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Economic analysis of a large scale solar updraft tower power plant

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ABSTRACT

This research article provides an economic analysis of a large-scale solar updraft tower power plant (SUTPP) having 100 MW capacity and installed in Udat, Rajasthan, India, with position coordinates of 27° 35′ and 72° 43′ for meteorological conditions. A cost model developed for optimized parametric values, received from thermal and dimensional optimization of previous study, to analyse the optimized cost of electricity generation and revenue analysis with the consideration of electricity selling, carbon credits, and the levelized electricity cost. The results of the analysis suggest that the proposed plant has a higher capital and operating cost than photovoltaic and wind energy, but it also has a lower levelized cost of electricity generation. As, for a fixed power output, the optimized cost of electricity generation is inversely proportional to $R_{collector}$ and R_{tower}, and obtained an optimum value between ₹9.16 to ₹10.57 for power plants ranging from 100 MW to 200 MW. The results also show that the cost of construction of such a power plant largely depends on plant configuration and can lie between ₹4.5cr. to ₹12cr. per MW, which indicates that a large-scale SUTPP can be installed economically. Although the optimum values of optimized cost of electricity generation came with larger dimensional values of the power plant, that also create challenges during the construction and operation of the power plant. Based on these findings, the authors conclude that, with proper subsidies and support, a large-scale SUTPP can be considered a promising renewable energy technology for power generation.

Introduction

Solar updraft tower power plants (SUTPP) employ a tall tower encircled by a greenhouse-like structure constructed of plastic or glass [1]. Wind draws heated air from the sun up the tower. This air powers turbines [2]. The towers are efficient and cost-effective and may be built in distant areas without alternative renewable energy. Solar updraft towers are being tried in numerous places across the world [3]. SUTPP have minimal construction and operational expenses, little environmental effect, and can generate power on overcast days [4]. SUTPP have limited power-generation capability and aren't appropriate for harsh weather [5].

The SUTPP components are basic and authentic, accessible to less developed nations that are sunny and have fixed raw material supplies, but space for new technology adoption is always open for each section of the plant such as the turbo-generator and collector [6]. SUTPP construction materials (primarily glass and concrete) are cheap and easily accessible [7]. Similar component designs and heavy use might minimise building time. Deserts and low-value regions with high radiation are suited for SUTPP [8]. The SUTPP has a longer operational life without substantial changes in technology adoption and doesn't need cooling water, waste disposal, or ash disposal. Based on renewable energy, SUTPP earns carbon credits. Secondary benefits include employment creation during construction, using a collector area as a greenhouse for agriculture, and increased tourism [9,10]. SUTPP's poor conversion efficiency rises with solar tower (ST) height. Due to its massive size, the initial cost of building and installation per MW of such a facility is considerable compared to other power plants. SUTPP is concerned with electricity output throughout the day or year, at high demand times, and in the colder months. Development may alleviate these drawbacks [11].

A verbal description of a solar chimney, or SUTPP, was proposed by Isidoro Cabanyes in 1903 [12–14]. A Spanish artillery colonel gave a proposal titled "Proyecto de motor solar" (solar engine project), in which the author introduced a setup having an air heater integrated into a building with a chimney for electricity production based on experiment of solar chimney proposed by Günter in 1931 [15].

Schlaich et al. [16] did detailed theoretical preliminary investigation and research with a broad range of wind tunnel experiments, which led to the establishment of a pilot plant with a peak power output of 50 kW in Manzanares, 150 km south of Madrid, Spain, in 1981–82 [17]. No

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Nomenclature

Symbols

A	Area, (m^2)
C_p	Specific heat capacity, J/(kg K)
g	gravitational acceleration, (m/s^2)
h	Convective coefficient of heat transfer, (W/m^2K)
H	Tower height, (m)
I	Average Insolation, (W/m^2)
L	Duct length, (m)
$\dot{m}$	Mass flow rate, (kg/s)
P	Pressure, (Pa); Power, (W)
q	Heat transfer, (m)
r	radius, (m)
R	Universal gas constant, (J/mol-K); Radius, (m)
T	Temperature, (K)
V	Volume flow rate, (m^3/s)
W	Duct width, (m)

Greek symbols

Δ	Drop, gradient
η	Efficiency
ν	air velocity (m/s)
τ	Dynamic viscosity (Pa·s)
θ	collector slop (^{o})
ρ	density of air (kg/ m^3)

Subscripts

a	Ambient
avg	Mean/average
coll	collector
g	Ground
f	Friction factor
h	Hydraulic
s	Smooth
sc	specific cost
support	Farm support
turbine	Turbine
tg	Turbine-Generator
th	Thermal
max.	Maximum
t	Tower
v	Volume
z	Elevation

Abbreviations

SUTPP	Solar updraft tower power plant
HTVTS	Horizontal to vertical transition section
APO	Annual Power Output
DALR	Dry Adiabatic Lapse Rate
PCU	Power Conversion Unit
TG	Turbine Generators
OCEG	Optimized Cost of Electricity Generation
CSCPP	Commercial solar chimney power plants
C	Currency/Costs
O&M	Operation and maintenance
GHG	Greenhouse gas
CC	Carbon credits
PM	Particulate matter

sizable SUTPP has been constructed yet; therefore, it's impossible to acquire actual quotes for components and materials. Scholars offered several SUTPP economic models. Schlaich [16] and Bernardes [18,19] assessed 100 MW plant component costs, examined the Optimized Cost of Electricity Generation (OCEG), and investigated the levelized electricity cost (LEC) response to economic factors. Bernardes [20] develops a parametric cost model for an SUTPP with plant systems. Schlaich et al. [16] assessed plant and LEC costs. Fluri et al. [21–24] offered a more extensive cost model to estimate the cost of two commercial plants equivalent to the 100 MW plants and the influence of carbon credits on LEC. Papa Georgiou [25,26] analysed the component cost of a 100 MW solar chimney power plant (SCPP) omitting carbon credit income, whereas Zhou [5,27–29] examined the LECs of probable SCPPs with FSCs supported by high mountains in Northwest China's deserts and likewise omitted carbon credit revenue. Zhou [14,30] studied commercial solar chimney power plants (CSCPPs), and novel SCPP costs have been calculated.

Zhou et al. [31] developed a technique for evaluating the cost of producing electricity by merging a solar collector with a built-in mountain hollow without carbon credits. Zhou et al. [32] offer an economic study of power output from a 100 MW FSCPP by comparing cash flows throughout their whole service life. Cao et al. [34] analysed investment returns over the 30-year serviceability of traditional and tilted SCPP with three distinct power capacities in North-western China. In Zhou et al. [32] and Cao et al. [34], carbon trading earnings is tax-exempt, and income tax expense are not compensated. Large-scale SUTPPs are planned for Australia, Southern Africa, Brazil, and other sunny regions, but none have been erected.

The objective of this study is to find out the optimized cost of electricity generation (OCEG) and the values of dimensional parameters on which these cost are lies, by varying different parameters in limited rang and find out the trends between them for different sets of SUTPP.

Economic optimization of SUTPP has been identified for a variety of designs, where such optima are defined as plants with the lowest cost per unit of yearly power output. Using specific parametric assumptions, a reference plant design is used to create an objective function. All expenses are described in terms of a consistent currency "C", where "C" can consider as an independent variable that can be converted into any global currency, to produce results in any regional currency. [11]. Then, in order to evaluate the SUTPP's cost-effectiveness and economic viability, it is translated to Indian rupees () and compared to other renewable energy technologies, such as solar photovoltaic and wind energy.

In the first step, a set of the most prominent plant dimensions is selected to optimize, and detailed cost assumptions are considered for collector, tower, and power conversion unit (PCU) in terms of uniform currency to develop an approximate plant cost model by using an objective function with the optimum dimensional configuration for several cost structuring as discussed by Singh and Dwivedi [15]. In further steps, a concept of Optimized Cost of Electricity Generation (OCEG), expenditure (loan, insurance, deprecation life of plant, operation and maintenance (O&M) cost), and revenue (annual electricity selling cost, revenue gain by selling carbon credits) calculations are added to find out the cost of electricity generation on the basis of /kWh. With the help of simulation programmes, the trends of cost of plant installation and cost of electricity generation are also developed with respect to the power output of plants. Other graphs that are developed show the optimized values of dimensions for various power outputs. These graphs are very helpful for plant designers and operators, as they provide basic idea for selecting dimension configurations and power output selection for the SUTPP.

Analysis of SUTPP

Singh and Dewedi [15] presented the governing conservation equation for collector, TG, PCU, and thermal analysis. Different dimensions' factors affect SUTPP output power as follows: Tower height directly affects power generation, although this connection is not linear due to friction. This connection can't calculate tower height. SUTPP collector radius directly regulates power output. Collector efficiency affects output power, which can be boosted with slightly raised glasses with glazing, a smooth soil surface, and a roof support system with low drag forces. Assuming the internal air temperature remains constant, power output rises as the ambient temperature falls. Tower shadow, partially cloudy weather, 24-hour use, and glazing impact SUTPP's power generation, which is not investigated. A techno-analysis and optimal dimensional configuration for this work is discussed by the previous study conduct by the Singh and Dwivedi [15].

Reference purposed SUTPP specification

In India, the best places to build huge SUPPs are in the Rajasthan desert, where solar radiation is high and land is free or cheap. In this study, Udat, Rajasthan, India, is considered a reference location for an SUTPP with position coordinates of 27° 35′ and 72° 43′ for meteorological conditions and other specifications for performance evaluation by the use of power output equations with real ground conditions described by power output equations as per Singh and Dewedi [15]. A real-world site with more specific data yields better results for power output calculations and other considerations. This reference site has the most solar radiation in India and the most monthly daylight hours, 12.15 h.

Meteorological data of reference site

According to researches [3,11,35–39], environmental factors impact SUTPP output power. The reference plant reports solar irradiance, air temperature, wind speed, and humidity. It's near Bikaner, Rajasthan, India. The reference site is hot, dry, and clear day and night. The reference site is flat and low-density[40–42]. Photovoltaic and solar thermal energy systems work well in this arid region of India [43,44]. These factors and others make Udat, Rajasthan, India, an ideal site for the development of a major SUTPP.

Evaluation of the SUTPP model

Plant output power has a direct relationship with collector area (radius) and tower height [18,26]. If the power output is fixed, then the optimized collector area for a plant can be calculated in terms of the minimum plant installation costs per annual power output [17,45,46].

The most prominent solar updraft power plant dimensions are collector radius ($R_{Collector}$), tower height (H_{Tower}) and tower radius (R_{Tower}), which are presented in Table 1 and Table 2, with dimensional limits and intervals. In this model, the design, material, and construction considerations for the collector, tower, and PCU have been discussed in detail in a previous study conducted by Singh and Dewedi [15]. The dimensional details of Table 1 are applied to the reference SUTPP configuration as discussed in Table 2.

Modelling considerations for economic optimization of a SUTPP

Economic viability is a very important parameter in the selection of plants because the cost of power generation by renewable energy sources is very high relative to non-renewable energy sources. Many different SUTPP dimensions and configurations have been suggested in the previous study by several researchers, including Schlaich [45], Chitsomboon [26,47], Tingzhen et al. [26,48], Zhou et al. [49], Bernardes [11,20,26], T.P. Fluri [21,22,26] and J.P. Pretorius [11].

Table 1
Selection of the SUTPP dimensions, boundaries and periods for optimization.

Dimension	Dimensional limits	Periods
H_{Tower}	500 m to 2500 m	500 m
R_{Tower}	05 m to 25 m	05 m
$R_{Collector}$	1000 m to 3000 m	500 m
Power Output	100 MW to 200 MW	25 MW

Table 2
Reference SUTPP configuration.

Collector-Roof	
Material	Glass
Roof Shape exponent	$b = 1$
Inlet height	$H_1 = 6\ m$
Outlet (tower side) height	$H3 = 30\ m$
Outer radius	$R_1 = 2{,}000\ m$
Inlet radius	$R_4 = 120\ m$
Ground	
Type (material)	Sandstone
Shape (Geometry)	Flat
Tower	
Material	Reinforced high performance concrete
Height	$H_{tower} = 969.3679m$
Geometry effect	not considered
Bottom Inside diameter tower radius	$R_{tower} = 21.6525m$
Chimney shadow effects	neglected
Tower inside base temperature	328.15 K
Guiding Cone	
Geometry	conical
Head shape	hemispherical
Power conversion unit (Turbine and generator)	
Rated Power output	100 MW
Positioning of the turbine	Bottom
Type of flow	Axial
Numbers of turbine	16
Turbine rated power producing capacity	6.25 MW
Turbine positioning configuration:	multiple horizontal axes at bottom
Turbine diameter	30 m
Number of rotor blades in one turbine	06
Turbine speed	100 rpm
Generator speed	1000 rpm
Gear ratio	10
Turbine-generator efficiency	$\eta_{tg} = 85\%$
Horizontal to vertical transition section (HTVTS)	Curved junction with Guiding cone
Ambient Condition	
Ambient temperature	$T_a = 303.15K$
Total Temperature difference	$\Delta T = 25$ K
Specific heat capacity	$C_p = 1.005$ KJ/kg K
Design solar irradiation	1000 W/m^2
Gravitational acceleration	9.81 m/s^2
Wind velocity at bottom of the tower	24.866 m/s
Wind velocity at release point of the tower	37.299 m/s
Lapse rate of atmospheric air temperature	DALR

Schlaich [45] proposed the cost model for all plant components for various plant sizes with the calculation of the optimised cost of electricity generation (OCEG) and developed the relation between OCEG and the length of the depreciation period of the plant. Schlaich et al. [45] also show the cost model for the component cost of SUTPP and the OCEG for various plants for fixed economic parameters (equipment, construction with transportation and labour costs, insurance, O&M, depreciation period etc.). Bernardes [11] presents a similar study as

Table 3
Economic parameters used in carrying out cost-benefit analysis of SUTPP.

Economic parameter	Value
Inflation rate, i	8%
Interest rate of loans, i_l	8%
Inflation rate on electricity selling (i_{solar})	12%
Inflation rate on insurance ($i_{insurance}$)	5%
Discount rate f (for present worth factor)	10%
Inflation rate on carbon credit i_{cc}	8%
Income tax rate for first 15 years r_{tax}	5%
Income tax rate for more than 15 years r_{tax}	10%
Inflation rate on O & M cost i_{om}	8%
Years of depreciation n_d	30
Years of loan payment n_l	15
The whole service period, n	120 years
Initial investment, Ci	$C_{investment}$
Annual electricity output, E	255.2 GWh/a
Solar electricity sale price, P_{Solar}	₹15/kWh
Price of carbon credit, P_{cc}	₹100/t
Interest rate of loans (%)	8%
Inflation rate (%)	8%
Annual increasing rate of market price of electricity (%)	12%

Schlaich [45] with the added calculation for the cost of various sizes of plants; he also presents a procedure to evaluate the LEC and investigates the sensitivity of the LEC to the economic parameters. In addition to that, he derives a parametric cost model for the main SUTPP components (collector roof, ST. and PCU).

Fluri et al. [21] offered a more extensive valuation method, including the first detailed cost framework for the collector and PCU, in which the influence of carbon trading on LEC was also taken into account, and contrasted the final outcome to Schlaich et al. [45] and Bernardes [18,50]. In this study, for the objective of equivalency, two different solar chimney power plants (SCPP) with identical capacities as 100 MW facilities were chosen, as indicated by Schlaich et al. [45] and Bernardes et al. [2,11]. Fluri et al. [21] projected the output power of identical reference SCPP using Pretorius's thermal framework, in which the simulated results display a smaller value of maximum output power, which is approximately 66 MW for Schlaich et al. [16] reference plant model, and 62 MW for Bernardes's reference plant model rather than 100 MW.

In the initial phase, a set of notable plant dimensions is picked to be optimised, and then cost estimation hypotheses are taken into account for collector, solar tower, and PCU in uniform currency to develop a plant cost model by using an objective function that can find optimal plant dimensions for various cost frameworks. In further steps, an OCEG, expenditure (loan, insurance, depreciation life of plant, O&M cost), and revenue (annual electricity selling cost, revenue gain by selling carbon credits) calculations are added to find the optimise cost of electricity generation in ₹/kWh. To discover patterns and generate graphs between variables, many simulations for the goal function are done and compared to the optimal cost of each facility. The economical parameters used in carrying out cost-benefit analysis of SUTPP are discussed in Table 3.

Cost Model: Equations and objective functions for economic optimization of SUTPP

Objective function

To determine optimal plant dimensions and annual power output, an SUTPP cost model is introduced, based on total expenditure (interest of loan, annual insurance, annual depreciation expenses, operation and maintenance (O&M) cost) and revenue (Annual electricity selling cost, revenue gain by selling carbon credits) calculations [51,52]. In the goal function, the concepts of OCEG and carbon credits are presented. Schlaich et al. [53], Bernardes [18], Pretorius [26,11] and T.P. Fluri et al. [22] provided detail.

Equations for SUTPP construction cost calculations

Tower cost equation. All costs are defined in terms of C. The tower (material, transportation, and construction) specific cost (T_{sc}) is defined as one C per meter volume of tower ($T_{sc} = 1C/m^3$). It is assumed that the average tower thickness has a change of one millimetre for every one-meter height. Therefore, the total tower cost is simply determined as the volume of the tower multiplied by the specific tower cost:

$$C_{tower} \propto (2\pi R_{tower} H_{tower}) \times t_{tower} T_{sc}$$

Since the thickness of the tower is linearly proportional to the tower height,a constant Z is introduced to replace the proportionality signs. This depends on the tower thickness to tower height ratio.

Value of Z has been considered as 0.001.

$$Z = \frac{t_{tower}}{H_{tower}} \tag{1}$$

By putting the value of Z in equation, the cost of tower is

$$C_{tower} = Z2\pi R_{tower} H_{tower} H_{tower} T_{sc} \tag{2}$$

$$C_{tower} = 0.002\pi R_{tower} (H_{tower})^2 T_{sc} \tag{3}$$

where T_{sc} is a specific cost of construction for the tower in ₹/m^3.

Collector cost equation. The collector cost is directly proportional to the area covered by the collector. Let the base cost of the collector per square meter with an additional material charge due to a gradual increase in collector inlet height (given by the equation $H_{in} = H_{out} \left[\frac{r_{out}}{r}\right]^b$, as the value of the roof shape exponent is constant at b = 1, all roofs will have the same shape) from the periphery to the centre of the collector will be C_{coll}. In addition, it is assumed that the base cost of the collector per square meter will be ψ_{coll} % of the cost of T_{sc} plus an additional ψ_h% of collector per meter square cost for every one meter height at the collector inlet [54].

As a result, the total collector cost is as follows:

$$C_{coll} = C_{coll,base} + C_{coll,slop} \tag{4}$$

$$C_{coll} = \pi R_{coll}{}^2 \{(0.01\psi_{coll}) T_{sc}\} \{1 + (0.01\psi_H) H_{out}\} \tag{5}$$

PCU cost equation. It is assumed that the PCU, which includes sets of turbo-generators, has a cost equal to 20% of the total collector and tower cost [26,55].

So the PCU cost:

$$C_{PCU} = 0.2(C_{tower} + C_{coll}) \tag{6}$$

The total construction cost of SUTPP. The total construction cost of SUTPP is given by:

$$C_{investment} = C_{tower} + C_{coll} + C_{PCU} \tag{7}$$

$$C_{investment} = 1.2(C_{tower} + C_{coll}) \tag{8}$$

$$C_{investment} = 1.2\left[0.002\pi R_{tower} (H_{tower})^2 T_{sc} + \pi R_{coll}{}^2 \{(0.01\psi_{coll}) T_{sc}\} \{1 + (0.01\psi_H) H_{out,collector}\}\right] \tag{9}$$

So the specific cost of installation of the SUTPP can be calculated as follows:

$$S = \frac{C_{investment}}{P_{out}} \tag{10}$$

where P_{out} is the installed capacity of the SUTPP.

Overall construction cost of SUTPP

Schlaich et al. [16] and Bernardes [18] specify 2-year construction. If the whole capital is borrowed before development, interest will be charged on it. This study considered capital cost with 8% interest after $n_c = 2$ years:

$$C_{\text{Construction}} = C_{investment}(1+i)^{n_c} \tag{11}$$

Optimized cost of electricity generation (OCEG): Expenses and revenue analysis

This work compares cash inflow with cash outflow. SUTPP costs are divided into initial installation and yearly operation. In the detailed cost model, the major plant installation cost can be divided into collector cost, solar tower (ST) cost, and the PCU cost; the collector cost includes material, construction, and transport costs; the ST cost includes material, construction, hoisting, and transport costs; and the PCU cost includes balance of station, turbines, generators, ducts, power electronics, central structure, and controls costs. Loan interest, yearly insurance cost, income tax, annual depreciation charges, and operation and maintenance (O&M) costs are additional important SUTPP expenditures. Selling generates most of SUTPP's revenue. Carbon credits provide annual electricity and cash flow.

Revenue analysis

The major revenue received by SUTPP has two components: cash inflow generated by selling annual generated power and cash inflow generated by selling carbon credits.

Revenue generated by selling annual generated power. Cash inflow, or money earned by SUTPP, includes selling energy to the power grid or another utility and selling carbon credits to other carbon emitting organisations due to reduced greenhouse gas (GHG) emissions [56,57]. Government policies affect the value of selling electricity to the grid or other utilities. Most of the EPG is supplied to the power grid at a price above the market level of particulate matter (PM) per kWh, while the EOC is consumed by other customers at PM per kWh [58]. The present value of SUTPP's annual revenue from utilities and other customers may be computed by:

$$P_{E,n} = P_{solar}E_{utility}(1+i_{solar})^{n-1} + P_m E_{OC}(1+i_m)^{n-1} \tag{12}$$

where $E_{utility}$ and E_{OC} are the annual increasing rates of P_{solar} and P_m, respectively. When P_{solar} is m times more than P_m, this eq. will become

$$P_{E,n} = (mE_{utility} + E_{OC})P_m(1+i_m)^{n-1} \tag{13}$$

When all the electricity E is sold to the utility, in the n year the annual revenue generated by SUTPP will become

$$P_{E,n} = P_{solar}E(1+i_{solar})^{n-1} \tag{14}$$

where $P_{solar} = P_{local} + P_{subsidy}$ is the electricity price per kWh sold to the power grid, with the cost components P_{local} and $P_{subsidy}$.

It is assumed that this amount will increase with the inflation rate i_{solar} each year.

When inflation with an optional discount rate is included in the economic model, the annual equivalent discount rate will become

$$i_d = i_{ODR} + i_{solar} + i_{ODR} \times i_{solar} \tag{15}$$

where i_{ODR} is the country's anticipated or optional discount rate.

In India, the government subsidises power by charging a high price per kWh. For simplicity, this study assumes no government subsidy in terms of extra discount rate, rather than offering optional discount government/power grid or utility are acquiring this electricity with P solar electricity price per kWh [59].

The present value of cumulative yearly income earned by selling energy over n years may be determined by dividing the right hand side by $(1+f)^n$ (present worth factor), where f is the discount rate, and then summing the annual revenue.

$$P_{E,n} = P_{solar}E\sum_{n=1}^{n}\frac{(1+i_{solar})^{n-1}}{(1+f)^n} \tag{16}$$

By summing the progression

$$P_{E,n} = \frac{P_{solar}E}{f - i_{solar}}\left[1 - \left(\frac{1+i_{solar}}{1+f}\right)^n\right] \tag{17}$$

The annual electricity (E) generated through the plant, which is also known as Annual Power Output (APO) can be calculated as

$$E = Power_{avg} \times 365 \times 24kWhr \tag{18}$$

where Annual average power output $Power_{avg}$ is 36% of peak power output of SUTPP [45].

Impact of carbon credits. In India, for thermal power plants, average CO_2 emissions per unit of electricity generation range between 0.82 and 1.0 kg/kWh from 2001 to 02 to 2009–10, with a mean average of 0.933 kg/kWh [60]. To estimate the impact of carbon credits on the OCEG, a 0.95 kg CO_2/kWh coal-fired power station is assumed to be replaced by the SUTPP. A SUTPP with reference plant configuration would cut CO_2 and make money depending on India's carbon credit pricing, the estimated first-year carbon credit revenue:

$$P_{cc,1} = E \times 0.95 \times R_{cc} \tag{19}$$

where E is the annual power output in kWh by the reference plant and R_{cc} is the carbon credit per tonne of CO_2 in rupees, where $R_{cc} = \frac{400\times\$}{1000}$.

Carbon credits will improve SUTPP's cash flow after the first year by i_{cc} per year. In the n^{th} year, the annual revenue generated by SUTPP by selling carbon credits can be calculated by

$$P_{cc,n} = P_{cc,1}(1+i_{cc})^{n-1} \tag{20}$$

The present value of cumulative yearly income earned by SUTPP by selling carbon credits over n years may be found by dividing the right hand side by $(1+f)^n$, where f is the discount rate, and then summing the annual revenue generated by selling carbon credits, which is:

$$P_{cc,n} = P_{cc,1}\sum_{n=1}^{n}\frac{(1+i_{cc})^{n-1}}{(1+f)^n} \tag{21}$$

By summing the progression

$$P_{cc,n} = \frac{P_{cc,1}}{f - i_{cc}}\left[1 - \left(\frac{1+i_{cc}}{1+f}\right)^n\right] \tag{22}$$

The value of this Annual profit due to selling of Carbon credits $P_{cc,n}$ will be add on annual total revenue.

Expense analysis

Equivalent yearly cost includes annual insurance, loan interest, operation and maintenance (O&M) cost, auxiliary cost, income tax, and depreciation. Collector, PCU, and tower last longer than traditional plants. n is the number of years since first operation.

Annual Investment cost $C_{annual,ex}$, which is equal to the sum of present value (PV) of loans (C_{loan}), and cost of annual insurance $(C_{insurance})$, income tax $(C_{incometax})$, annual deprecation expenses $(C_{depreciation})$, Cost of fuel/ electricity consumed by auxiliary $(C_{aux.})$ and operation and maintenance (O&M) cost (C_{OM}) is expressed as:

$$C_{annual,ex} = C_{insurance} + C_{OM} + C_{aux.} + C_{depreciation} + C_{loan,int} + C_{incometax} \tag{23}$$

Expense due to insurance. First-year insurance premiums are typically less than 1% of construction costs. This exercise assumes 0.8%. First-year insurance is [26,61]:

$$C_{insurance,1} = 0.008C_{Construction} \tag{24}$$

The annual insurance $C_{insurance,n}$, after the first year of operation increases year by year with inflation.

Where $C_{insurance,1}$ is the total insurance pay by the SUTPP at the end of the first year operation, $i_{insurance}$ is the inflation rate ($i_{insurance} = 5\%$) and n is the lifetime in years.

The annual insurance cost for n^th year can be calculated by the formula, given below:

$$C_{insurance,annual} = C_{insurance,1}(1 + i_{insurance})^{n-1} \tag{25}$$

Where $C_{insurance,1}$ is the annual insurance in the first year of operation, $i_{insurance}$ is the annual increasing rate of insurance cost and n is the number of year.

The present value of cumulative yearly insurance charges over n years may be found by dividing the right hand side by $(1+f)^n$, where f is the discount rate, and then summing the annual insurance charges, which will be:

$$C_{insurance,n} = C_{insurance,1}\sum_{n=1}^{n}\frac{(1 + i_{insurance})^{n-1}}{(1+f)^n} \tag{26}$$

By summing the progression

$$C_{insurance,n} = \frac{C_{insurance,1}}{f - i_{insurance}}\left\{1 - \left(\frac{1 + i_{insurance}}{1+f}\right)^n\right\} \tag{27}$$

This value of $C_{insurance,n}$ will add on the total amount of expenditures.

Annual operation and maintenance (AOM) charges. Schlaich et al. [16] estimated the AOM cost of a 100 MW reinforced concrete SUTPP to be 1.9 M€ (Million Euros) in the first year of operation (which is 0.5% of total construction cost), while Bernardes [18] specifies an AOM cost for the first year of operation of 1 M€ (which is 0.3% of total construction cost). Fluri et al. [21] also present a cost compression model with same consideration as Schlaich [16] have with 1.9 M€ AOM cost for the first year of operation. Papageorgiou [62] assumed the AOM costs of Floating Solar Chimney (FSC) to be 0.5 M€ in the cost estimate of a 100 MW FSCPP, while Zhou [26] is assumed to be 2.4 M€ cost for AOM for same reference plant.

The annual power output and construction cost of SUTPP are considered based on the dimensional details of reference plant. This analysis employs the 0.75% AOM charges of total cost of construction of SUTPP for the first year, while assuming that the amount will increase with 5% inflation ($f = 5\%$) and the interest rate is 8%,($i = 8\%$).

So the first year operation and maintenance cost is

$$C_{OM,1} = 0.0075C_{counstruction} \tag{28}$$

This amount is expected to cover operation and maintenance of the entire system, including removing dust from the collector's roof, mending and repairing the glass roof, maintaining electronic equipment, and paying management employees.

The auxiliary cost (C_{aux}.) is also considered part of the AOM cost and covers auxiliary equipment's power use. The AOM cost grows each year after the first, as seen in the following equation for the nth year:

$$C_{OM,annual} = C_{OM,1}(1 + i_{OM})^{n-1} \tag{29}$$

where $i_{OM} = 8\%$ is the annual increasing rate of inflation for OM cost.

Where $C_{OM,1} = 0.0075C_{counstruction}$ is the cash flow at the end of the first year of operation, ε_{OM} is the inflation rate ($i_{OM} = 8\%$) and n is the lifetime in years.

The present value of the annual operation and maintenance expenses:

$$C_{OM,n} = C_{OM,1}\sum_{n=1}^{n}\frac{(1 + i_{OM})^{n-1}}{(1+f)^n} \tag{30}$$

By summing the progression

$$C_{OM,n} = \frac{C_{OM,1}}{f - i_{OM}}\left\{1 - \left(\frac{1 + i_{OM}}{1+f}\right)^n\right\} \tag{31}$$

This value of $C_{OM,n}$ will add on the total amount of expenditures.

Cost of power consumed by auxiliary ($C_{aux.}$). In this model, the cost of auxiliary power ($C_{aux.}$) is not addressed individually because of its low contribution to SUTPP's overall cost, but it is included in yearly operating and maintenance costs.

Annual depreciation cost. For a steady power output, an SUTPP with precise dimensions has been utilised due to its long duty cycle and reliable components. Therefore, no SUTPP part will be replaced over its life cycle. In this study, yearly depreciation expenditure values are computed using the straight-line technique due to the continual reduction in value of SUTPP components. The straight-line method is ideal for structures with a lengthy life cycle. Find n_d year's depreciation by:

$$C_{deperecation} = \frac{C_{Construction} - C_{residualvalue}}{n_d} \tag{32}$$

With $C_{residual\ value}$ is SUTPP's insignificant residual value at the conclusion of its service period [21,45]. In this paper, the residual cost of SUTPP is estimated to be 5% of the initial construction cost.

So yearly depreciation is:

$$C_{deperecation} = \frac{C_{Construction} - 0.05C_{Construction}}{n_d} \tag{33}$$

The value of this annual depreciation $C_{deperecation,n_d}$ will be the same for all years of operation limited up to when $n \le n_d$ and$C_{deperecation,n_d} = 0$; when $n > n_d$.

It is assume that the tax deduction is permissible on the deprecation amount with the rate of depreciation $C_{deperecation,n_d}$ with income tax rate r_{tax}, which can be found as

$$C_{taxsaving,dep,n_d} = \frac{C_{deperecation,n_d} \times r_{tax}}{f} \tag{34}$$

The deprecation cost of SUTPP will add to annual total expenses.

The present value of the annual savings be:

$$C_{taxsaving,dep,n} = C_{deperecation,n_d} \times r_{tax}\sum_{n=1}^{n_d}\frac{1}{(1+f)^n} \tag{35}$$

By summing the progression

$$C_{taxsaving,dep,n_d} = \left[\frac{C_{deperecation,n_d} \times r_{tax}}{f}\right]\left[1 - \left\{\frac{1}{(1+f)^{n_d}}\right\}\right] \tag{36}$$

if $n \le n_d$

$$C_{taxsaving,dep,n_d} = 0 \tag{37}$$

if $n > n_d$

This saving on depreciation costs will be subtracted from annual total expenses.

Cost of interest on the loan. In this scenario, the complete initial construction cost $C_{Construction}$ for SUTPP is borrowed at an interest rate i_l from a prominent financial institution and repaid in equal yearly instalments C_{loan} over a period of n_l years. Taking each yearly repayment's value at the time of the initial investment, it follows:

$$C_{Construction} = \sum_{n=1}^{n_l}\frac{C_{loan}}{(1+i_l)^n} = \frac{C_{loan}}{i_l}\left[1 - \left\{\frac{1}{(1+i_l)^{n_l}}\right\}\right] \tag{38}$$

Therefore, the cost of loan

$$C_{loan} = \frac{C_{Construction} \times i_l}{\left[1 - \left\{\frac{1}{(1+i_l)^{n_l}}\right\}\right]} \tag{39}$$

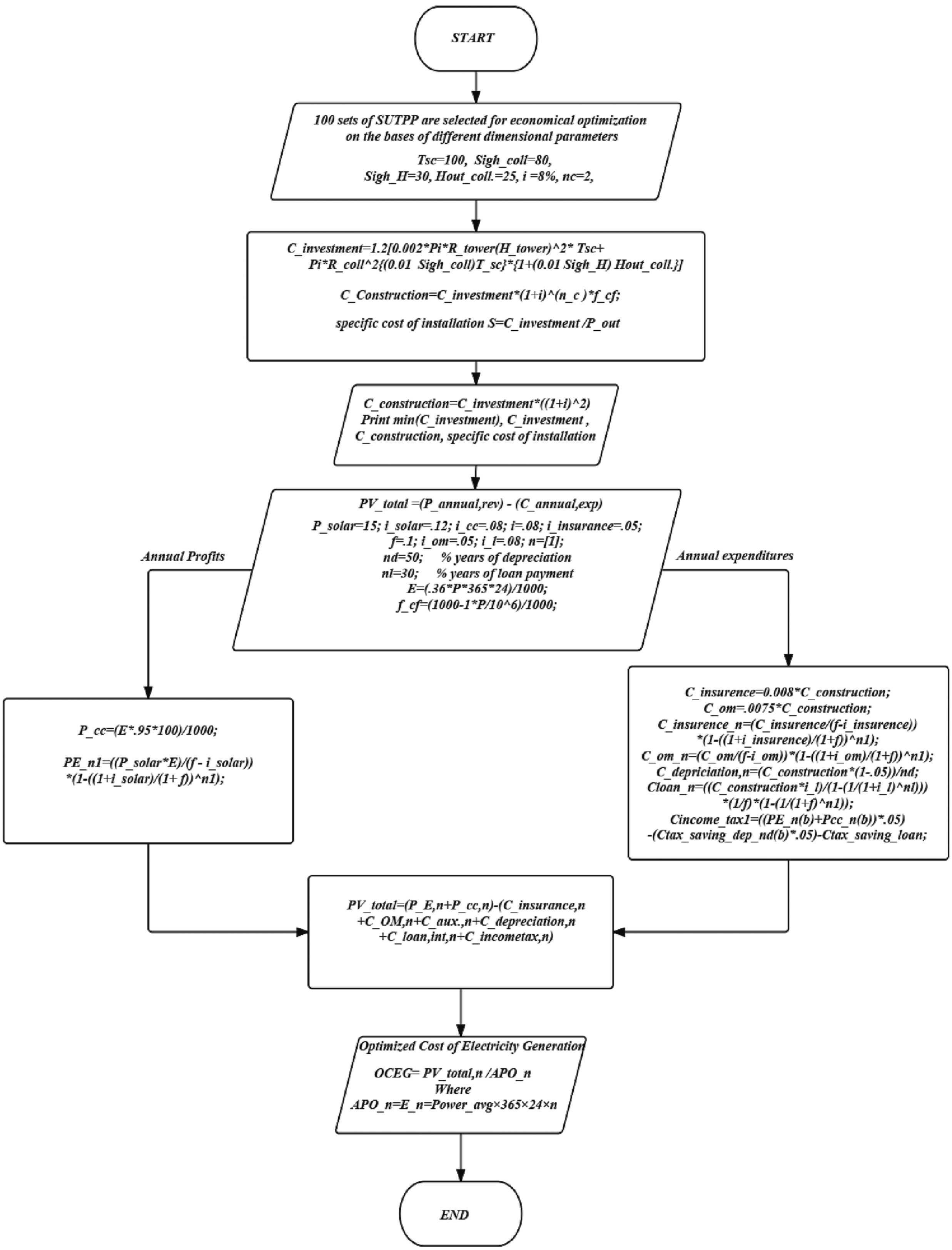


Fig. 1. Flow chart diagram for steps followed to find out the Economic Analysis of SUTPP.

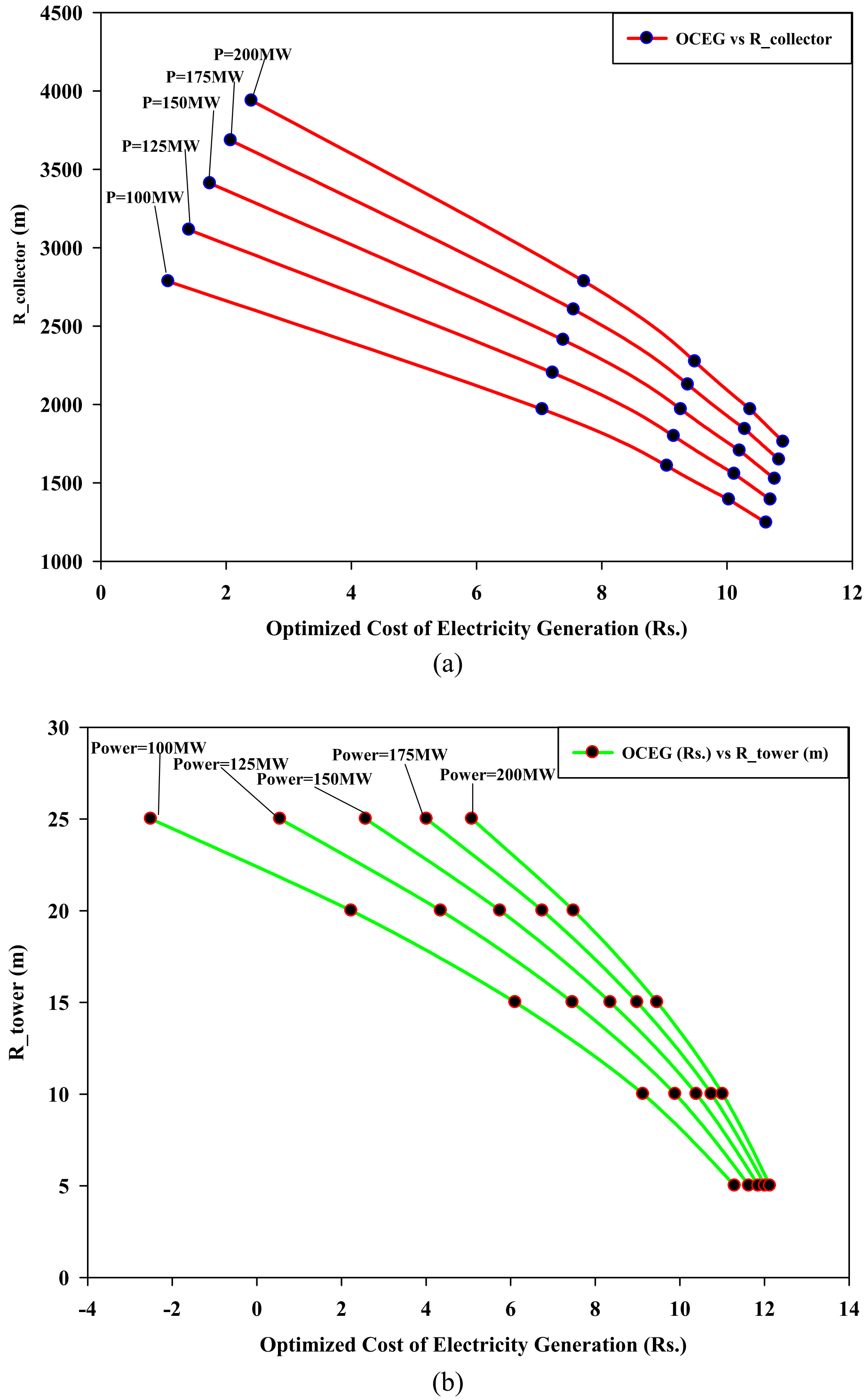


Fig. 2. (a) $R_{collector}$ (m) vs. OCEG (₹), (b) R_{tower} (m) vs. OCEG (₹) for different values of power output (MW).

The present value of the annual instalments of loan will be:

$$C_{loan,n} = \frac{C_{Construction} \times i_l}{\left[1 - \left\{\frac{1}{(1+i_l)^{n_l}}\right\}\right]} \sum_{n=1}^{n_l} \frac{1}{(1+f)^n} \tag{40}$$

By summing the progression

$$C_{loan,n} = \frac{C_{Construction} \times i_l}{\left[1 - \left\{\frac{1}{(1+i_l)^{n_l}}\right\}\right]} \frac{1}{f} \left\{1 - \frac{1}{(1+f)^{n_l}}\right\} \tag{41}$$

if $n \geq n_l$

And

$$C_{loan,n} = \frac{C_{Construction} \times i_l}{\left[1 - \left\{\frac{1}{(1+i_l)^{n_l}}\right\}\right]} \frac{1}{f} \left[1 - \frac{1}{(1+f)^n}\right] \tag{42}$$

if $1 \leq n < n_l$

This value of annual instalment of loan will add on expenditure analysis.

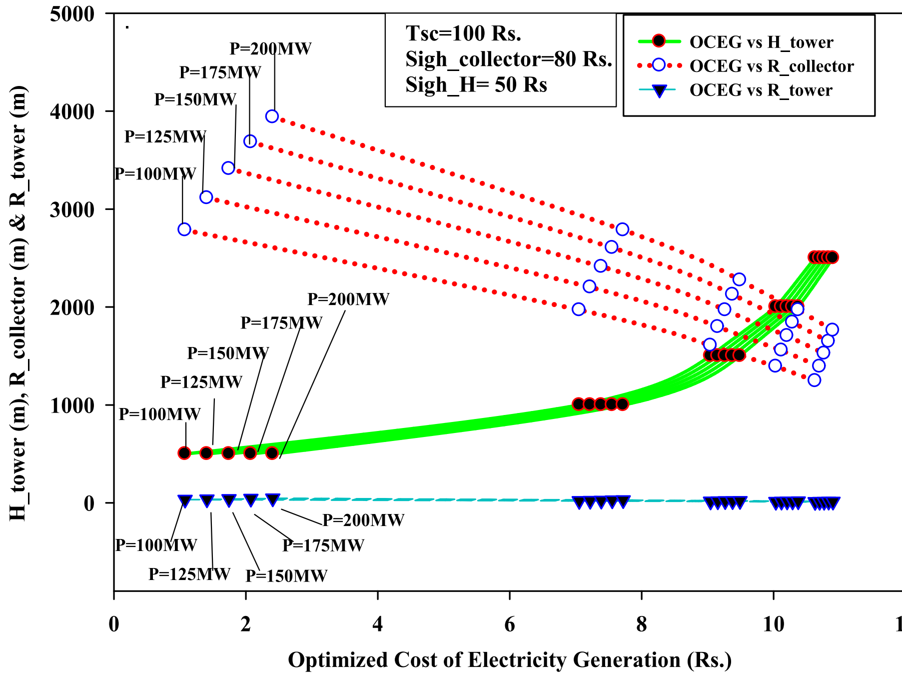


Fig. 3. OCEG (₹) vs. $R_{collector}$ (m), R_{tower} (m) and H_{tower} (m) for different values of power output (MW).

Every yearly repayment includes a loan repayment and interest payment, Cause of first component grows and second component shrinks. It can be shown that after n year, the interest component factor:

$$F_{taxsaving,loan} = \left[1 - \frac{(1+i_l)^{n-1} - 1}{(1+i_l)^{n_l} - 1}\right] C_{Construction} \times i_l \tag{43}$$

The present value of the annual savings, which will be:

$$C_{taxsaving,loan,n_l} = C_{Construction} \times i_l \times r_{tax} \sum_{n=1}^{n_l} \frac{1}{(1+f)^n}\left[1 - \frac{(1+i_l)^{n-1} - 1}{(1+i_l)^{n_l} - 1}\right] \tag{44}$$

By summing the progression

$$C_{t,l,n_l} = C_{Constrction} i_l r_{tax}\left[\frac{(1+i_l)^{n_l}}{(1+f)^{n_l}}\frac{1}{f}\left\{\frac{(1+i_l)^{n-1} - 1}{(1+i_l)^{n} - 1}\right\} - \frac{1}{\{(1+i_l)^{n_l} - 1\}}\frac{1}{(f - i_l)}\left\{1 - \left(\frac{1+i_l}{1+f}\right)^{n_l}\right\}\right] \tag{45}$$

if $n \geq n_l$
And

$$C_{t,l,n_l} = C_{Con.} i_l r_{tax}\left[\frac{(1+i_l)^{n_l}}{(1+f)^{n}}\frac{1}{f}\left\{\frac{(1+i_l)^{n} - 1}{(1+i_l)^{n_l} - 1}\right\} - \frac{1}{\{(1+i_l)^{n_l} - 1\}}\frac{1}{(f - i_l)}\left\{1 - \left(\frac{1+i_l}{1+f}\right)^{n}\right\}\right] \tag{46}$$

if $1 \leq n < n_l$
Where r_{tax} is the income tax rate and $C_{tax\ saving,\ loan,n_l} = C_{t,\ l,n_l}$.
This value of $C_{tax\ saving,\ loan,n_l}$ will add on the total amount of annual income tax with negative sign due to its nature of saving.

Effect of the annual income tax. The yearly income tax will be paid on the net value of revenue earned by selling energy and carbon credits, with loan repayment and depreciation as tax deductions. The formula below can be used to compute the yearly cost of income tax for n years:

$$C_{incometax,n} = \left\{\left(P_{E,n} + P_{cc,n}\right) r_{tax} - C_{taxsaving,dep,n_d} - C_{taxsaving,loan,n_l}\right\} \tag{47}$$

$$\begin{aligned} C_{incometax} = & \left[\frac{P_{solar}E}{f - i_{solar}}\left\{1 - \left(\frac{1+i_{solar}}{1+f}\right)^n\right\} + \frac{P_{cc,1}}{f - i_{cc}}\left\{1 - \left(\frac{1+i_{cc}}{1+f}\right)^n\right\}\right] r_{tax} \\ & - \left[\frac{C_{deperecation,n_d} \times r_{tax}}{f}\right]\left[1 - \left\{\frac{1}{(1+f)^{n_d}}\right\}\right] \\ & - C_{Constrction} i_l r_{tax}\left[\frac{(1+i_l)^{n_l}}{(1+f)^{n_l}}\frac{1}{f}\left\{\frac{(1+i_l)^{n-1} - 1}{(1+i_l)^{n_l} - 1}\right\} \right. \\ & \left. - \frac{1}{\{(1+i_l)^{n_l} - 1\}}\frac{1}{(f - i_l)}\left\{1 - \left(\frac{1+i_l}{1+f}\right)^{n_l}\right\}\right] \end{aligned} \tag{48}$$

where r_{tax} is the annual average income tax rate applicable to annual income.

In this model, it is assumed that due to relaxation in government policies for renewable energy-based solar power plants, a low value of income tax ($r_{tax} = 5\%$) is charged for the first 15 years of operation, and then it will be 10% for the total life cycle of the plant.

So
If $n \leq 15$ then.$r_{tax} = 05\%$; $r_{tax} = 0.05$
If $n > 15$ then.$r_{tax} = 10\%$; $r_{tax} = 0.10$

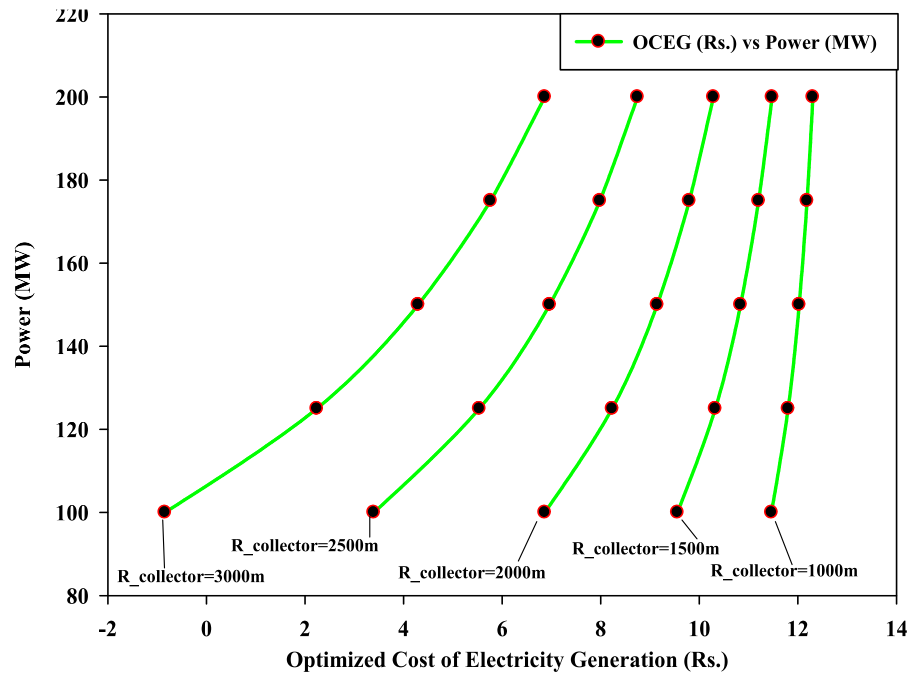
The present value of cumulative savings owing to tax deductions on depreciation over n years is also calculated. The tax computation equation also considers the present value of cumulative tax savings on loan interest over n years.

Equitation for present value (PV)

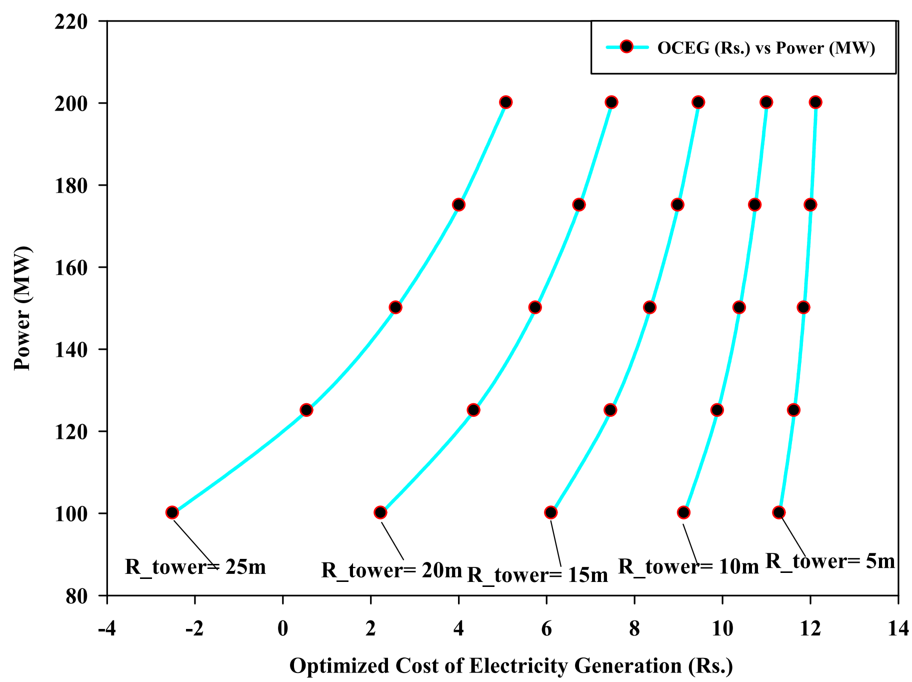
The present value (PV) of all costs in terms of equivalent cumulative saving over a period of n years is obtained by summing the present worth of all annual saving components and subtracting by all annual expenditure components.

$$PV_{total} = P_{annual,rev} - C_{annual,exp} \tag{49}$$

$$PV_{total} = \left(P_{E,n} + P_{cc,n}\right) - \left(C_{insurance,n} + (C_{OM,n} + C_{aux.,n}) + C_{depreciation,n} + C_{loan,int,n} + C_{incometax,n}\right) \tag{50}$$

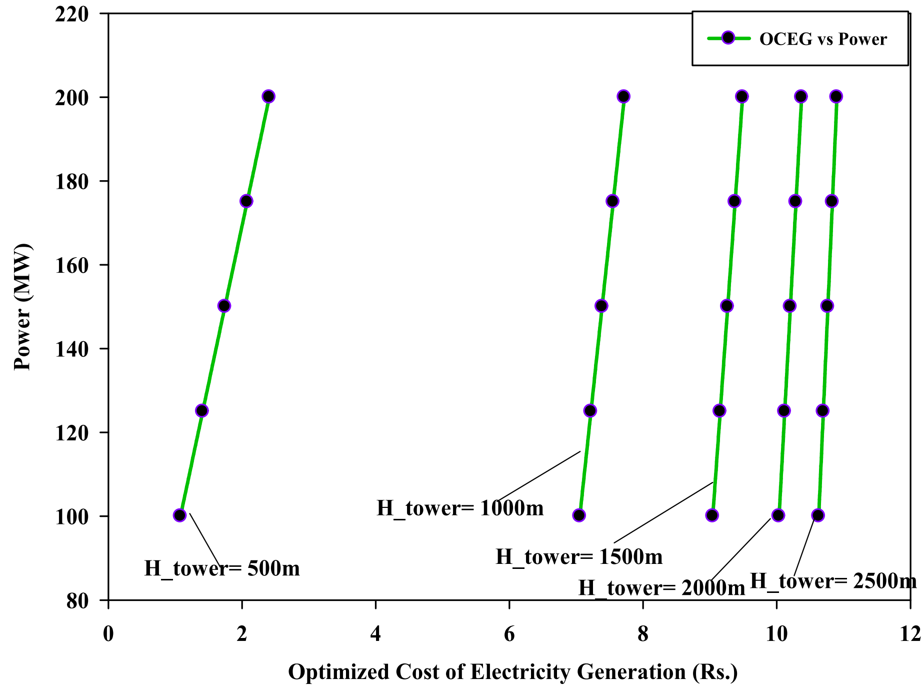


(a)



(b)

Fig. 4. Power (MW) vs. OCEG (₹) for different values of (a) $R_{collector}$ (m), (b) R_{tower} (m) and (c) H_{tower} (m).



(c)

Fig. 4. (*continued*).

$$PV_{total} = \left[\frac{P_{solar}E}{f - i_{solar}}\left\{1 - \left(\frac{1+i_{solar}}{1+f}\right)^{n}\right\} + \frac{P_{cc,1}}{f - i_{cc}}\left\{1 - \left(\frac{1+i_{cc}}{1+f}\right)^{n}\right\}\right] - \left[\frac{C_{insurance,1}}{f - i_{insurance}}\left\{1 - \left(\frac{1+i_{insurance}}{1+f}\right)^{n}\right\} + \frac{C_{OM,1}}{f - i_{OM}}\left\{1 - \left(\frac{1+i_{OM}}{1+f}\right)^{n}\right\} + \frac{C_{Construction} - 0.05C_{Construction}}{n_d} + \frac{C_{Construction} \times i_l}{\left[1 - \left\{\frac{1}{(1+i_l)^{n_l}}\right\}\right]}\frac{1}{f}\left\{1 - \frac{1}{(1+f)^{n_l}}\right\} + \left\langle\left[\frac{P_{solar}E}{f - i_{solar}}\left\{1 - \left(\frac{1+i_{solar}}{1+f}\right)^{n}\right\} + \frac{P_{cc,1}}{f - i_{cc}}\left\{1 - \left(\frac{1+i_{cc}}{1+f}\right)^{n}\right\}\right]r_{tax} - \frac{C_{deperecation,n_d} \times r_{tax}}{f}\left[1 - \left\{\frac{1}{(1+f)^{n_d}}\right\}\right] - C_{Constrction}i_l r_{tax}\left[\frac{(1+i_l)^{n_l}}{(1+f)^{n_l}}\frac{1}{f}\left\{\frac{(1+i_l)^{n-1} - 1}{(1+i_l)^{n_l} - 1}\right\} - \frac{1}{\{(1+i_l)^{n_l} - 1\}}\frac{1}{(f - i_l)}\left\{1 - \left(\frac{1+i_l}{1+f}\right)^{n_l}\right\}\right]\right\rangle\right] \tag{51}$$

If $n \le 15$ then.$r_{tax} = 05\%; r_{tax} = 0.05$
If $n > 15$ then.$r_{tax} = 10\%; r_{tax} = 0.10$

Optimized cost of electricity generation (OCEG)

$$OCEG = PV_{total}/APO_n \tag{52}$$

Where *OCEG* is the Optimized Cost of Electricity Generation charges in ₹/kWh, PV_{total} is the present value of all costs, i.e., the sum of the total plant Expenditures and revenue costs and APO is the sum of Annual power output for n year is defined as:

$$APO_n = E_n = Power_{avg} \times 365 \times 24kWhr \times n \tag{53}$$

$n = 30, 60, 90, 120$

Economical optimization of SUTPP

A detailed investigation is required for the selection of dimensions that must be optimized to find out the optimized result for a SUTPP. According to Schlaich et al. [1716], Kröger [63] Bernard [18] and Pretorius [11], it can be determined that plant power output has a direct relation with the collector area (radius) and tower height. If the power output of plant is fixed, then optimized value of collector radius and tower height can be calculated for a plant in terms of minimum plant installation cost per annual power output. The reference plant configuration has been discussed in Table 3.

Analyses for the SUTPP model for selecting dimensions, limits, and intervals for optimization

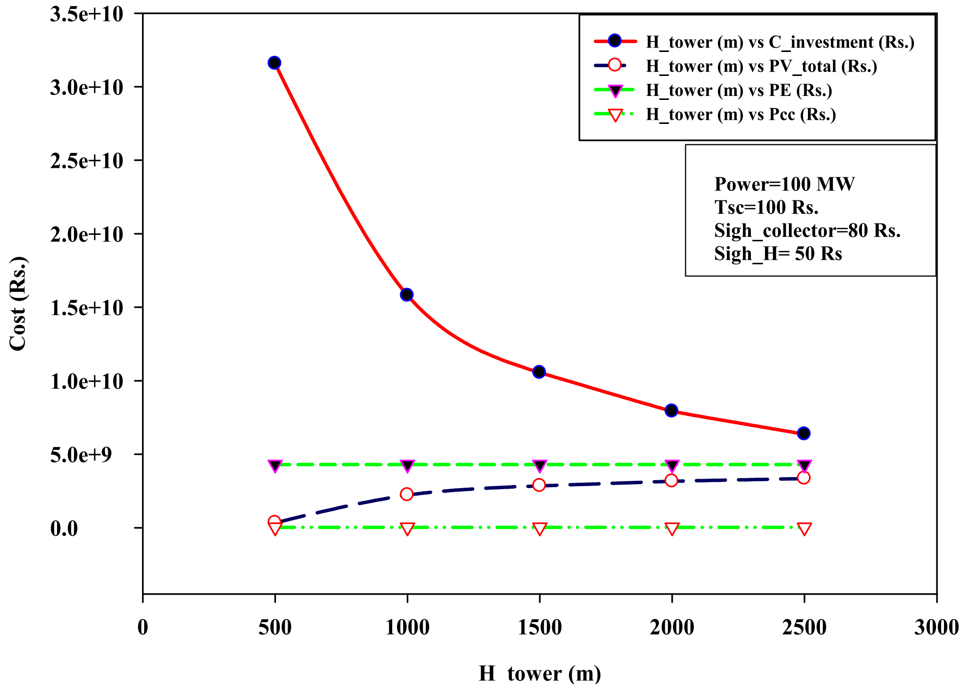
The most prominent solar updraft power plant dimensions were selected: collector radius ($R_{Collector}$), tower height (H_{Tower}) and tower radius (R_{Tower}) presented in Table 2, with dimensional limits and intervals.

As per Schlaich et al. [17,16], for a net power output, a direct relation between tower height (H_{Tower}) and collector radius ($R_{Collector}$) for a SUTPP can be presented as:

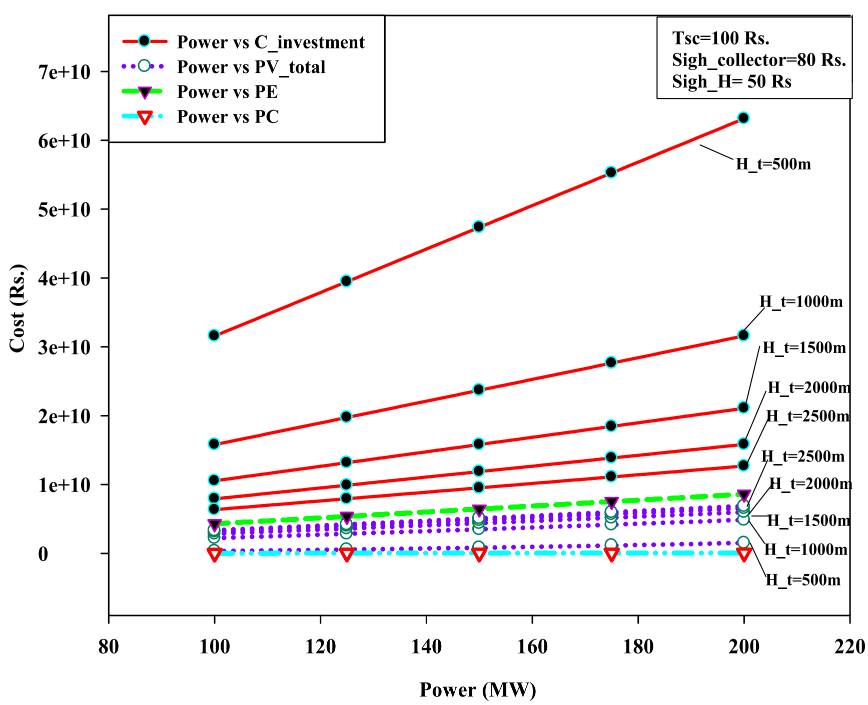
$$P = \frac{2}{3}\frac{\eta_{f,loss}\eta_{tg}\eta_{collector}gH_{tower}\pi R_{collector}{}^{2}I}{C_pT_a}$$

Here, g is the "gravity (m/s^2)", H_{tower} is the "tower height (m)", I is the solar irradiation (W/m^2), C_p is the "heat capacity of air (J/kgK)", and T_a is the "ambient-temperature (K)", $\eta_{collector}$ is the collector efficiency, $\eta_{f.loss}$ is the friction factor and η_{tg} is the turbine-generator efficiency.

For the given range of above parameters, a plant with a detailed specification is considered a reference plant with the specification given in Table 1. For a fixed power output, by fixing the range of parameters, and varying above-mentioned parameters, different sets can be calculated for tower height (H_{Tower}), tower radius (R_{Tower}) and collector radius ($R_{Collector}$) for the reference plant to develop various sets for a fixed power output.



(a)



(b)

Fig. 5. (a) H_{tower} vs. various cost parameters (₹) for 100 MW power output, (b) Power (MW) vs. $C_{investment}$, PE, P_{cc} and PV_{total} (Rs.) for different H_{tower} (m).

Parameter value

The cost and benefit of SUTPP are determined by the initial investment, inflation rate, life span, loan interest rate, income tax rate, operation and maintenance costs, etc. India's 10-year average inflation rate is 6% to 10%. This paper uses 8% of Schlaich et al. [64] and Fluri et al. [21,26]'s inflation rate. In India, 10-year loans have a 5% interest rate. Western nations provide lower-interest loans (around 2%) for solar photovoltaic (SPV) power. MNRE implements incentive measures to encourage India's solar power sector. It comprises national and state subsidies for solar equipment purchases, incentives for power sales, attractive financing rates, and income tax exemptions. Suppose the SUTPP can acquire a 30-year, 3%-interest loan.

This study assumes the SUTPP is taxed at 15%. In the past few years, solar-generation prices have dropped from ₹18 a kWh to about ₹7/kWh, while power from imported coal and domestically produced natural gas costs roughly ₹4.5/kWh and is rising. On-grid prices for solar photovoltaic and solar thermal power generation are 15/kW. This paper calculates SUTPP's NPV at ₹15/kWh. Schlaich et al. [64] estimated a bigger electrical output of 320 GWh/a compared to Bernard [18] 281 GWh/a, which is also this reference power plant output, and Fluri et al. [16]. The average of three projections is 255.2 GWh/a. Table 3 (Appendix A) shows the economic parameters and their values used in carrying out cost-benefit analysis of SUTPP.

Experimental methodology

In this work, firstly, a programme for objective functions is developed in MATLAB to solve the power output equations for different sets of tower height (H_{Tower}), tower radius (R_{Tower}) and collector radius ($R_{Collector}$) on the basis of the minimum cost of construction of SUTP plant. Secondly an another programme is also developed to find out the optimal values of tower height (H_{Tower}), tower radius (R_{Tower}) and collector radius ($R_{Collector}$) individually for varying power output, range between 100 MW and 200 MW by fixing other cost parameters. In next step a series of graphs and tables are developed which shows the relation and trends between economical parameters with power output (MW), tower height (H_{Tower}), tower radius (R_{Tower}) and collector radius ($R_{Collector}$). The flow charts for the programmes are shown in Fig. 1.

Results and discussion

The results obtained from the mathematical simulation of SUTPP have been reported and discussed here. The effect of parameters like collector radius ($R_{Collector}$), tower height (H_{Tower}) and tower radius (R_{Tower}) on the cost of construction and cost of power generation with optimum values of dimensional parameters for a suitable configuration of SUTPP is discussed in this section. The developed programme for optimization of power output, dimensions, and cost of electricity generation by SUTPP is applied to several plant configurations. In the next step, to find out the effect of construction cost factors like T_{sc}, ψ_{coll} and ψ_{h} and cost of electricity generation for fixed power output, the values of T_{sc}, ψ_{coll} and ψ_{h} are varies in objective function. Optimal solutions are presented in terms of graphs and tables for the various configurations of the SUTPP.

Research summary

Based on 100–200 MW power plant simulations and calculations, the SUTPP was economically optimised. Multiple computer simulations for different plant characteristics are compared to the cost of each simulated plant. The optimization technique only examined the most significant plant dimensions, namely the collector radius ($R_{\mathrm{Collector}}$), tower height (H_{Tower}), and tower radius (R_{Tower}). These ideal plant designs provide optimised cost of electricity generation (OCEG) for multiple power plants.

By the results, it can be observed that the value of the cost of construction of a SUTPP per MW lies between ₹4.5cr. to ₹12cr., which indicates that a large scale SUTPP can be installed economically. The values of OCEG for different sets of SUTPP power plants vary between ₹9.16 to ₹10.57. These optimized values of electricity generation indicate that a large scale SUTPP can be economically operated and compete with other kinds of power plants.

Comparison of SUTPP with solar photovoltaic and wind energy

The cost-effectiveness and economic feasibility of large-scale SUTPP compared to other renewable energy technologies such as solar photovoltaic and wind energy depends on a variety of factors.

The major contributing factor is the geographic location and the amount of solar energy available. SUTPP require large areas of land to function effectively and efficiently, whereas solar photovoltaic and wind energy may require less space and can be modified as per land availability. The land cost for large-scale solar updraft towers may be a significant factor in their cost-effectiveness and economic feasibility. The cost of the technology itself is another factor. Solar updraft towers may require more complex and expensive components than solar photovoltaic and wind energy. This can increase their cost-effectiveness and economic feasibility. The efficiency of the technology is also an important factor. Solar updraft towers are relatively inefficient compared to solar photovoltaic and wind energy. This reduces their cost-effectiveness and economic feasibility. Finally, the cost of operation and maintenance is another important factor. Solar updraft towers may require more frequent and expensive maintenance than solar photovoltaic and wind energy. This can increase their cost-effectiveness and economic feasibility.

In summary, the cost-effectiveness and economic feasibility of large-scale solar updraft tower power plants compared to other renewable energy technologies such as solar photovoltaic and wind energy is largely dependent on geographic location, the cost of the technology, its efficiency, and the cost of operation and maintenance.

A flow chart diagram for steps followed to find out the economic analysis of SUTPP on MATLAB has been shown in Fig. 1. 100 sets of SUTPP are selected for economical optimization on the basis of range of different dimensional parameters as per Table 1.

Effect of variation in construction cost factors on optimized cost of electricity generation (OCEG) of SUTPP

Values of building cost parameters can vary in objective function to determine their influence on plant layout and optimal cost of electricity generation for fixed power output. Graphs and tables show ideal SUTPP layouts and combinations.

Cost of building a solar updraft tower power plant is an important component in OCEG (OCEG). OCEG will rise with building costs. Increased construction costs lead to higher capital expenditures, which raises operational and power generating costs. Higher capital and operational costs for the solar power facility drove up OCEG. Thus, a solar updraft tower's building cost affects its OCEG.

Fig. 2 shows the graph between $R_{collector}$ (m) and R_{tower} (m) vs. Optimized Cost of Electricity Generation (OCEG) for different values of power output (MW). While Fig. 3 shows the trends for OCEG vs. $R_{collector}$, R_{tower} and H_{tower} for different values of power output. As, the OCEG is a measure of the cost of producing electricity from a power plant. It is based on the total cost of all inputs, including fuel and other resources, labour, and capital, as well as all taxes and fees associated with the production of electricity. For a fixed power output OCEG is inversely proportional to $R_{collector}$ and R_{tower}, and obtained an optimum value between ₹9.16 to ₹10.57 for power plant ranged 100 MW to 200 MW. The effect of variation in OCEG on $R_{collector}$, R_{tower} and H_{tower} for different values of power output (MW) of SUTPP will depend on the specific plant design and the cost of inputs. Generally speaking, as OCEG increases, the cost of inputs will also increase, resulting in an increase in the size of the collector, the tower, and the height of the tower. This is because more resources will be required to produce the same amount of energy, leading to a larger physical footprint of the power plant. Additionally, higher OCEG may result in higher costs for maintenance and operation, which could also contribute to an increase in the size of the components, by these graphs one can easily find out minimum cost of electricity generation for different configuration of SUTPP for any desired power output.

Fig. 4 shows the graph between Power output (MW) vs. OCEG (₹) for different values of $R_{collector}$ (m), R_{tower} (m) and H_{tower} (m). The Power output of a SUTPP is directly proportional to the total energy generated by the SUTPP. As the Power output (MW) increases, the total energy generated by the solar updraft tower also increases, thus increasing the OCEG.

The parameters $R_{collector}$, R_{tower} and H_{tower} also affect the OCEG. Increasing the $\mathrm{R}_{\mathrm{collector}}$ increases the area of the collector, which increases the amount of solar energy absorbed by the collector, thus increasing the Power output and the OCEG. Similarly, increasing the R_{tower} and H_{tower} increases the height of the tower, which increases the air velocity inside the tower and thus increases the Power output and the OCEG. In conclusion, increasing the Power output and the parameters $R_{collector}$, R_{tower} and H_{tower} of a SUTPP increases the OCEG.

Fig. 5 explain the relationship between H_{tower} vs. various cost parameters for 100 MW power output and Power vs. $C_{investment}$, *PE, Pcc* and PV_{total} for different H_{tower}. H_{tower} is a measure of the height of the solar updraft tower in the power plant. The higher the tower, the more efficient the power plant will be. Therefore, the higher the H_{tower}, the lower the various cost parameters for 100 MW power output, such as Capital Investment ($C_{investment}$), Power Purchase Price (PE), Plant Capital Cost (Pcc) and Total Present Value (PV_{total}). Conversely, the lower the H_{tower}, the higher the cost parameters for 100 MW power output. This is because higher towers allow for a greater air flow, which increases the efficiency of the system, resulting in lower cost parameters.

Conclusion

The economic analysis of a large-scale solar updraft tower power station shows that SUTPP can be consider as a viable energy source, as the cost of electricity produced by the SUTPP is little higher and can be competitive with subsidies with other renewable energy sources, as SUTPP may cut emissions, generate employment, and boost energy security of the region. At constant power output, OCEG obtained an optimum value in-between ₹9.16 to ₹10.57 for power plant ranged 100 MW to 200 MW. The value of OCEG largely depends on $R_{collector}$, R_{tower} and H_{tower} for different values of power output (MW) of SUTPP for a specific plant design and the cost of inputs. The results also show that the cost of construction of a SUTPP largely depend on $R_{collector}$, R_{tower} and H_{tower} values and can lies between ₹4.5cr. to ₹12cr. per MW, which indicates that with proper government supports and subsidies a large scale SUTPP can be installed economically. According to the study. Although the optimum values of OCEG came for larger values $R_{collector}$, R_{tower} and H_{tower}, which also create constructional and operational challenge of SUTPP.

This approach will help designers optimise plant layouts for electricity output. In this study, the influence of construction cost factors is also highlighted, so an estimated SUTPP cost may be found during design and development. This paper provides statistics on optimised energy generating costs, which may be used to determine SUTPP's economic viability. In this study, a thorough objective function is constructed to compute the optimum cost of energy generation, comprising elements such as building cost, time, and income and expenditure analysis. The revenue and expenditure analysis also includes power sales, carbon credit sales, loans, insurance, operation and maintenance costs, taxes, depreciations, and income tax.

SUTPP's tower cold influx wasn't considered during optimization. The cold may halt SUTPP. This task requires updating the optimal plant setup objective function. Several plant simulations exhibit cold infiltration. This study doesn't address wind speed, temperature lapse rates, thermal conductivity, or nocturnal temperature inversions. Results show that dominating ambient winds and night-time temperature changes at the reference site can reduce plant production by 10% compared to a plant with no wind all year. Double-glazed collector roofs can boost plant performance in the full-day plant model.

For further study, a potential future scope of modified performance parameters can further accurately modify the SUTPP's power output estimate. In this study, collector radius ($R_{Collector}$), tower height (H_{Tower}), and tower radius (R_{Tower}) for various power outputs are studied, while other aspects also affect SUTPP power output and performance. A comparable region may be studied to determine the influence of these characteristics on SUTPP power output and performance. Thermal insulation and double glazing on SUTPP's collector roof affect plant efficiency and financial feasibility. Re-examining SUTPP cost factors can improve OCEG per-site estimations, while calculating SUTPP power selling prices based on the minimum acceptable rate of return (MARR) may be another potential work for the future.

CRediT authorship contribution statement

Varun Pratap Singh: Data curation, Formal analysis, Funding acquisition, Methodology, Validation, Investigation, Resources, Software, Visualization, Writing – original draft. **Siddharth Jain:** Conceptualization, Supervision, Project administration, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Further reading

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