TECHNO-ECONOMIC FEASIBILITY STUDY OF USING SOLAR ENERGY FOR OPERATING SEWAGE TREATMENT PLANTS

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ABSTRACT

Sewage treatment plants are the major consumers of energy throughout the world and most of the studies consider completely self-sufficient treatment plants or off-grid solar PV. This study presents the findings of the techno-economic feasibility study of using on-grid fixed tilt polycrystalline solar photovoltaic (PV) modules to generate power for operating small capacity sewage treatment plants (STP) ranging from 1 to 10 MLD. Recent ongoing 4 STP projects in Rajasthan, India is considered for the study. With fixed-tilt solar PV system, the maximum PV array capacity need to be installed is found to be 99kWp, 131kWp, 172kWp and 403kWp for 1.5, 2, 3, 8 MLD STP's respectively. Life Cycle Cost Analysis of a base case scenario with 30 years of service life and 10% discount rate indicates that the Net Present Value (NPV) of the system comes around 3.7 Million INR, 5 Million INR, 6.5 Million INR and 15.3 Million INR for 1.5, 2, 3, 8 MLD respectively. The Internal rate of return (IRR) is found to be 18.5%, the normal payback period to be 5.4 years and Discounted Payback period to be 8 years for all 4 STP's. Life Cycle Assessment results of the Solar PV modules indicates that the energy payback period is coming around only 1.6 years with carbon payback period of 142 days in comparison with conventional coal-based power plants. It is found that application of Solar PV in operating STP's is highly favourable technically, economically as well as environmentally in a tropical Country like India.

Keywords:*Life Cycle Cost; Power Generation; Sewage Treatment Plant; Solar Photovoltaic.*

1. INTRODUCTION

Sewage treatment plants (STP's) are widely used to remove the harmful emissions before mixing with receiving water bodies (Enger et al., 2000). But most STP's are widely designed to cater to the desired treated effluent characteristics without much consideration given to energy (Rojas & Zhelev, 2012). Municipalities more often rank STP's as the major individual energy consumers (Wett et al., 2007). It was recorded that in a conventional STP, about 25-40% of operating costs is directly linked with energy consumption (Panepinto et al., 2016). In addition to high energy consumption, the greenhouse gas emissions in STP is of great concern (Ashrafi et al., 2014). Therefore, there is an immediate need either to bring down the energy consumption from STP's or otherwise reduce the energy dependency on conventional sources of energy.

2. LITERATURE REVIEW

Energy efficient STP's is a common topic of interest among scientific community (Awe et al., 2016; Matos et al., 2014; Estrada et al., 2015). Many researches have been done in the past to record the energy consumption of STP's and different options for producing energy from the renewable sources have been tried out. In the beginning, recovery of biogas from sludge to partly meet out the energy demand in wastewater infrastructure was recommended (Tran et al., 2015). Going further, studies described such methods in detail for recovering biogas from the sludge (Van der Hoek et al., 2016). A study recorded the energy consumption during operation

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for different methods of treating waste water which includes oxidation ditch process, Activated Sludge Process (ASP), and ASP with lime stabilization (Rodriguez-Garcia et al., 2011). By latest, possibility of energy self-sufficient wastewater treatment plants along with their challenges was explored. One of the main energy resource described is the biogas from the digestor (Gu et al., 2017). However, there is a huge gap for the self-sustaining STP's in developing as well as developed countries because of the technology used, costs and environmental protection issues. Presently, Sequential Batch reactor (SBR) is one of the key technology used for sewage treatment widely used along the globe and this is one of the most energy consuming technology in comparison with other conventional treatment technologies like conventional activated sludge systems (CAS). The energy consumption for different technology treatment plants was investigated in China and found that the average energy consumption of STP's working with SBR technology is 0.336 kWh/m3 and that of CAS as 0.269 kWh/m3 (Yang et al., 2010).

SBR technology is a variant of conventional ASP preferred now mostly throughout the world and especially in India because of seemingly high advantages. SBR requires almost 40% area compared to conventional ASP because of its compactness of treatment occurring in a single tank. SBR is mostly completely automated while conventional ASP is not fully automatic. These are some of the reasons for choosing STP's operating with SBR technology as the scope of study because of its applicability in the entire world and especially in India.

A STP operating in India with SBR technology consumes total Energy consumption of 28.21 kWh/pe-per year (i.e. 28.21 kWh per capita per year) over the complete life cycle of the Plant of which 99.7% is operational phase energy (Kalbar et al., 2012). Construction phase contributes only 1% for the impacts when compared to the Overall Life Cycle impact of the STP and can be neglected (Kalbar et al., 2012). The highest environmental impact during Operation and Maintenance (O&M) is mainly because of the energy consumption required for aeration in SBR process because of the continual supply of air (Machado et al., 2007; Gaterell & Lester, 2000).

Generating biogas from STP's sludge to meet out some power was tried in many places throughout India but was not successful as planned. According to Ministry of Environment & Forests Parivesh Bhawan (2007), the report of complete Evaluation of O&M of STP's in India was carried out and it was inferred that there was no gas generation and utilization in 13 plants in spite of having anaerobic reactors/digesters. One of the main problem faced in India is that the gas generated from the treatment options are either not enough or flared or not utilized to be used as a fuel to run gas engines or generators. Even after construction of digesters, procurement of gas engines/generators, the quality of the gas produced doesn't help them to get power in most of the STP sites in India. This demands for alternative resources for power generation not affecting the eco-system at the same time.

And in a developing country like India, the resources and energy consumed are relatively high in the present built environment consequently leading to greater impacts to the ecosystem (Horvath, 2004). Therefore, globally as well as in India, there is a pressing need to accelerate the development of advanced clean energy technologies to fight back the global challenges of energy security, climate change and sustainable development. Solar PV is a key technology option to realize the shift to a decarbonized energy supply and is projected to emerge as an attractive alternate electricity source in the future.

According to International Energy Agency Photovoltaic Power System Annual Report 2016, the cumulative installed capacity worldwide is about 300 GW in which close to 75 GW was installed in 2016 alone accounting 50% above than that of 2015. And that too, in a tropical country like India where there is a longer duration of sunshine having about 300 sunny days in a year, there is greater potential to harness Solar Energy for operation (Srivastava & Srivastava, 2013). According to Ministry of Statistics and Program Implementation Government of India Report 2017, the total potential for solar power generation in the country is 748990 MW (62.48% of the total potential for renewable power generation in the country) as on 31.03.2016.

One of the study in Tough-Egypt tried to check the feasibility of Self-Sustained Waste Water Treatment plants by using solar Power by (Helal et al., 2013). However, the study is for completely self-sustained STP and Off-Grid applications where STP need not rely on electrical grid line at all. And study by Yifan et al. (2017) focusses completely self-sufficient wastewater treatment plants. But this study checks for the trade-off between the conventional grid power and solar Power to be used by the STP's operating with SBR technology and checking the feasibility of using On-grid Solar power for operating STP's considering both technical and financial figures.

The objectives of this study are as follows: a) estimating the maximum energy for which Solar PV system should be designed for STP's b) Fixed tilt PV sizing for the STP's c) perform Life Cycle Cost Analysis of the Solar PV to estimate the financial benefits out of the project

The study starts with the brief introduction of case study followed by research methodology adopted and then by the technical and financial analysis performed finally followed by the results of maximum PV array sizing, financial analysis, life cycle assessment ending with summary and scope of future work.

3. CASE STUDY

Rajasthan is India's largest state by area which comprises 10.4 % of India's total area. For the past few years, many wastewater projects have been commissioned in Rajasthan.

This study considers recent ongoing 4 STP projects with capacity 1.5 MLD, 2 MLD, 3 MLD, 8 MLD located in Rajasthan. The main intent of this selection is to check the feasibility of using solar energy for small capacity sewage treatment plants with capacity less than 10 MLD. The influent and desired treated sewage is same for all the 4 STP's. The influent raw sewage characteristics are given in Table 1. The treated sewage characteristics are given in Table 2. The abbreviations are expanded and given in Appendix 1.

Table 1: Influent Raw Sewage Characteristics

S.No.	Parameter	Unit	Value
1	BOD_5 (at 20^0C)	mg/l	300
2	COD	mg/l	650
3	TSS	mg/l	650
4	TKN (as N)	mg/l	55
5	TP	mg/l	6
6	pH	mg/l	6 to 9

Table 2: Treated Sewage Characteristics

S.No.	Parameter	Unit	Value
1	BOD_5 (at 20^0C)	mg/l	< 10
2	COD	mg/l	< 50
3	TSS	mg/l	< 10
4	NH4-N	mg/l	< 5
5	N Total	mg/l	< 10
6	Total Phosphorus	mg/l	< 2
7	Fecal Coliform	MPN /100 ml	< 100

3.1. TREATMENT SCHEME OF SBR BASED STP'S

The treatment scheme broadly consists of the following unit operations & processes:

1. Inlet chamber of STP
2. Screening – Mechanical & Manual Fine Screens
3. De-gritting – Mechanical & Manual Grit Chambers
4. Biological treatment - Sequential Batch Reactors (SBR)
5. Disinfection – Chlorination
6. Sludge management - Gravity Thickening and Mechanical Dewatering

The raw sewage is received in the inlet chamber and passed through mechanical fine screen and grit removal chamber. It is biologically treated in the SBR and then disinfected by chlorination. The surplus sewage sludge is subjected to thickening by gravity thickener and mechanical dewatering using centrifuge to remove excess water content before safe disposal (Gupta & Singh, 2012)

3.2. SCOPE OF THE STUDY – INCLUSIONS AND EXCLUSIONS

The raw sewage pumping station and treated sewage pumping is excluded from the study. All the electromechanical equipment's inside the sewage treatment plant is included for the study. Ventilation and Air-conditioning is excluded from the study. TRINA Solar TSM-320PD14 (320 Wp) polycrystalline silicon solar PV panel is selected for the study. The solar PV panels are assumed to work ideally. The tariff order issued by the Rajasthan Electricity Regulatory Commission for the year 2017-18 is considered for economic analysis of the solar PV's which includes the local and national taxes corresponding to Indian market. The service life of solar panels is taken as 30 years.

3.3. *HOURLY ELECTRICAL LOAD PROFILE OF THE STP'S*

The Solar PV system is grid connected and the electrical energy generation will be only required from 6 AM to 6PM when solar energy can be harnessed and used. The Electrical hourly load variation from 6 AM to 6 PM for all the 4 STP's were recorded and the summary is listed in Table 3.

Table 3: Electrical Hourly Load List Summary for the STP's from 6 A.M. To 6 P.M.

Summary	1.5 MLD (kW)	2 MLD (kW)	3 MLD (kW)	8 MLD (kW)
Total Consumption from 6 A.M. to 6 P.M. in terms of kWh	458.09	603.35	796.69	1860.02

4. METHODOLOGY

Sample of Sewage Treatment Plants (STPs) in Rajasthan in India is analyzed for the Techno-Economic Feasibility. The following field data are required from sewage treatment plants operating with SBR technology to design and analyse the solar PV powered STP.

1. Total power consumption details
2. Hourly electrical load profile
3. Topographical details of the location
4. Solar insolation levels at the location
5. Total land area occupied

Solar PV system is sized for grid-tied to arrive at the final capacity of the solar PV power plant. Life cycle cost analysis is the research methodology adopted for performing financial analysis.

Life cycle stages of the solar PV power plant covers the following stages which includes primarily production of raw materials, processing and purification, manufacture of modules and balance of system (BOS) components, secondly, transportation of the modules to the power plant, thirdly, installation and use of the systems and finally decommissioning and disposal or recycling. The decommissioning and disposal or recycling has not been considered in this study because of lack of reliable history of data.

4.1. *FINANCIAL ANALYSIS*

Investment in solar energy is not different from any other area of financial management. Financial analysis of solar PV system follows a similar procedure indifferent to any other investment. So, when the organization first decides to invest in solar energy, it should check the feasibility of the System by checking some of the significant financial figures.

The basic financial figures that should be estimated to check the feasibility include the following:

1. Simple payback period (SPBP)

SPBP refers to the time in number of years that is required to recover the initial investment considering only the net annual saving. SPBP is influenced only by the net cash flow of the system and the total service life. SPBP is calculated using following equation:

SPP = Project cost / Annual cash inflows (without considering the time value of money) Eq. (01)

2. Discounted payback period (DPBP)

DPBP represents the time in number of years that is required to recover the initial investment considering the time value of money. DPP is influenced by the net cash flow of the system and the total service life similar to SPP but along with the discount rate considering time value of money. DPBP is calculated using the following equation:

DPBP = Project cost / Annual cash inflows (considering time value of money) Eq. (02)

3. Net Present Value (NPV)

NPV is the difference between the present value of cash inflows and the present value of cash outflows. NPV is used in project capital budgeting to analyze the profitability of an investment. NPV analysis is sensitive to the reliability of future cash inflows that an investment will yield. For a project to be profitable or at least feasible, NPV should always be greater than zero or positive. Projects with negative NPV is not financially profitable. NPV is determined using the following equation:

$$NPV = \sum CF_t / (1 + K)^t, \; t = 0 \text{ to } n \qquad \text{Eq. (03)}$$

where
CF_t = Net cash flow occurring at the end of year (t = 0, 1,…. n)
n = life of the project in years
K = Discount rate

4. Internal Rate of Return (IRR)

IRR refers to the discount rate used at which the NPV of a particular project is equal to zero. A higher IRR indicates that it is more desirable to undertake the project. Hence, IRR is used to rank alternate project execution scenarios and the scenario with highest IRR is considered as the best possible option to undertake. IRR is sometimes referred as "economic rate of return" (ERR). IRR calculates the rate of return that an investment is expected to yield. IRR is determined using the following equation.

$$0 = \sum CF_t / (1 + IRR)^t, \; t = 0 \text{ to } n \qquad \text{Eq. (04)}$$

where
CF_t = Net cash flow occurring at the end of year (t = 0, 1,…. n)
n = life of the project in years

4.2. LIFE CYCLE COST ANALYSIS (LCCA) COMPONENTS

LCCA is the scientific methodology adopted for the financial analysis which includes the following components.

1. Initial cost (Expense)
2. Replacement cost (Expense)
3. Operation and Maintenance cost (Expense)
4. Incentive from government (Revenue)
5. Salvage value (Revenue)
6. Savings from power generation (Revenue)

Following list gives the detailed inclusions and exclusions in the LCCA components of the study

- Initial Cost

Design, Engineering and Management (DM) cost is considered (Tidball et al., 2010)

The tariff order issued by the Rajasthan Electricity Regulatory Commission for the year 2017-18 is considered for fixing the initial cost of the solar PV's along with the DM cost

- Replacement Cost

Inverters usually come with the service life of 25 to 30 years and 10%-part replacement is done every 10 years (Fthenakis et al., 2011). But based on actual practice, most of the inverters get replaced every 5 years because of lack of maintenance. So, inverter replacement every 5 years is considered for the study.

- Operation and Maintenance Cost

Operation and Maintenance cost considered is 11.68 USD (748.64 INR.) per kW per year (Tidball et al., 2010)

- Incentive from the Ministry of New and Renewable Energy (MNRE)

No Subsidy from MNRE for installing solar Panels for Government buildings, Government institutions, Private, Commercial and industrial sector

- Salvage Value

Maximum Salvage value at the year of 2010 for Crystalline PV cells are $0.33 (Rs. 21.15). Most of the PV cells are imported and so this value shall be taken for the analysis (McCabe, 2011)

- Savings from power generation

The Unit cost of power is taken as 6.5 INR, i.e. 6.5 INR/kWh and practical observable degradation in India of 5% is considered in the first 5 years and then on 0.5% degradation of solar panels power is considered for consecutive years

4.3. *Solar PV - Life Cycle Assessment in comparison With Fossil Fuel Power Plants in India*

While there are no global warming emissions associated with generating electricity from solar energy, there are emissions associated with other stages of the solar life-cycle, including manufacturing, materials transportation, installation, maintenance, and decommissioning and dismantlement. The following are the system boundaries for life cycle assessment of Solar PV.

- The combination of PV module manufacturing, material for Balance of System (BOS) and PV energy production have been considered for the system.
- Mining of raw material is not included in the analysis
- All transportation steps are excluded (Assuming the Transportation influence is negligible compared to Manufacturing and Operation Cycle)
- Due to the lack of reliable data, recycling has not been taken in account (Mason et al., 2006)

Some of the important terminologies used are described below:

Energy Pay Back Period (EPBP)

EPBP is a measure of how long Energy mitigating process needs to run to compensate the Energy consumed during the life cycle stage.

EPBP = Energy consumed by solar plant (MWh)/Energy produced by Solar Power plant per year (MWh)

Carbon Payback Period (CPBP)

CPBP is a measure of how long a CO_2 mitigating process needs to run to compensate the CO_2 emitted to the atmosphere during the life cycle stage.

CPBP = (Life cycle CO_2 emission / Gross CO_2 emission avoided per year) x 365

The energy consumed for producing one poly-crystalline PV module is taken as 0.4464 MWh and the CO_2 emission by the production of one poly-crystalline PV module is taken as 71.49 kg (Marimuthu & Kirubakaran, 2013).

5. Results and Discussions

5.1. *Maximum PV Array Capacity*

According to Solar-Radiation data from Meteonorm database (Meteotest, 2017) average annual horizontal radiation in the specified location in Rajasthan is 5.51 kWh/m^2/day. The maximum radiation can be obtained by tilting the surface at an optimum angle, which is determined by the latitude of the location and further considering inter-row gap of arrays.

Solar PV panels are installed at optimum tilt of 25.3 degree which is the latitude of the location as per "Performance from Solar Panels in India" submitted to Central Electricity Regulatory Commission, New Delhi

The average Annual Tilt radiation with respect to the tilt angle of 25.3^o is 6.07 kWh/m^2/day

Considering the average annual tilt radiation with Performance Ratio of the solar panels as 0.8, module efficiency as 15% and 5% degradation in the power generation at the end of 5 years, the maximum PV sizing for all the 4 STP's were arrived and the summary of the results is shown in Table 4.

Table 4: Maximum PV Array Capacity for the 4 STP's

STP Capacity (MLD)	Maximum PV array capacity (kWp)
1.5	99.0
2.0	131.0
3.0	172.0
8.0	403.0

5.2. LIFE CYCLE COST ANALYSIS

Based on the PV array capacity determined, LCCA was performed keeping into considerations listed under LCCA components earlier according to the tariff order issued by the Rajasthan Electricity Regulatory Commission for the year 2016-17.

The results of the LCCA is summarised in Table5. IRR and DPBP is estimated with the discount rate of 10%

Table 5: LCCA Results for The PV Array Capacity Installed at All The 4 STP's.

STP Capacity (MLD)	NPV (Million INR)	IRR (%)	SPBP (years)	DPBP (Years)
1.5	3.77	18.5	5.4	7.9
2	4.99	18.5	5.4	7.9
3	6.56	18.5	5.4	7.9
8	15.37	18.5	5.4	7.9

The SPBP and DPBP values are independent of the capacity of the STP's because of the similar characteristics of the STP's and selected PV modules.

5.3. LIFE CYCLE ASSESSMENT IN COMPARISON WITH FOSSIL FUELS

Because of the similar characteristics of the selected STP's and Solar PV modules, the EPBP and CPBP results do not vary with capacity of the STP's. The summary of the EPBP, Carbon emissions per unit generation of the solar PV plant and CBPB for the 1.5 MLD STP is given in Tables 6, 7 and 8.

Table 6: Energy Payback Period for the Solar PV Power Plant Estimated for 1.5 MLD Capacity STP

Capacity (kWp)	Avg. radiation ($kWh/m^2/day$)	Power generation (MWh per year)	Total Power consumption for producing Solar PV (MWh/Plant)	EPBP (years)
99	6.07	167.20	265.16	1.6

Table 7: Carbon Emission Per Unit of Power Generation of The Solar PV Power Plant For 1.5 MLD Capacity STP

kg CO_2 emission per kWp	Total capacity (kWp)	kg CO_2 emission for PV	kg of CO_2 emission for BOS	Total kg of CO_2 emission	Total power production per year (MWh)	Life time production (MWh)	CO_2 intensity (kg/MWh)
428.94	99	42,465.06	17954.64	60,419.70	167.20	5016.08	12.0

Table 8: Carbon Payback Period for The Solar PV Power Plant For 1.5 MLD Capacity STP

kg CO_2 emission per MWh	Carbon emission of coal-based power plant (kg CO_2/MWh)	Carbon reduction (kg/MWh)	Life cycle CO_2 emission (kg)	kg of CO_2 reduction per year	CPBP (Days)
12.0	941	933.0	60,419.70	155,323.89	142

The CO_2 emissions of solar PV comes around 8 kg/MWh of electricity produced while it is 941 kg/MWh for coal-based power plant in India. The result also shows that the EPBP of Solar PV is less than a year with CPBP of just 94 days which is a huge advantage environmentally in comparison with conventional coal-based power plants. The CO_2 emissions reduction by using solar PV panels to operate STP's in the complete lifetime is huge making it highly eco-friendly and the summary is shown in Table 9.

Table 9: CO_2 Emissions Reduction by Using Solar PV Panels to Operate STP's In the Complete Lifetime of the Panels

STP Capacity (MLD)	CO_2 emissions reduction (metric tonnes)
1.5	4660
2.0	6138
3.0	8104
8.0	18,921

6. SUMMARY

This study presents the ideal estimate of maximum solar power than can be utilised by the Solar PV for different capacity STP's less than 10MLD which can be used as reference in planning future projects. The results also show us that the kWh/MLD that can be generated with Solar PV reduces with increase in the capacity of STP. This study helps us to know that using on-grid Solar PV system for power generation in STP's with capacity less than 10 MLD is highly feasible both technically and financially. The yield or the rate of return is greater than 18% which gives enough propel for executing this in near future. The simple and discounted pay back periods fall less than 8 years which is considerably very less than the entire lifetime of the Solar PV as well as the STP which is normally 30 years. And also, the Life Cycle Assessment results shows that Solar PV is highly environment friendly with very less EPBP and CPBP in comparison with coal-based conventional power plants. This project Study, if executed, industries which bid for STP construction can not only place their foot-print on a hallmark project bridging the gap between STP and Solar Power but also can get along in winning the bid by virtue of the Power Guarantee. (Power Guarantee is a document to be given by the bidder along with the bid documents guaranteeing that the treatment plant will only take the specified units of power from the grid after which the contractor is liable for penalty for each unit consumed by the plant which poses huge risk in the longer run to the contractor bidding). Thus, project outcome encourages trying out power generation through solar PV to operate STP's which will make the country march on to sustainable construction practices along with financial profitability leading the future generation to have a sustainable future.

7. SCOPE OF FUTURE WORK

The current study only deals with STP's with capacity less than 10 Million Litres per Day and lot of other detailed studies can be to check the feasibility of using Solar PV for higher capacities. The challenge is, most of the STP's differ in their electromechanical components when the capacity is increased. Normalising into one category like this study may be little tedious when the capacity of STP is increased. Also, different type of Solar PV system also can be used as a variant from the fixed-tilt and the results can be compared. Thus, keeping in mind the trend of renewable energy and its applications in the present world, there is huge scope of improvement and research that can improve the technical and financial benefits of the Solar PV installed in STP's.

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APPENDIX 01

The list of abbreviations used are given below:

BOD	Biological Oxygen Demand	MW	Megawatt
CO_2	Carbon di-oxide	MWh	Megawatt hour
COD	Chemical Oxygen Demand	NH4	Ammonium
CPBP	Carbon payback period	NPV	Net Present Value
DPBP	Discounted payback period	pH	power of hydrogen
EPBP	Energy payback period	PV	Photovoltaic
GW	Gigawatt	SBR	Sequential batch reactor
IRR	Internal Rate of Return	SPBP	Simple payback period
kg	Kilogram	STP	Sewage Treatment Plant
kW	kilowatt	TKN	Total Kjeldahl Nitrogen
kWh	kilowatt hour	TP	Total phosphorus
LCC	Life Cycle Cost	TSS	Total suspended solid
MLD	Million litres per day	Wp	Watt peak