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Research paper

Adaptable pathway to net zero carbon: A case study for Techno-Economic & Environmental assessment of Rooftop Solar PV System

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ABSTRACT

Several countries have a critical need to enhance their electricity production to satisfy the tremendously increasing energy demand and to minimize the black outs. Due to scarcity of fossil fuels and degrading environment, rooftop Solar Photovoltaic (SPV) can be a suitable renewable alternative of green and clean energy. In this paper, due to the techno-economic, environmental and social benefits of Solar PV, the modelling and planning of a solar PV plant to fulfil the energy demand of an academic building is carried out. The analysis is done including all the financial and environmental aspects considering recent market prices and future price escalation. A Modified Greedy Search based optimal planning of the SPV to minimize grid dependence considering load variation pattern with its assessment analysis for an academic building is proposed in this research work. The various financial parameters that affect the feasibility of Solar PV plant i.e., energy payback period, grid dependency, rate of investment return, economic payback period, rate of escalation with actual cost of electricity, annual maintenance cost, depreciation and taxation are considered and evaluated. The environmental factors related to the generation from Solar PV i.e., CO_2 emission reduction and carbon credit are also included in analysis. The results obtained for the proposed Solar PV plant shows that the energy payback period is 8 years and IRR with depreciation and taxation is 21% (approx.) with net CO_2 mitigation of 1199 tCO_2 during the useful life span (25 years) of the plant.

1. Introduction

Presently, the era of electricity generation is becoming more prone for the use of renewable technologies. Due to the scarcity of fossil fuels, concentration of fuel reserves and continuous price hike of electricity, the world is facing the energy security concerns. India, one of the largest economies in the world with a fast-growing population, demands higher energy security in order to achieve sustainable economic growth. The country's per capita electricity consumption has increased from 15.6 kWh in 1950–51 to 1208 kWh in 2019–20 (Prabhu et al., 2021). The Indian Govt. intends to have 100 GW generations from the Solar Photovoltaic (SPV), including 40 GW from the rooftop plants (Ministry of New and Renewable Energy, 2022). India is nurturing an ambitious renewable energy elevation project for achieving a target of 175 GW of renewable power by 2022, which is targeted to reach to 450 GW by 2030 (Ministry of New and Renewable Energy, 2022).

The solar energy is a great alternative for power generation and must be utilized to its maximum, where yearlong solar radiation is available abundantly. Being the less efficient, it becomes necessary to identify the condition where the SPV system will be more efficient through a real time techno-economic analysis (Gielen et al., 2019b). Further, the energy needed for production and installation, must be identified for the exact evaluation of energy payback period. A review on the application of Particle Swarm Optimization in order to improve the performance of Solar Photovoltaic (SPV) system and to identify the gap for future research is represented in Elsheikh and Abd Elaziz (2019). The amount of sunlight that strikes the SPV module's surface determines the SPV module's power output (Wu et al., 2016). An idea to develop

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Nomenclature

CF	Cost Factor for one carbon credit
CTAE	College of Technology and Engineering
CUF	Capacity Utilization Factor
DOD	Depth of Discharge
E_D	Energy Demand
E_{R_PV}	Energy required from PV module
EPBT	Energy Payback Time
EF	Emission Factor
EPF	Electricity Production Factor
GHG	Green House Gas
I_d	Daily Solar Irradiance
I_{std}	Standard Solar Irradiance
IRR	Rate of Investment Return
kW_P	Kilo watt Peak
kWp_PV	Watt peak rating for PV module
LCCE	Life Cycle Conversion Efficiency
LCF	Loss Correction Factor
MGSA	Modified Greedy Search Algorithm
MPPT	Maximum Power Point Tracking
One_CC	One Carbon Credit
PGF	Panel Generation Factor
P_A	Annual electricity gen. in primary energy
P_{EOL}	Energy demand for end-of-life management
P_{INST}	Primary energy demand to installation
P_L	Plant life
P_{MAT}	Primary energy demand to produce materials
P_{MF}	Primary energy demand to manufacture
P_{SOL}	Solar energy of plant
P_{TEE}	Total embodied energy of plant
P_{TRANS}	Energy needed for transportation of goods
PV_output	PV module Peak rated Power
SCF	Size Correction Factor
V_{OC_INV}	Voltage across the inverter's open circuit
V_{OC_PV}	Solar PV Open circuit voltage
V_{IN_MAX}	Max. voltage to inverter at input terminal
$\eta_{BATTERY}$	Efficiency of battery

an environment friendly solar PV plant was proposed in Chen et al. (2012) to sustain the earth's life cycle. This paper also discussed the problems associated with the large PV plants and also the waste produced in the development of such huge plants. In Tamer et al. (2013), a study has been carried out regarding the optimal size selection of PV system and the results shows that the optimization of PV system strongly depends on the meteorological variables such as solar energy, ambient temperature and wind speed. This article considered the hybrid solar PV system with wind and diesel generator and evaluate the performance using Artificial Intelligence technique. A case study on Gambia to evaluate the feasibility between crystalline Si (c-Si) and thin film (Cd–Te) modules on the basis of net present value and Rate of Investment Return (IRR) was carried out in Samba et al. (2014). Based on technical and economic assessments of the c-Si and Cd–Te PV power plants, the Cd–Te PV power plant presented the reasonable technology for rural electrification in The Gambia. Similar case study (Sarah et al., 2014) having two 2.4 kWp grid-connected SPV systems installed at different locations i.e. Tepic and TemixcoMorelos concluded that the TemixcoMorelos PV system supplied nearly 90% of electrical energy need for the house and identifies grid-connected PV in the urban and suburban areas or stand-alone PV systems for the remote agricultural communities in Mexico is feasible for both the cases. In Soni and Gakkhar (2014), the parameters required installing the solar PV and the concentrating solar power plant are identified and discussed. A comparative life cycle assessment analysis for an old installed PV plant as compared to the newly installed plant having maximum potential is done in Sharma and Tiwari (2013). The same environmental conditions were considered during the analysis. In Tiwari et al. (2009a), energy metrics (energy payback time, electricity production factor and life cycle conversion efficiency) of hybrid photovoltaic (PV) modules were analysed and presented for the composite climate of New Delhi, India. This paper utilized the embodied energy and annual energy output to enhance the energy metrics. A review on life cycle assessment from silicon extraction to the final panel assembling is done in Sherwani et al. (2010). This paper considers the life cycle assessment for amorphous, mono-crystalline, poly-crystalline and other most prominent and advanced technology. A study on the life cycle assessment of PV systems (Kannan et al., 2006) used EPBT as an indicator for primary energy use, lifecycle cost analysis was performed for a distributed 2.7 kWp grid-connected mono-crystalline solar PV system operating in Singapore and concludes that GHG emission from electricity generation from the solar PV system is less than one-fourth that from an oil-fired steam turbine plant and one-half that from a gas-fired combined cycle plant, it shows great impact on the environment. A review study about different meta-heuristic approached has been presented by (Oliva et al., 2019). Such methods are applied to solar cell parameters estimation which may be beneficial to enhance the efficiency of such devices. This study provides different comparisons to define which of them is the best alternative for solar cells design. In Elsheikh et al. (2019), an attempt has been made to scrutinize the applications of artificial neural network (ANN) as an intelligent system-based method for optimizing and the prediction of different SE devices' performance, like solar collectors, solar assisted heat pumps, solar air and water heaters, photovoltaic/thermal (PV/T) systems, solar stills, solar cookers, and solar dryers. A method to find the global maximum power point was discussed in Agrawal et al. (2019).

In Behura et al. (2021), Behura discussed the design of the SPV plant to improve the energetic efficiency including the performance parameters as electric energy injected in the grid, energy conversion efficiency and reduction in CO_2/SO_2/NO emission. An analysis of the off-grid solar SPV plant considering the mathematical modelling has been presented for residential users in Jos, Nigeria (Akinsipe et al., 2021). The presented modelling claimed to be satisfying both technical and economic viability of the off-grid SPV system. In Barua et al. (2021), Barua discussed a grid connected micro-grid at residential level in Madhya Pradesh, India and uses HOMER Energy software for simulation and design. In Mokhtara et al. (2021), a study of the SPV system has been carried out to reduce the cost of energy, grid dependency and CO_2 emission for the University of Ouargla province in Algeria. This paper contributed in limiting the grid blackouts in university campus using the Ecotec, ArcGIS and HOMER software for analysis and optimization of the SPV plant. A techno-economic analysis of the hybrid solar PV/ fuel cell system was done in Ghenai et al. (2020) including the effect of dust and temperature with the objective to develop an off-grid hybrid system to reduce the cost of energy, Green House Gas (GHG) emission and fossil fuel consumption. In Goh et al. (2022), Daroń and Wilk (2021), Wood and Roelich (2019), Colak et al. (2020), Shorabeh et al. (2019), Khatib et al. (2013), Nguyen and Van (2021), Kumar et al. (2018), Raj et al. (2016), Khatri (2016), design and analysis of

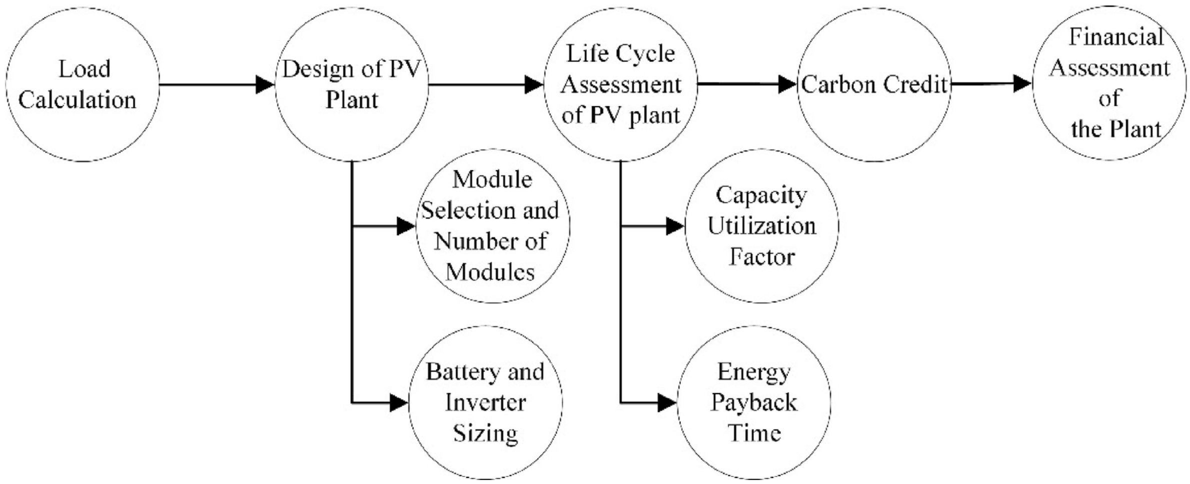

Fig. 1. Flow chart for Design and implementation of Solar PV system.

rooftop solar PV plants considering the technical, economic and environmental aspects was presented.

This article presents planning of the SPV system to minimize grid dependence considering load variation pattern with complete financial, technical and environmental analysis and assessment of the SPV plant at a building of Maharana Pratap University of Agriculture and Technology (MPUAT), Udaipur. The feasibility assessment for the plant site is also done, along with the energy payback time, capacity utilization factor, and life cycle conversion efficiency, among other factors. The main contributions of this paper are as follows:

(1) This paper created a conceptual and mathematical scheme for the site selection of solar power plant, considering technical, economical and environmental aspects.
(2) The Modified Greedy Search Algorithm is used for optimal site selection and it provides the new solutions for adequate decision making.
(3) This research work presents the design and analysis of the SPV with complete financial analysis related to real-time market pricing and future price escalation, depreciation & taxation, IRR.
(4) This paper includes the case study of a 42 kWp solar power plant including all financial, environmental (carbon credit and reduction in CO_2 emission) and technical factors.

The organization of the paper is as follows: Section 2 provides mathematical modelling for designing of the SPV plant. The framework for optimal site and size of plant is included in Section 3. In Section 4, data collection and energy audit of an academic building is presented followed by result and discussion in Section 5. The concluding statements are presented in Section 6.

2. Mathematical modelling

The design of a solar PV plant is proposed in this paper considering various factors (size of battery, cost of land, capacity of inverter, make of SPV modules, irradiation etc.) to get the optimal size of the plant. While designing the SPV plant, the site selection is the prime objective followed by the calculation of area required for the selected site (Mokhtara et al., 2021).

The parameters that affect the site selection are solar irradiance, shading effect (Partial or full), cost of land in that area, concentration of dust particles in the environment etc. Next, the load calculation is to be made to identify the capacity of the SPV plant followed by the estimation of the number of modules, inverter and battery size. The calculation of Energy Pay Back Time (EPBT) and Capacity Utilization Factor (CUF)is part of the SPV plant's lifetime evaluation. The financial analysis includes the cost of various equipment's like cost of module, battery and inverter cost, cost of operation and maintenance, IRR, depreciation etc. (Raj et al., 2016; Khatri, 2016). A brief process of analysis and design is shown in Fig. 1.

The cost of any government land is decided by the government and it is an important parameter while planning SPV system. Since, the area of the land required is dependent on the size of inverter and other arrangement of the SPV modules. Hence, the modelling for Solar Photovoltaic system, lifecycle assessment, carbon credit and financial benefits are presented in Table 1 and in Tables 3 to 5.

(A) Modelling of the Solar PV system

The SPV systems modelling includes the calculation of plant capacity, panel generation factor, plant utilization factor, number of modules required, rating of inverter, area requirement, rating of batteries and designing of module circuit etc. (Khatri, 2016). The panel generation factor is an important factor in the design of the SPV plant installation which is expected to achieve an average Wh/day for every Wp of power on the panel and it varies across the site. The amount of electricity required from the SPV modules can be determined by the site's daily electrical energy consumption as well as the amount of energy required to compensate losses, which are estimated to be 30% for this case study. The total peak wattage rating for the SPV modules is required to be calculated to determine the size of the system. This depends on the required power of the modules and the radiation factor of the panel. The total number of modules required depends on the maximum rating of modules. The size of the inverter depends on the peak power requirement of the plant. The inverter should be 28%–32% larger than the overall peak rating needed. A 30% bigger size is considered here for analysis (Khatri, 2016). The size of battery should be big enough to power the equipment on overcast days. The basic meaning of module circuit is to identify the number of modules connected in series, input voltage of the inverter and count of arrays for the site.

(B) Modelling for Lifecycle Assessment

The lifecycle assessment modelling includes the calculation of energy payback period, electricity production factor and capacity utilization factor and lifecycle conversion efficiency. The Energy Payback Period is defined as the amount of time the SPV system must run in order to recoup its energy expenditure. The Electricity Production Factor is the ratio of the annual electricity generation to the total input energy and it shows overall

Table 1
Modelling of the SPV system (Khatri, 2016).

Parameter	Mathematical expression	Eq. No.
Panel Generation Factor	$PGF = \frac{I_d}{I_{std}}$	(1)
Energy needed from the PV module	$E_{R\_PV} = E_D * LCF$	(2)
Rating of the SPV module	$kW_{P\_PV} = \frac{E_{R\_PV}}{PGF}$	(3)
No. of modules required	$= \frac{kW_{P\_PV}}{PV\_output}$	(4)
Rating of Inverter	$= kW_{P\_PV} * SCF$	(5)
Module circuit	$Size_{ARRAY} = \frac{V_{OC\_INV}}{V_{OC\_PV}}$ $V_{IN\_MAX} = V_{MAX\_PV} * Module_{SERIES}$ $No.\_of\_array = \frac{No.\_of\_Modules}{Size_{ARRAY}}$	(6)
Battery Sizing	$Battery\_Ah\_req = \frac{Wh\_total*Autonomy\_days}{V_{BATTERY\_NOMINAL}*(1-DOD)*\eta_{BATTERY}}$ $No.\_of\_Batteries = \frac{Battery\_Ah\_req}{One\_Battery\_capacity}$	(7)

performance of the SPV module electricity production factor is reciprocal of energy payback time. The Capacity Utilization Factor factories the ratio of annual electricity generation by the SPV plant to the equivalent energy output at its rated capacity over the yearly period. The Life cycle conversion efficiency is defined as the net energy efficiency of a photovoltaic system to solar energy (radiation) over the useful life of the photovoltaic system.

(C) Modelling of Carbon Credit

The modelling of carbon credit includes the estimation of CO_2 emission, mitigation, net mitigation and carbon credit. The main source of carbon emissions is the burning of organic materials. The CO_2 mitigation is the amount of CO_2 that will be reduced by generating electricity from solar plant which would otherwise be released by thermal power plant. The net CO_2 mitigation is described as difference between the whole lifetime of CO_2 emissions and reductions for the planned SPV plant. Carbon credits are given out in exchange for lowering greenhouse gas emissions. One carbon credit is gained for every ton of CO_2 (tCO_2e) emission that is reduced.

(D) Financial Assessment Modelling for the plant

The financial modelling includes the various cost such as cost of module, batteries, inverters, miscellaneous cost and land cost. The cost of any government land is decided by the government and it is an important parameter while planning the SPV system (Nguyen and Van, 2021). The worldwide module cost is reducing continuously and is now approximately \$0.33/Wp in India (polycrystalline SPV module pricing) (Khatri, 2016). It is estimated as the multiplication of cost of one inverter with the number of inverters. The cost of batteries is estimated by multiplying the no. of batteries with the cost of one set of batteries with rack. The miscellaneous cost includes the operation and maintenance cost, installation cost, electrical cable cost, etc.

3. Modified greedy search based algorithm for optimal site selection for the solar pv plant

This research assesses the economic, technical, environmental and social factors of the study region to maximize the benefits from the SPV plant. A precise approach is developed for the optimal site selection. The Fig. 2 proposes the process of site selection for the construction of the SPV plant. The site selection is done by Modified Greedy Search Algorithm (MGSA) to get the accurate size and location for the plant. This method is used for solving optimization problems. This approach is the simplest and straightforward method to find the optimal solution. As compared to the other heuristic optimization algorithms, the MGSA is fast to approach at global optimal solution. In comparison to the Greedy Search Algorithm, this MGSA go back at the initial stage and repeat the steps till the optimal solution achieve to get the global optimal solution. The main function of this approach is that the decision is taken on the basis of the currently available information. Some steps are described below.

(1) Develop a model for site selection, considering various technical, economic, environmental and social factors including constraints for potential site selection.
(2) Collect and evaluate relevant data for each site in continuation to the site selection.
(3) Arrange the sites considering the benefits as compared to the other sites.

This algorithm explores all the possibilities for site and size. Thereafter, evaluate them step-by-step to provide the optimal result as per the objective function. This strategy would enhance the accuracy and reliability of site selection process. A brief comparison between various approaches to identify the optimal site for solar PV plant is represented in Table 2.

4. Data collection and energy audit

A detailed survey has been made for data collection including the various parameters (irradiance, shadow effect, total number of sun days, land cost, dust particles in environment etc.). In Figs. 3 and 4, a satellite picture of the campus with its sun path, illustrates the land availability adjacent the proposed location. A detailed energy audit of the campus has been carried out to identify the connected load. The detail of different equipment's, their wattage and hour of operation are included for the most suitable location is shown in Tables 6 to 9. Further, the average monthly solar radiation data of Udaipur (Rajasthan, India) is represented in Table 10. The city receives an annual average solar irradiance as 5.18 kWh/m^2/day. The sky remains clean and sunny during the most of the days in the city. The number of sun days is considered 300 for this study. For the financial assessment of the plant, a 3% of electricity price escalation per year is consider with escalation of 5% in operation and maintenance cost. The power generation degradation is considered 2.50% for the first year and 0.7% for succeeding years.

5. Results and discussion

The optimal location proposed by the algorithm is the library building in the campus. Further, assessment result shows that total, 165 units (kWh) per day will be required from the SPV system to satisfy the energy demand of the most suitable building (Library) of the campus. The SPV system is designed for this building as per the output of the algorithm. The SPV plant of 42 kWp capacity is obtained for the building to meet its daily electricity requirement. A polycrystalline make 330 W solar module

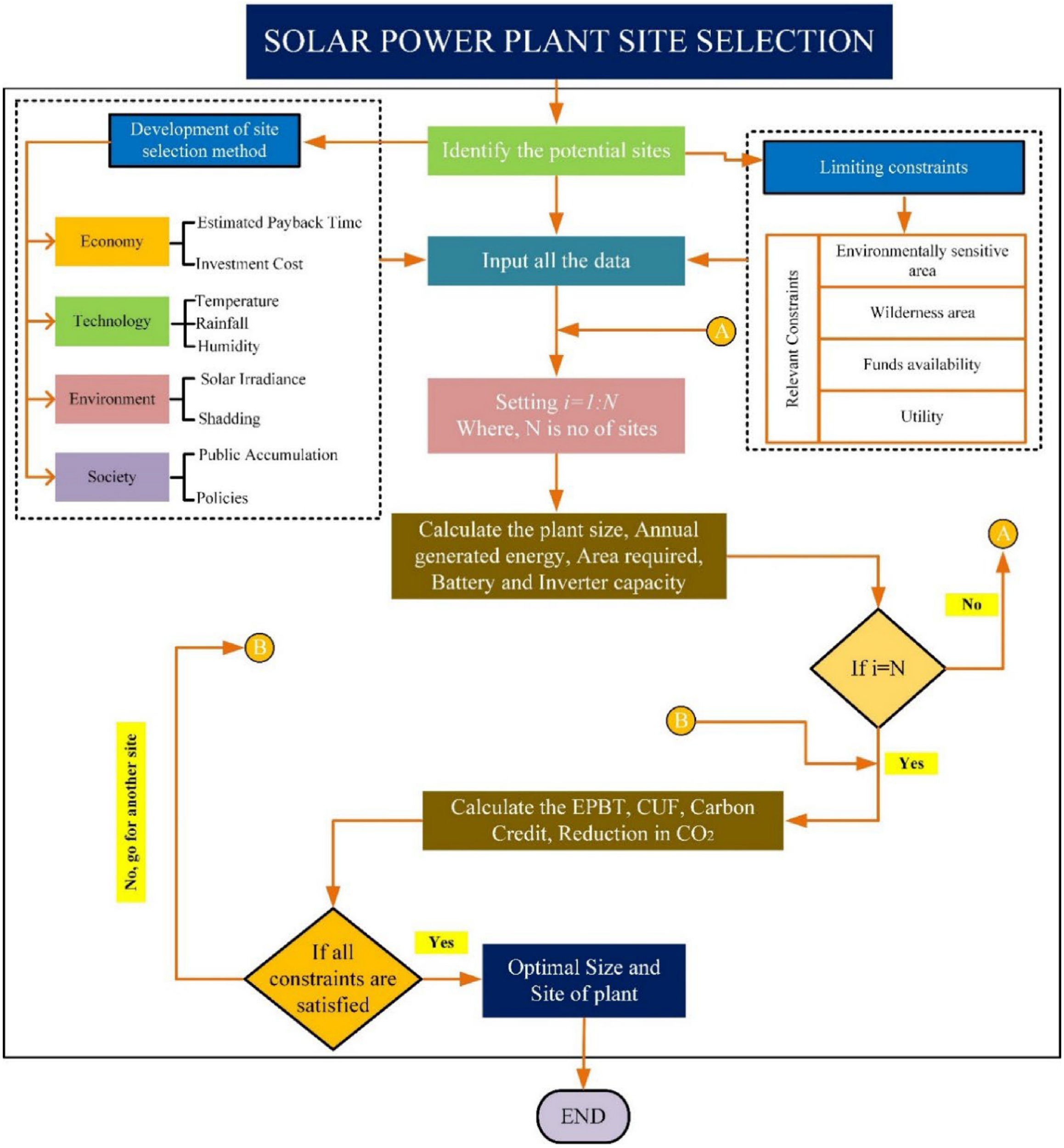

Fig. 2. Solar PV plant site selection framework using Modified Greedy Search Algorithm.

Table 2
Benefits and shortcomings of several site selection approaches (Elsheikh and Abd Elaziz, 2019; Elsheikh et al., 2019; Kutlu Gündoğdu and Kahraman, 2020; Ulutaş et al., 2020; Solangi et al., 2019).

S. No.	Methods	Benefits	Shortcomings
1	Particle Swarm Optimization	Provides global optimal solution for optimal site and size selection.	Deep understanding of all the parameters and other alternatives is must.
2	Artificial Neural Network Approach	Efficient forecasting approach.	Weights and number of neurons in hidden layer are required to be optimize.
3	Choose by Advantage Method	Cost is taken as an individual factor in this method. It chooses the parameters on the basis of benefits on choosing.	Complete idea about the alternatives is needed to optimize the site.
4	VIKOR	It is based on the principle of compromised programming.	It needs initial weights.
5	MARCOS	Takes the ideal and nonideal solutions before the formation of solution matrix.	Its applicability in most of the area is not yet implemented.
6	TOPSIS	It allows to interpret the absolute evaluation of certain site alternatives	Its Euclidean distance does focus on the correlation of the attributes
7	PROMATHEE	It does not require the criteria to be proportionate	It does not provide a clear framework for assigning the weights
8	Modified Greedy Search Algorithm	Easy to implement and no deep knowledge of parameters requires.	May provide local solution in highly complex problems.

Table 3
Modelling for the lifecycle assessment (Khatri, 2016).

Parameter	Mathematical expression	Eq. No.
Energy Payback Time	$EPBT = \frac{P_{MAT}+P_{MF}+P_{TRANS}+P_{INST}+P_{EOL}}{P_A}$	(8)
Electricity Production Factor	$EPF = \frac{P_A}{P_{MAT}+P_{MF}+P_{TRANS}+P_{INST}+P_{EOL}}$	(9)
Capacity Utilization Factor	$CUF = \frac{AnnualenergygeneratedforeachkWpeak}{8760}$	(10)
Lifecycle Conversion Efficiency	$LCCE = \frac{P_A * P_L - P_{TEE}}{P_{SOL} * P_L}$	(11)

Table 4
Modelling for carbon credit (Khatri, 2016).

Parameter	Mathematical expression	Eq. No.
CO_2 Emission	$CO_2\_Emission = P_{TEE} * EF$	(12)
CO_2 Mitigation	$CO_2\_Mitigation = P_A * EF$	(13)
Net CO_2 Mitigation	$Net\_CO_2\_Mitigation = (CO_2\_Mitigation * P_L) - CO_2\_Emission$	(14)
Carbon Credits	$One\_CC = CF * reduction\_CO_2(inton)$	(15)

Table 5
Modelling for financial assessment (Khatri, 2016).

Parameter	Mathematical expression	Eq. No.
Cost of the SPV Module	$COST\_PV_{MODULE} = kW_P * 10^3 * COST\_1W_P$	(16)
Cost of Inverter	$COST\_INV = No.\_of\_INV * COST_{ONE\ INVERTER}$	(17)
Cost of Batteries	$COST\_BAT = No.\_of\_BAT * COST_{ONE\ BATTERY}$	(18)
Miscellaneous Cost	$Miscellaneous\_COST = 30\%(COST_{MODULEandINVERTER})$	(19)

Table 6
Ratings and operating hours of various equipment's in library.

S.No.	Name of equipment	Nos.	Rating (W)	Hours of operation	Energy required (kWh)
1.	UPS 1 kVA	5	900	2	9
2.	UPS 3 kVA	1	2700	2	5.4
3.	Fan + Table fan	70+2	60+70	10	21.7
4.	AC (window + split)	6	3385	8	40.752
5.	Cooler	7	200	4	5.6
6.	Exhaust fan	2	70	7	0.98
7.	CFL+LED	16+2	15+12	7+7	1.68+0.168
8.	Fluorescent lamp	118	40	7	33.04
9.	Incandescent lamp	3	100	2	0.6
10.	Computer	14	130	5	9.1
11.	Printer + Scanner	2+1	40+18	1+0.5	0.08+ 0.009
12.	CCTV camera	15	8	7	0.84
13.	DVR 16 channel	1	32	7	0.224
14.	TV	1	60	7	0.42
15.	Lamination machine	1	800	5	4
16.	Xerox machine	1	1656	1	1.656
17.	Water cooler	1	1550	7	10.85
18.	Refrigerator	1	300	7	2.1
19.	Heater	1	1944	1	1.944
20.	biometric machine	1	2	1	0.002
21.	Bell	1	1	0.5	0.0005
	Total				165.505 kWh

Table 7
Daily loading data for each section of library at ground floor during working hours (10 AM–5 PM).

S.No.	Area	kWh/Day	S.No.	Area	kWh/Day
1.	Library main hall	29.188	8.	Kitchen	4.380
2.	Library server room	13.403	9.	Male toilet	1.000
3.	Internet section room	8.846	10.	Female toilet	1.000
4.	Librarian room	4.682	11.	Photo copy room	2.236
5.	Not to be issue	33.755	12.	Store room	0.280
6.	General book bank	13.741	13.	Lobby	2.061
7.	SC/ST book bank	13.741		Total	132.313 kWh

is selected for the proposed site with a loss compensation factor of 1.3 (Khatri, 2016).

It was also looked at if using solar energy instead of a carbon-emitting fossil fuel-based thermal power plant would reduce CO_2

Fig. 3. Anon (2022a).

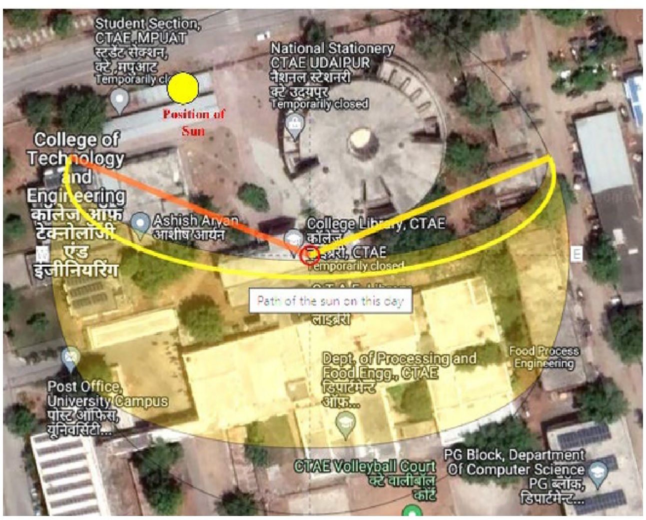

Fig. 4. Sun Path on 18 − 08 − 2022 for the campus (Suncalc, 2022).

Table 8
Daily loading data for each section of the library at first floor.

S.No.	Area	kWh/Day
1.	Reading room 1	10.176
2.	Reading room 2	6.496
3.	Corridor	1.160
Total		17.832kWh

Table 9
Total energy required per day at library.

S.No.	Area	kWh/Day
1.	Ground floor	132.313
2.	First floor	17.832
3.	Miscellaneous	15.360
	Total Energy Required	165.505

emissions. Additionally, the plant's embodied energy must be taken into account in order to provide an appropriate evaluation, which was used to calculate the plant's energy payback period, which is obtained as 8.34 years with a capacity utilization factor of 12.39%. The SPV technology employed earns the carbon credits

Table 10
Monthly average solar radiation data for Udaipur (Anon, 2022b).

Month	Average (kWh/m^2)	Month	Average (kWh/m^2)
January	4.04	July	5.01
February	4.78	August	4.72
March	5.52	September	5.30
April	6.39	October	5.05
May	6.69	November	4.36
June	6.27	December	3.86
Annual average = 5.18 (kWh/m^2/day)			

through reductions in CO_2 emissions and the plant is having potential of generating roughly 1199 carbon credits worth USD 19435.79 (Fthenakis and Raugei, 2017; Bansal and Ahmed, 2021; Barua et al., 2021; Gielen et al., 2019a; Makhija et al., 2021; Lupangu and Bansal, 2017; Agarwal et al., 2021; Tiwari et al., 2009b; Anon, 2021; Das et al., 2021; Messina et al., 2014; Sowe et al., 2014).

Table 11 includes the details of the SPV module. It is observed from the calculation that two types of inverters can be employed. One is PVI 28 TL and other is PVI 60TL. The land requirement and array configuration depend on the rating of inverter. Table 12 shows the parameters for both type of inverter. The battery specifications and total area required for plant is presented in Tables 13 and 14 for various inverter ratings. It can be summarized that the SPV plant with two inverters of rating 28 kW will be cost effective among all the other rating with 3 × 2 configuration of the PV array. Further, the cost of module, inverter, batteries, land and miscellaneous are discussed in Table 15. The lifecycle assessment of the proposed plant is included in Table 16 with the brief calculation of all the parameters.

As per the current market price scenario, at the time of installation, the solar company will charge USD 787.93 for each kW with the total project cost of USD 33093.31. The electricity rate is USD 0.112 per unit and an escalation of 3% per year is expected. The first-year generation will be 50,400 units. During 2nd year, the generation will be 49,140 units with reduction of 2.5%. In subsequent years, reduction in power generation is considered of 0.70%.

The service and maintenance charges are zero for first five years due to free servicing policy of many solar companies. Normally, after five years, there are 5% operation and maintenance charges of the total cost with 5% increment per year. To promote the solar share in industries and commercial place, accelerated depreciation (AD) policy by Govt. of India provides a tax shielding to the industries and commercial. As the industries and commercial comes under the 30% tax slab.

Therefore, an attractive tax saving in less time attracts the users for solar plant installation at their locations. In this plant, 40% depreciation will be claimed for 1st and 2nd year and 20% for the 3rd year. Because of this AD policy, tax saving of USD 3971.2 will be obtained for first two years and of USD 1985.59 in 3rd year. With the first-year generation, the total savings will be USD 5666.35. In addition of above, due to depreciation, the tax saving was USD 9928. Overall equity rate of investment return rate (IRR) after 1st year was USD 9637.552 and equity turnaround was USD 23,455.75. After four years of successful operation, in the 5th year, the plant will start to produce the benefit of an amount of USD 6052.78. The obtained rate of investment return will be 21% for this 42 kW plant. The detailed financial analysis and IRR calculation for 25 years (assumed lifetime of the plant) is shown below in Table 17.

Table 11
Specifications of the SPV module (Anon, 2022c).

Brand	Luminous	Module Height	991 mm
Model	LUM 24330	Short Circuit Current (I_{sc})	9.22 Amp
Panel Type	Polycrystalline	Voltage	24 V
Frame Material	Aluminum	Voltage at Max Power	38.03 V
Current at Max Power (Imp)	8.68 Amp	Open Circuit Voltage	45.53 V
Modules Width	1976 mm	Power	330 W
Warranty	25 Years	Application	Commercial Applications, Homes & Small Shops
Dimensions	1976 × 991 × 35 mm		

Table 12
Specification of 28 kW & 60 kW Inverter (Yaskawa solectria, 2022).

Parameters of inverter	PVI 28 TL	PVI 60 TL	Parameter of inverter	PVI 28 TL	PVI 60 TL
Absolute Maximum Input Voltage	1000 VDC	600 VDC	Strike Voltage	330 V	330 V
Maximum Power Input Voltage Range (MPPT)	500-800 VDC	312-500 VDC	Nominal Output Voltage	480 VAC, 3-Ph	480VAC, 3-Ph
Operating Voltage Range (MPPT)	240-950 VDC	296-500 VDC	Maximum Output Current	27.7 A	125 A
Maximum Operating Input Current	108 A	201 A	Efficiency	98.6%	98.8%
Maximum Available PV Current (I_{sc} × 1.25)	48 A	212 A	Standard Limited Warranty	10 Years	10 Years
Maximum PV Power (per MPPT)	19 kW	33 kW			

Table 13
Battery specifications (Anon, 2022d).

Brand	Trojan	Battery capacity	175 Ah
Model	J185E-AC 12 V Deep Cycle Battery	Battery Efficiency	90%
Nominal Voltage	48 V	Life of a Battery	4 years
Depth of Discharge	40%		

Table 14
Area requirement for solar module.

S. No.	Type of inverter	Size of array	Area in m^2
1.	Case 1 (PVI 60 kW)	3*3	414.96 m^2
2.	Case 1 (PVI 60 kW)	1*9	465.92 m^2
3.	Case 2 (PVI 28 kW)	2*3	430.76 m^2
4.	Case 2 (PVI 28 kW)	3*2	387.69 m^2

6. Conclusion

This paper has provided an in-depth assessment of a solar PV plant for library building in an academic premise employing Modified Greedy Search Algorithm. It examines the financial viability using real-time market prices of the solar PV module. The outcomes of the study are as follows:

(1) The optimal size of the SPV plant is 42 kWp capacity for library, which requires 128 modules of 330 Wp each. The land requirement is 387.69 m^2 to 465.92 m^2.
(2) The plant's anticipated energy payback period is 8.34 years, which is based on a life cycle conversion efficiency of 6.56%.
(3) The proposed photovoltaic plant has a CUF of around 12.39% in terms of capacity utilization.
(4) The carbon credits from the plant results as 1199 tCO_2 worth rupees USD 19,435.79 at the rate of USD 16.24 per ton.
(5) The rate of investment return may be 21% (approximately).

It can be depicted for the results that the financial feasibility of the solar PV plant can get affected by the real-time market pricing, rate of price escalation, rate of inflation and cost of land. Therefore, careful analysis of all these parameters must be done before installation of solar PV plant where cost of land has significant effect on the price of plant. The proposed work may enhance the solar energy usage to make more sustainable and pollution free environment. This study can be used to uncover flaws in energy policies and plans for governments or states attempting to cut GHG emissions and make this technology more appealing and financially viable.

The biggest shortcoming of this article is that it does not address the treatment of PV modules after a solar power plant's lifespan has expired. Future research will closely link the optimal site selection of solar power plants by considering waste recycling and other relevant factors related to the energy harvesting.

Consent for publication

All authors have read and agreed to the published version of the manuscript.

CRediT authorship contribution statement

Umesh Agarwal: Conceptualization, Methodology, Formal analysis, Writing – original draft. **Narendra Singh Rathore:** Validation, Writing – review & editing. **Naveen Jain:** Conceptualization, Formal analysis, Validation, Writing – original draft, Writing – review & editing. **Pawan Sharma:** Validation, Writing – review & editing. **Ramesh C. Bansal:** Validation, Writing – review & editing. **Mayur Chouhan:** Conceptualization, Methodology, Formal analysis, Writing – original draft. **Manoj Kumawat:** Validation, 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

No data was used for the research described in the article.

Table 15
Cost of module, inverter, batteries, miscellaneous and land for the PV plant.

S. No.	Particular	Condition	Cost (USD)	S. No.	Particular	Condition	Cost (USD)
1.	Module cost		13,860	6.	Miscellaneous cost	PVI 28 kW	5914.2
2.	Inverter cost	PVI 60 kW	4550	7.	Cost of land with various inverter configuration	PVI 60 kW(3*3)	180,416.30
3.	Inverter cost	PVI 28 kW	5854			PVI 60 kW(1*9)	193,338.16
4.	Batteries cost		9160.48			PVI 28 kW(2*3)	178,748.16
5.	Miscellaneous cost	PVI 60 kW	5523			PVI 28 kW(3*2)	160,875.84

USD 1.00 = 79.88 Rs. (Accessed 23.08.22) online.

Table 16
Lifecycle and environmental assessment of the proposed PV plant.

S. No.	Particular	Calculation	Value
1.	Energy demand	Ground floor + First floor + Miscellaneous (132.313+17.832+15.360 = 165.505 kWh/day)	165.505 kWh/day
2.	Panel Generation Factor (Avg.)	$PGF = \frac{5.18*10^3}{1000} = 5.18$ (kWh/m^2/day)	5.18 (kWh/m^2/day)
3.	Energy requirement from PV	$E_{R\_PV} = 165.505 * 1.3 = 215.1565$ kWh/day	215.1565 kWh/day
4.	Plant life	Standard	25 Years
5.	Peak capacity of plant	$kW_{P\_PV} = \frac{215.1565}{5.18} = 41.5360 \cong 42$ kW$_p$	42 kW$_p$
6.	Total no. of modules required	$= \frac{42*10^3}{330} = 127.27 = 128$	128
7.	Total Embodied Energy	Total area of module $*(P_{MAT} + P_{MF} + P_{TRANS} + P_{INST} + P_{EOL})$ = 250.65 m^2 * 1516.59 kWh/m^2	380.13 MWh
8.	First year Electricity Generated	165*300 (No. of clear sunny days in Udaipur)	50 MWh/yr.
9.	EPBT	$EPBT = \frac{380.13}{1139520/25} = 8.34$ years	8.34 year
10.	No. of batteries required	$Battery\_Ah\_req = \frac{(165.505*10^3)*1}{48*0.6*0.9} = 6385.22$ Ah $No.\_of\_Batteries = \frac{6385.22}{175} = 37$	37
11.	CUF	$CUF = \frac{\frac{1139520^*}{42}}{8760\times25} = 0.1239$	0.1239
12.	EPF	$EPF = \frac{1139.520/25}{380.13} = 0.1199$	0.1199
13.	LCCE	$LCCE = \frac{(1139520^*)-380.13*10^3}{462.70*10^3*25} = 0.0656$	0.0656
14.	CO_2 Emission from Embodied energy	$CO_2\_Emission = 380.13 * 10^3 * 1.58 = 601$ tons of CO_2	601 ton of CO_2
15.	Yearly average CO_2 mitigation	$CO_2\_Mitigation = 1139520/25 * 1.58 = 72$ tons of CO_2	72 ton of CO_2
16.	Net CO_2 mitigation	$Net\_CO_2\_Mitigation = (72 * 25) - 601 = 1374$ tons of CO_2	1199 ton of CO_2
17.	Carbon credits earned	$One\_CC = 16.21 * 1199$	USD 19435.79

Table 17
Financial analysis for 42 kWp solar power plant.

Power generation		Income (USD)		Expenses (USD)				Depreciation & taxation (USD)			IRR	
Years	Power generation units kWh	Power rate	Total savings	O & M expenses	Interest payment	Loan payment	Total expenses	Depreciation absorbed	Depreciation	Available tax shield	Equity IRR	Equity turn around
1	50400	0.1124	5666.35	0	0	0	0	40.00%	13237.32	3971.2	9637.552	−23455.75
2	49140	0.1157	5690.44	0	0	0	0	40.00%	13237.32	3971.2	9661.626	−13794.12
3	48796	0.1192	5820.115	0	0	0	0	20.00%	6618.662	1985.59	7805.722	−5988.407
4	48454	0.1228	5952.753	0	0	0	0	0.00%	0	0	5952.753	−35.65369
5	48115	0.1265	6088.420	0	0	0	0	0.00%	0	0	6088.421	6052.780
6	47778	0.1303	6227.184	1654.665	0	0	1654.665	0.00%	0	0	4572.519	10625.28
7	47444	0.1342	6369.099	1737.404	0	0	1737.404	0.00%	0	0	4631.695	15256.98
8	47112	0.1382	6514.245	1824.263	0	0	1824.263	0.00%	0	0	4689.982	19946.96
9	46782	0.1424	6662.703	1915.484	0	0	1915.484	0.00%	0	0	4747.22	24694.18
10	46455	0.1466	6814.555	2011.256	0	0	2011.256	0.00%	0	0	4803.299	29497.48
11	46129	0.1510	6969.853	2111.822	0	0	2111.822	0.00%	0	0	4858.032	34355.51
12	45807	0.1556	7128.692	2217.409	0	0	2217.409	0.00%	0	0	4911.283	39266.81
13	45486	0.1603	7291.153	2328.275	0	0	2328.275	0.00%	0	0	4962.879	44229.68
14	45168	0.1650	7457.331	2444.688	0	0	2444.688	0.00%	0	0	5012.63	49242.31
15	44851	0.1700	7627.278	2566.931	0	0	2566.931	0.00%	0	0	5060.347	54302.66
16	44537	0.1751	7801.104	2695.274	0	0	2695.274	0.00%	0	0	5105.83	59408.49
17	44226	0.1804	7978.887	2830.039	0	0	2830.039	0.00%	0	0	5148.849	64557.34
18	43916	0.1858	8160.724	2971.536	0	0	2971.536	0.00%	0	0	5189.188	69746.53
19	43609	0.1914	8346.707	3120.116	0	0	3120.116	0.00%	0	0	5226.592	74973.12
20	43303	0.1971	8536.932	3276.128	0	0	3276.128	0.00%	0	0	5260.805	80233.94
21	43000	0.2030	8731.493	3439.935	0	0	3439.935	0.00%	0	0	5291.558	85525.50
22	42699	0.2091	8930.483	3611.929	0	0	3611.929	0.00%	0	0	5318.554	90844.05
23	42400	0.2154	9134.011	3792.527	0	0	3792.527	0.00%	0	0	5341.484	96185.53
24	42104	0.2218	9342.170	3982.146	0	0	3982.146	0.00%	0	0	5360.024	101545.5
25	41809	0.2284	9555.082	4181.258	0	0	4181.258	0.00%	0	0	5373.825	106919.3

Economic Payback Period – 4 Years

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