simulation was carried out in ebsilon [23] and SAM. The simulation in ebsilon was carried out based on considering two 50MW plants. The modelling of a design case with storage is shown in figure 4. During night-time operation, the storage supplies thermal energy to the power block. The simulation result with storage is shown in figure 5. In case of storage unavailability, the simulation at an instance is shown in figure 6. A time series based ebsilon simulation is carried out for finding annual generation with Bhadla site. Based on the solar radiation data for the site (DNI in this case), SAM was used to compute the energy generated from the parabolic trough system with thermal energy storage. Excess generation from the CSP and conventional system is stored in the thermal energy storage system while the deficit is withdrawn based on requirement. The analysis determines the parabolic trough plant to have a turbine capacity of 100 MW with the storage system capacity of 2,500 MWh to provide 9 hours of thermal storage. According to the simulations in SAM, 450 Loops with associated components are required to drive the turbine with the required thermal energy storage system.

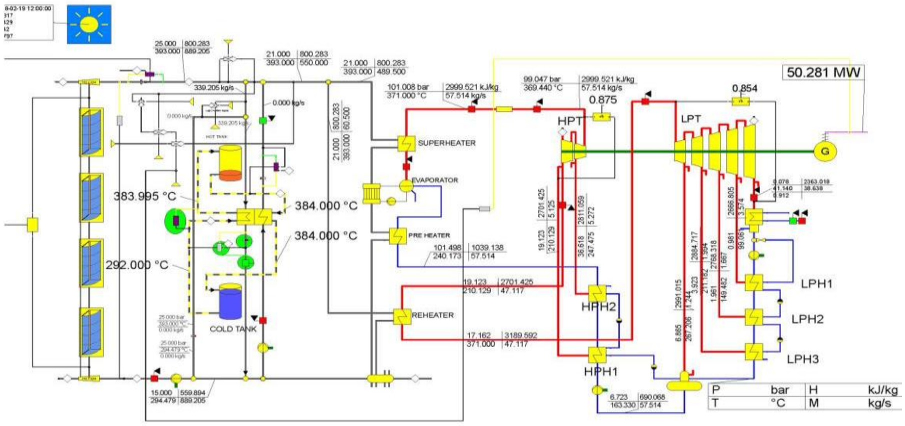

Figure 4: Design simulation-CSP (Parabolic) with Storage

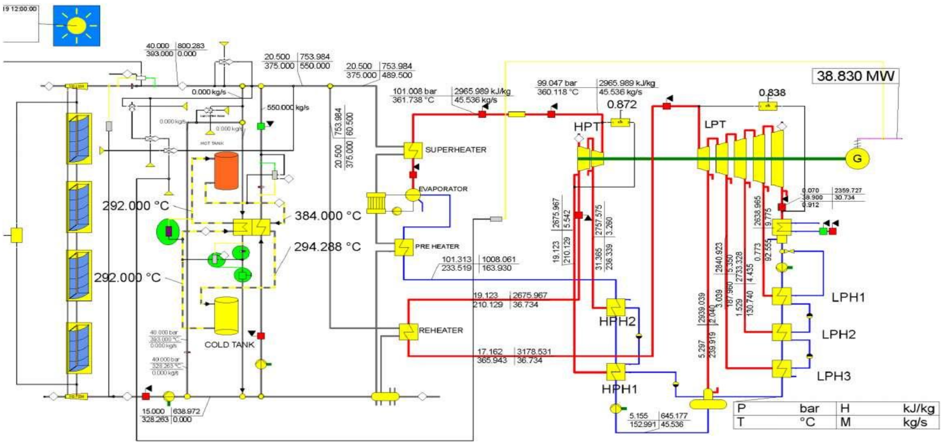

Figure 5: Night time simulation - CSP (Parabolic) with Storage

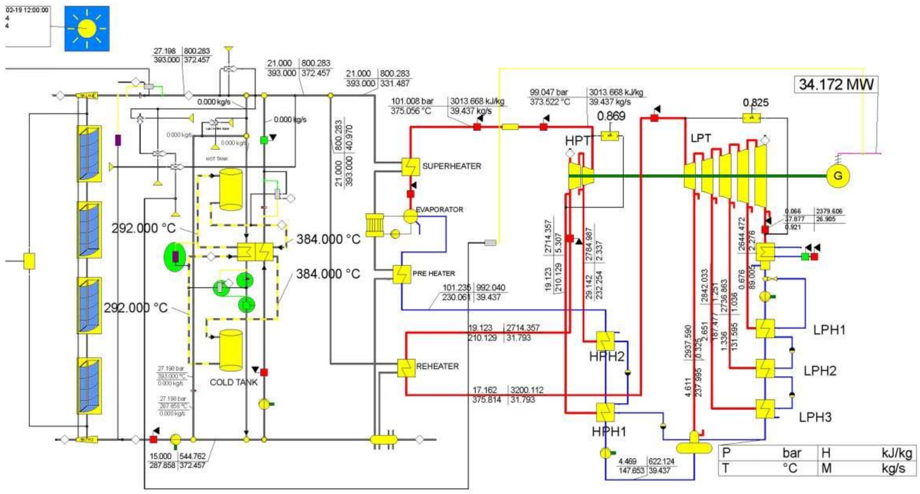

Figure 6: Simulation of CSP (Parabolic) without Storage

3.4. PV and CSP with thermal energy storage Hybrid:

The final option considered is a hybridized system that meets the energy demand. Based on load analysis and sizing, it was found that the hybrid system should have a PV capacity of 100 MWp and parabolic trough plants with 311 loops are required to drive a 100 MW turbine.

3.5. Capital Cost

The costs of PV and parabolic trough plants are based on actual EPC cost of operating plants in India, although a further reduction may be anticipated due to larger size of the respective plants. There are no plants in India with thermal storage but internationally, there are many plants. Hence, the cost is being taken appropriately in consultation with manufacturers and sector experts. The cost is presented in Table 2.

3.6. Financial modelling:

A custom financial analysis has been carried out based on CERC [24] tariff calculation methodology. The yield was obtained from SAM simulations and the 235 cost data from Tables 2. Debt percentage, rate and tenure; return on equity expectations as prevailing in India for the large size of the project have been summarized in Table 3. The economic analysis has many components. The net present value and LCOE are the important ones among them.

3.7. Net Present Value

Net present value (NPV) of any capital investment can be defined as the cumulative sum of present value of all cash flows amalgamated with it during its useful life. The NPV can be calculated using the equation 16.

$$NPV = \sum_{n=0}^{N} \frac{F_n}{(1+d)^n} = F_0 + \frac{F_1}{(1+d)^1} + \frac{F_2}{(1+d)^2} + \cdots + \frac{F_n}{(1+d)^n} \quad (16)$$

Table 2: Capital Cost

S.No.	Plant Type	Sub details	USD / MWp
1	PV Plant Cost Estimates	Modules	2,85,82,857
		PCU	1,00,00,000
		BOS	1,14,30,000
		TOTAL	5,00,12,857
		Loops	17,52,84,512.70
		HTF	6,44,82,790.10
		P/Block	4,86,41,452.27
2	Parabolic Trough Estimated cost	BOS	1,07,11,831.33
		TES	7,30,35,213.62
		TOTAL	37,21,55,800

Where, NPV is net present value, Fn is net cash flow in a year, N is analysis period & d is annual discount rate.

3.8. Levelized Cost of Energy

LCOE [17] can be defined as the present value of the unit cost of electricity over the useful life of the generating resources.

Table 3: Financial Data

S.No	Financial data	Sub details	Values
1	Financial assumptions	Debt	70%
		Tenure	12 years
		Pre-tax Return on Equity for 10 years	12%
		Pre-tax Return on Equity for 11 -25 year period	12%
		Debt rate of Interest	9%
2	Cost of Production	O & M	\$ 20,000 + 5.72% annual escalation
		Interest on Working	12%
		Capital Depreciation	90% capex, over 10 years at 7% Differential Depreciation Approach and Straight Line for balance
3	Calculation for Interest on Working Capital	O & M (1 month)	1 month
		Spares	15%
		Account Receivables (months)	2 months
		Rate of Interest	12%

$$LCOE = \frac{TLCC}{\sum_{n=1}^{N} \frac{Q_n}{(1+d)^n}} \quad (17)$$

Where, TLCC is total life-cycle cost, Qnis energy output in year n, d is discount rate & N is the analysis period

These are adjusted from operating PV and parabolic trough plants including CERC recommended project costs.

IV. RESULTS

4.1. System costs

Table 2 summarizes the total cost of each system based the system parameters, capacities and prevailing component unit-costs. Table 3 summarizes major component unit costs as a basis for the computations.

Levelized Cost of Electricity. The CERC recommended methodology has been used to compute the Levelized Cost of Electricity. The main financial assumptions are summarized in Table 3. CERC has also published the national Average Power Purchase Cost (APPC) at 0.04$ per kWh. To compute the impact of additional usage of energy in the case when the PV battery bank is charged with energy from the grid, the national average APPC with 2% and 5% annual escalation for the 25 year period were assumed. The LCOE is summarized in Table 4.

4.2. Justification of storage considered

With 9 hours thermal storage, it is possible to achieve an average turbine efficiency of 40% with multi-stage / sliding pressure turbines. The Irradiation at Design used was 750 watts/metre based on the Cumulative Distribution Function of beam radiation. Hours of thermal storage were optimized based on plant cost with different Solar Multiples (SM) to obtain the lowest LCOE for 3, 6, 9 & 12 hours. After determining the hours of storage, the size of the solar field size was optimized again for different solar field areas with the lowest LCOE. Simulation results revealed 9 hours of storage and 450 loops as the optimal plant configuration. In actual operation however, both the size of thermal storage (thermal capacity) and the size of the solar field optimization depend on energy requirements available from the grid operators. For example, considering storage capacity of 2,500 MWth leads to dumping of thermal energy, particularly in the months of higher incident solar radiation (March June). On the other hand, increasing the size of thermal storage (3,330; 4,162 & 4,995 MWth) reduces the thermal energy dumped and increases the electric generation but with a corresponding increase in LCOE (0.084, 0.088 & 0.092 $ / kWh). In the present case the solution presented is optimal based on no standby and best turbine efficiency. Logically, when the power demand is higher in these months (March June), the grid operators may be willing to pay a higher price. As storage costs decrease, increasing the size of storage may provide a more optimized solution. The actual size of storage and solar field depend on nature of PPA and other local contracting factors. The scope of this paper is to demonstrate the benefits of hybridizing PV with thermal storage and not to design the project to specific needs. However, this flexibility in project design is an important point which needs to be emphasized. It would be appropriate to point out again that the efficiency of the turbine depends on the turbine operating conditions. Different operating conditions depending on the power demand may require the turbine to operate at part load or be on standby; both would reduce the overall efficiency of the turbine. On the other hand, if no electricity is required from the trough plant during the day and the thermal energy is stored for use in generating electricity during peak and night time, the size of the solar field would reduce. Both would alter the LCOE, although slightly.

V. CONCLUSION

This paper has presented a comparative economic analysis of supplying power to a particular load using four different options based on solar PV, CSP and respective energy storage technology types along with the utility grid. The economic viability of supplying a substation load in India using solar CSP coupled with thermal storage has been established and compared with other options. The other options considered are solar PV-BESS alongside utility grid, solar PV-BESS without charging from the utility grid and a hybrid system based on solar PV-CSP with thermal storage. Since thermal energy storage has a lifespan equal to that of a CSP project, it can provide more economic value than a battery despite its higher upfront capital cost in comparison to a BESS. Accordingly, a levelized cost-based approach has been followed for comparison. Hence, the levelized cost of electricity produced from all four supply options, for serving a given load, has been found and compared to determine the most economically viable option. Detailed modeling of each type of power plant using actual site meteorological data and engineering details has been done in relevant simulation platforms to estimate the power generation and performance of each plant. The study also presents some preliminary attempts to estimate and provide a benchmark cost of electricity from solar CSP-thermal storage based projects that can still be a promising option of clean and renewable energy based power supply in India.

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REFERENCES

1. IRENA . Renewable capacity statistics 2018. Tech. Rep.; International Renewable Energy Agency; Abu Dhabi; 2018.
2. MNRE . A target of installing 175 gw of renewable energy capacity by the 325 year 2022. 2018. URL: pib.nic.in/newsite/PrintRelease.aspx?relid= 180728.
3. MNRE . Tentative state-wise break-up of renewable power target to be achieved by the year 2022. 2018.
4. IRENA . Renewable power generation costs in 2017. Tech. Rep.; International Renewable Energy Agency; Abu Dhabi; 2018.
5. Kaseem A, Al-Haddad K, Komljenovic D, Schi_auerova A. A value tree for identi_cation of evaluation criteria for solar thermal power technologies in developing countries. Sustainable Energy Technologies and Assessments 2016;16:18-32.
6. Bijarniya JP, Sudhakar K, Baredar P. Concentrated solar power technology in india: A review. Renewable and Sustainable Energy Reviews 2016;63:593-603.
7. Kaushik S, Abhyankar Y, Bose S, Mohan S. Exergoeconomic evaluation of a solar thermal power plant. International journal of solar energy 2001;21(4):293-314.
8. Sharma AK, Sharma C, Mullick SC, Kandpal TC. Financial viability of solar industrial process heating and cost of carbon mitigation: A case of dairy industry in india. Sustainable Energy Technologies and Assessments 2018;27:1-8.
9. Ibrahim H, Ilinca A, Perron J. Energy storage systemscharacteristics and comparisons. Renewable and sustainable energy reviews 2008;12(5):1221-50.
10. Coppez G, Chowdhury S, Chowdhury S. Review of battery storage optimisation in distributed generation. In: Power Electronics, Drives and Energy Systems (PEDES) & 2010 Power India, 2010 Joint International Conference on. IEEE; 2010, p. 1-6.
11. Hill CA, Such MC, Chen D, Gonzalez J, Grady WM. Battery energy storage for enabling integration of distributed solar power generation. IEEE Trans- actions on smart grid 2012;3(2):850-7.
12. Dugan RC, Taylor JA, Montenegro D. Energy storage modeling for distribution planning. IEEE Transactions on Industry Applications 2017;53(2):954-62.

13. Akinyele D, Rayudu R. Review of energy storage technologies for sustainable power networks. Sustainable Energy Technologies and Assessments 2014;8:74- 91.
14. Garg H, Mullick S, Bhargava VK. Solar thermal energy storage. Springer Science & Business Media; 2012.
15. Gil A, Medrano M, Martorell I, L_azaro A, Dolado P, Zalba B, et al. State of the art on high temperature thermal energy storage for power generation. Part 1concepts, materials and modellization. Renewable and Sustainable Energy Reviews 2010;14(1):31-55.
16. Kuravi S, Trahan J, Goswami DY, Rahman MM, Stefanakos EK. Thermal energy storage technologies and systems for concentrating solar power plants. Progress in Energy and Combustion Science 2013;39(4):285-319.
17. Sherwani A, Usmani J, et al. Life cycle assessment of solar pv based electricity generation systems: A review. Renewable and Sustainable Energy Reviews 2010;14(1):540-4.
18. Pb Agus Ristono*,"Design Of Reliable And Efficient Manchester Carry Chain Adder Based 8-Bit Alu For High Speed Applications",Journal Of VLSI Circuits And Systems, 1 (01), 1-4,2019
19. NHK K. ISMAIL*,"Estimation Of Reliability Of D Flip-Flops Using Mc Analysis",
20. Journal of VLSI Circuits And Systems 1 (01), 10-12,2019
21. Pitz-paal R. Parabolic trough, linear fresnel, powertower a technology comparison. 2011. URL: https://www.iass-potsdam.de/sites/default/files/files/12.5-iass_pitz-paal.pdf.
22. G. Ganesh, G Vijay Kumar, A.R.Vijay Babu, G. Srinivasa Rao, Y.R.Tagore, Performance Analysis and MPPT Control of a Standalone Hybrid Power Generation System, Journal of Electrical Engineering, ISSN: 1582-4594, Volume 15, Edition: 1, pp. 334-343, 2015.
23. Mehos MS. Concentrating solar power (csp) overview. 2017.
24. Ebsilon professional. 2017. URL: www.steag-systemtechnologies.com/ebsilonprofessional0.html.
25. Pujari P, Singhal AK, Bakshi AS, Iyer MK. CERC RE Tari_ Order 2018-19; 2018.