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Overall efficiency enhancement and cost optimization of semitransparent photovoltaic thermal air collector

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A semitransparent photovoltaic-thermal (PV/T) air collector can produce electricity and heat simultaneously. To maximize the thermal and overall efficiency of the semitransparent PV/T air collector, its availability should be maximum; this can be determined through a Markov analysis. In this paper, a Markov model is developed to select an optimized number of semitransparent PV modules in service with five states and two states by considering two parameters, namely failure rate (λ) and repair rate (μ). Three artificial neural network (ANN) models are developed to obtain the minimum cost, minimum temperature, and maximum thermal efficiency of the semitransparent PV/T air collector by setting its type appropriately and optimizing the number of photovoltaic modules and cost. An attempt is also made to achieve maximum thermal and overall efficiency for the semitransparent PV/T air collector by using ANN after obtaining its minimum temperature and available solar radiation.

KEYWORDS
ANN, availability, photovoltaic-thermal (PV/T) air collector, semitransparent

1 | INTRODUCTION

Renewable energy resource is the most abundant resources and can have enormous potential with the appropriate technologies. Research related to photovoltaic (PV) technologies was mainly focused on the space industry, satellite industry, and space business owing to the high costs of solar cells. Since the 19th century, solar photovoltaic thermal (PV/T) collectors have been widely used commercially for the efficient conversion of solar energy into electricity and heat simultaneously to meet the future electricity and heat demands at a lower cost. After five decades of research and development, photovoltaic energy production is now growing rapidly across global markets.

The solar installed capacity of India has increased massively, and it reached 26 Gigawatts (GW) as of 30 September 2018, which means that PV is currently the most valuable renewable energy technology [1,2]. Large-scale PV plants, which are composed of several thousands of PV panels, should be developed with a nominal cost per watt. The design process of a large-scale PV plant can be performed by considering the system cost. The applications of the PV/T air collector have increased recently, and it is also advantageous to interface renewable energy sources with distributed power systems. Some researchers have developed a model for PV module electrical efficiency evaluation. They have considered a developed model with and without airflow as a function of climatic and design parameters. Researchers have also considered four different configurations of PV modules for an increment in electrical efficiency [3,4]. Recent advances, applications, and technologies for PV/T solar collectors, especially for air heating, were reviewed. They suggested that further research is required to improve efficiency, minimize cost, and resolve technical design issues of collectors [5]. In reference [6], it was suggested that PV/T systems can supply a major portion of domestic heating and cooling demands at a lower cost than that required by an equivalent PV-only system.

Different types of PV/T air collectors have been analyzed by researchers based on cost. They have compared the performance results of single pass and double-pass PV/T air collectors. The results indicated electrical efficiencies of 10% for the single-pass PV/T air collector and 12% for the double-pass PV/T air collector, as well as thermal efficiencies of 40% for the single-pass PV/T air collector and 45% for the double-pass PV/T air collector. Thus, they concluded that the efficiencies of the double-pass PV/T air collector are higher than those of the single-pass PV/T air collector [7]. Some researchers have evaluated different parameters, such as overall annual thermal energy and exergy gain and efficiency of different types of PV/T air collectors (glazed, unglazed, and conventional hybrid PV/T tiles air collectors), for the composite climate of Srinagar, India. They concluded that the instantaneous energy and exergy efficiency of PV/T air collectors varies between 55%–65% and 12%–15%, respectively [8,9]. A comparison of the different types of hybrid PV/T air collectors (glazed, unglazed, and conventional hybrid PV/T) by considering overall thermal energy and exergy gain, exergy efficiency, and carbon credit earned has been presented. The overall annual thermal energy and exergy gain of an unglazed hybrid PV/T air collector has been reported as higher than that of a glazed PV/T. They also concluded that the overall annual exergy efficiency of the unglazed and glazed hybrid PV/T tiles air collectors were higher than that for the conventional PV/T [10]. A hybrid solar PV/T collector was simulated by considering computational fluid dynamics with the ANSYS14 software, which indicates the heat transfer capabilities in the system [11].

The operation of the PV/T air collector is inherently dynamic in nature and very unpredictable. Therefore, the operational temperature cannot be predicted by the steady-state model. A researcher has developed an explicit dynamic model for a single-glazed flat-plate water-heating PV/T collector [12]. In [13], the outlet temperature and efficiency of a solar air heater were experimentally investigated by employing a jet plate on corrugated absorber plate. They found that thermal efficiency is enhanced by the proposed design owing to better heat transfer on the solar air heater, caused by the increased mass flow rate of air.

Reliability is the probability of successful operation within a specified time, whereas availability is the probability of the system being found in success states. Availability (or reliability) prediction is a necessary requirement when designing any PV system for prevention failure. Traditional availability/reliability prediction methods have been presented and the methodology used to collect and analyze PV system reliability data was also discussed [14–16]. Some researchers have studied the reliability or success state of grid-connected PV systems [17]. Researchers have developed and presented a photovoltaic module reliability model, based on field degradation studies of PV modules [18,19]. Researchers have presented a method for assessing the reliability of large-scale grid-connected photovoltaic systems. They have developed a model using experimental data, and the model was also applied to military data [20]. The reliability prediction model and different issues related to the reliability of the photovoltaic system and the electronic component have been explained [21–23].

Researchers have presented a methodology for symbolic steady-state availability evaluation with constant transition rates. This method is very efficient for a k-out-of-n: G-system when steady-state availability is evaluated repeatedly with several transition rates [24]. Authors have used this method for the availability evaluation of a semitransparent PV/T air collector with a five-state and two-state Markov model. The life-cycle of the PV/T air collector can be predicted accurately by using availability information. The semitransparent PV/T air collector performance parameters depend on environmental parameters such as ambient temperature, solar radiation, module configuration, module installation, cell temperature, and so on. Some researchers have presented a methodology for photovoltaic system availability estimation by using Petri networks. This methodology is useful for optimizing the performance of a PV system [25,26].

The Markov model is a computational model that allows us to model the system in terms of the operating parameters to assess the probability of availability/reliability. Researchers have presented Markov models to explain the stochastic behavior of the system. The presented methodology is used by researchers to determine the optimum size, for a given loss of load probability (LOLP), of a PV system. This PV system is used standalone [27,28]. Researchers have proposed an accurate practical methodology for solving complicated system reliability modeling problems. They have combined the concepts of Markov analysis and the approximation of the failure in their research [29]. The thermal design of an electronic-circuit layout has been presented to avoid hotspot issues on the circuit board for sensitivity and reliability analysis [30]. Researchers have reviewed the economics of solar power and provided empirical estimates of the solar market value. They have concluded that solar power is best utilized as a source of grid-connected electricity generation [31]. Many cost assessment schemes have been presented for different systems, such as the off-grid system and modular multilevel converters, [31–33]. The effect of carbon credit earned and interest rates on the annualized uniform cost of a glazed PV/T air collector has been analyzed by considering annual thermal energy and exergy. The results suggested that the annualized uniform cost is decreased by the number of carbon credits earned [34]. Researchers have presented a method for determining the optimum active area width of solar cells and relate this with sheet resistances, light intensity, and so on [35]. The economic and environmental aspects of solar drying have been discussed with respect to the thermal modelling of the PVT air collector integrated greenhouse drying system [36].

In the literature, various reliability estimation models have been presented for different types of PV systems. Researchers have also presented an algorithm to estimate the reliability of the semitransparent photovoltaic solar module. They have suggested that the electrical efficiency decrement of the semitransparent photovoltaic solar module is negligible even after 10 years of usage [37,38].

Therefore, the authors have been motivated to develop a computational model, using an artificial neural network (ANN) and Markov analysis, to enhance the thermal and overall efficiency of a semitransparent PV/T air collector with minimum cost and 100% availability. A Markov model has been developed to obtain the maximum availability of semitransparent PV modules by optimizing the number of PV modules in service with five states and two states by considering the failure and repair rates. The authors have also attempted to achieve the minimum cost, minimum temperature, and maximum thermal efficiency of a semitransparent PV/T air collector by developing three ANN models. The ANN has remarkable capabilities in deriving information from complicated or imprecise data. This property is used in research for solving problems that are too complicated for typical computer systems to understand.

The first ANN model was developed to minimize the cost of the semitransparent PV/T air collector by selecting its type, and it optimized the number of photovoltaic modules (*N*-modules + *X*-redundants) by using Markov analysis.

The second ANN model was developed to minimize the temperature of the PV/T air collector with two inputs, namely minimum cost and type.

The authors have also tried to develop a third ANN model to maximize the thermal efficiency of the PV/T air collector corresponding to minimum temperature and solar radiation.

2 | SYSTEM DESCRIPTION

A semitransparent PV/T air collector is a co-generation device that produces both heat and electricity from one system simultaneously. A semitransparent PV/T air collector is better than a standalone PV system with respect to overall efficiency. The electrical efficiency of a PV/T air collector is higher than that of a PV system alone owing to the low-solar cell temperature. The heat from the PV module can be removed by forced or natural air circulation; however, this method is ineffective if the ambient temperature exceeds 25 °C. The semitransparent PV/T air collector has better absorption capacity, minimum thermal resistance between the PV cells and the collector, and higher heat transfer than those of conventional PV/T.

Under standard test conditions (STC), that is, air temperature of 25 °C, solar intensity of 1000 W/m^2, wind velocity of 1.5 m/s, and humidity of 55%–75%, the typical PV air collector efficiency loss per degree centigrade is approximately 0.003 °C^{-1}–0.006 °C^{-1}. Therefore, an air-based PV/T collector is better than a water-based PV/T collector. Heat extracted from semitransparent PV/T air collector can be used for many heating and drying applications. The design parameters of the semitransparent PV/T air collector are shown in Table 1.

Different types of semitransparent PV/T air collectors, such as unglazed, glazed single duct, and glazed double duct, are considered for the analysis of various weather conditions. A semitransparent photovoltaic module with a duct that is encapsulated between module and tedler is known as an unglazed type PV/T air collector. The unglazed semitransparent PV/T air collector having four solar cells with the duct in series is considered for analysis in this paper. A semitransparent photovoltaic module having single duct below the tedler with air flow is known as a glazed semitransparent PV/T air collector.

The air flows below the semitransparent PV/T air collector remove the heat from the back surface of the semitransparent PV module and improve the module efficiency. This hot air can be utilized in various heating applications. The instantaneous thermal efficiency of the solar collector can be calculated by the (1) given by [40]:

$$\eta_{\text{th}} = F_o \left[(\alpha\tau) - U_L \frac{T_{\text{in}} - T_a}{I(t)} \right]. \tag{1}$$

Equation (1) indicates that a plot of instantaneous thermal efficiency versus temperature $\left(T_{\text{in}} - T_a\right) / I(t)$ will result in a straight line having an intercept $F_o(\alpha\tau)$.

The instantaneous electrical efficiency of a semitransparent PV/T air collector depends mainly on the incident solar radiation and PV module temperature. It can be calculated by (2) as follows:

TABLE 1 Specifications of semitransparent PV/T air collector design parameters [39]

Design parameters	Specifications
Standard efficiency	15%
Absorptivity of solar cell	0.9
Glass transmissivity	0.95
Packing factor	0.0045 K^{-1}
Air mass flow rate in duct	0.000108 kg/s
Specific heat of air	1012 J/kg K

$$\eta_{el} = \frac{I_{max} V_{max}}{A_{PVT} I(t)}, \tag{2}$$

where I_{max} and V_{max} are the current and voltage of the semitransparent PV module at maximum power, respectively.

Researchers [37] also demonstrated that a semitransparent photovoltaic solar module reliability of up to 99%/year can be achieved by considering different time trends of the failure rate of solar cells. Therefore, the electrical efficiency can be made constant for a short duration, but thermal efficiency is decreased even though it is calculated for a short duration. In this way, the overall efficiency of the semitransparent PV/T air collector is decreased. To improve the overall efficiency of the system, different types of PV/T air collectors (unglazed, glazed with single duct, and glazed with double duct) can be used in the optimized configuration. The optimized configuration can be determined using ANN. Glazed semitransparent PV/T air collectors with single duct and double duct have improved the efficiency by 54% and 58%, respectively over unglazed semitransparent PV/T air collectors. However, the cost of the unglazed semitransparent PV/T air collector is lesser than that of the glazed semitransparent PV/T air collector.

3 | MARKOV MODEL

The main purpose of determining the availability of the semitransparent PV/T air collector is to identify the success states. In this analysis, the failure rate (λ), repair rate (μ), and probability of failure of different components have been computed. The reliability is a function of mission time, type of failure, and repair characteristics of all components, that is, the probability of component survival beyond time t, which can be expressed by (3) as follows:

$$R(t) = e^{-\lambda t}. \tag{3}$$

The availability of the semitransparent PV/T air collector depends on the individual component downtime, repair time, and maintenance time. Therefore, a higher reliability requires multistage interconnection and a parallel system. Markov analysis (MA) is the mathematical abstraction required to model the system in computational form.

The survival function $R(t)$, or the reliability of the system, decreases exponentially as time increases. The mean time to failure (MTTF) is the mean uptime of a system [22]. The mean time to repair (MTTR) is an average time to repair a system component when the system is in a failure condition. The MTTF is $1/\lambda(t)$, MTTR is $1/\mu(t)$ then mean time between failure (MTBF) can be expressed as follows:

$$\text{MTBF} = \text{MTTF} + \text{MTTR} = 1/\lambda(t) + 1/\mu(t).$$

If $\mu(t) \gg \lambda(t)$, then

$$\text{MTBF} = \text{MTTF}.$$

The availability (A) is the probability of the semitransparent PV/T air collector being found in success states, which can be expressed by (4). The unavailability U is the probability of the semitransparent PV/T air collector component being found in failure states, with a mean time to failure that can be represented mathematically by (5) as follows:

$$A = \frac{\text{MTTF}}{\text{MTTF} + \text{MTTR}} = \frac{\mu(t)}{\mu(t) + \lambda(t)} \tag{4}$$

and

$$U = \frac{\text{MTTR}}{\text{MTTF} + \text{MTTR}} = \frac{\lambda(t)}{\mu(t) + \lambda(t)}. \tag{5}$$

If a subsystem has n components, then the component availability $A_i(t)$ can be calculated by (6) as follows:

$$A_i(t) = \frac{\mu_i}{\mu_i + \lambda_i} + \frac{\lambda_i}{\mu_i + \lambda_i} e^{-(\mu_i + \lambda_i)t}. \tag{6}$$

The system availability $A_s(t)$ can be calculated by (7):

$$A_s(t) = 1 - \prod_{i=1}^{n} \left(1 - A_i(t)\right). \tag{7}$$

The Markov process can be classified into two cases as follows.

3.1 | Case 1

Reliability (success states) of single system operation has been described in [37], where the reliability has been enhanced up to 99% and cost modeling has been performed.

3.2 | Case 2

Markov analysis has been considered as the most powerful computational model to solve availability and reliability problems. The availability and maintainability of the modern PV/T air collector or other PV systems increased considerably. Therefore, the flaws of the PV/T air collector or system must be identified with the determination of availability and probability of success for different components. The availability of the semitransparent PV/T air collector depends on the success time of individual components. In the modern age, higher reliability systems are more complicated. This complexity causes frequent failures of individual components and interconnections. A graphical representation of a Markov model that displays the different states and transitions is called a Markov diagram. The Markov model state represents all possible conditions in which the system can exist. The transition rates are represented by the failure rate (λ) and repair rate (μ) in the state transition diagram. In this research, two computational models, namely five-state and two-state, have been presented for two parallel semitransparent PV/T air collectors, namely A and B. The following assumptions have been made to compute the availability of semitransparent PV/T air collectors or system components.

- The failure of any subsystem makes the downtime for repair the same.
- After any repair, a failed component will be considered as new.

The five-state model having two parallel semitransparent PV/T air collectors (A and B) with failure rate λ and repair rate μ can be represented by the state space Equations in (8)-(12) as given below:

$$P_1^*(t) = \mu_A P_2(t) + \mu_B P_3(t) - \left(\lambda_B + \mu_B\right) P_1(t), \tag{8}$$

$$P_2^*(t) = \mu_B P_4(t) + \lambda_B P_1(t) - \left(\lambda_A + \mu_A\right) P_2(t), \tag{9}$$

$$P_3^*(t) = \mu_A P_5(t) + \lambda_B P_1(t) - \left(\lambda_B + \mu_B\right) P_3(t), \tag{10}$$

$$P_4^*(t) = \lambda_B P_2(t) - \mu_B P_4(t), \tag{11}$$

$$P_5^*(t) = \lambda_A P_3(t) - \mu_A P_5(t). \tag{12}$$

The system failure probability can be calculated using (13)–(15) as follows:

$$P_0(t) = \sum P_{\text{all}}(t), \tag{13}$$

$$R(t) = 1 - P_0(t), \tag{14}$$

$$\text{MTTF} = \int_0^\infty R(t)\, d(t). \tag{15}$$

The two-state model with two parallel semitransparent PV/T air collectors (A and B) considered a single unit with failure rate λ and repair rate μ can be represented using the state space equation in (16) as follows:

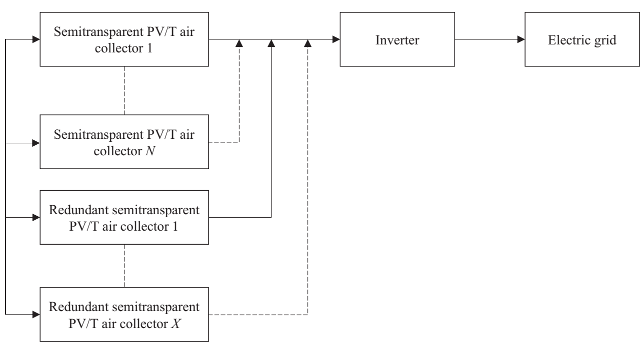

FIGURE 1 *N*-module + *X*-redundant architecture of PV/T air collector

$$P_0^*(t) = -\lambda P_0(t) + (1-\mu)\, P_0(t), \tag{16}$$

where

$$\lambda = \lambda_A + \lambda_B \tag{17}$$

and

$$\mu = \mu_A + \mu_{B.} \tag{18}$$

The reliability of the semitransparent PV/T air collector in two-state can be calculated using (19) and (20) as given below:

$$R(t) = 1 - P_0^*(t) \tag{19}$$

and

$$\text{MTTF} = \int_0^\infty R(t)\, d(t). \tag{20}$$

The two-state model for the semitransparent PV/T air collector with the architecture comprising *N*-module + *X*-redundancy in parallel is shown in Figure 1.

For a two-state Markov model architecture with *N*-module + *X*-redundancy, system reliability can be calculated by (21) and (22) as follows:

$$R(t)_{N+X} = \sum_{i=N}^{N+X} \begin{pmatrix} N+X \\ N \end{pmatrix} R^i (1-R)^{N+X-i} \tag{21}$$

and

$$\text{MTTF} = \int_0^\infty R(t)\, d(t) = \text{MTBF}. \tag{22}$$

The availability of a system with *N*-module + *X*-redundancy can be calculated by (23) as follows:

$$A_{N+X} = \sum_{i=N}^{N+X} \begin{pmatrix} N+X \\ N \end{pmatrix} A^i U^{N+X-i}. \tag{23}$$

The availability of the semitransparent PV/T air collector with system architecture (*N*-module + *X*-redundancy) increases the probability of achieving a success state. To maximize availability prediction, the ANN has been used with different *N* module + *X* redundancy for different semitransparent PV/T air collectors. When large-scale power is required and the repair cost per day is high, then this model will be significantly successful.

4 | COST OPTIMIZATION

A techno-economic analysis is important to identify the project cost, optimize the cost, analyze profit-benefit, plan, schedule, and optimize operational research, and so on. An efficacious analysis can be performed by using the knowledge of the costs of individual components. The initial cost of the semitransparent PV/T air collector mainly consists of the component costs at the time of installation of the system. In this study, the total cost is computed by considering different cost components, namely installation cost of the system,

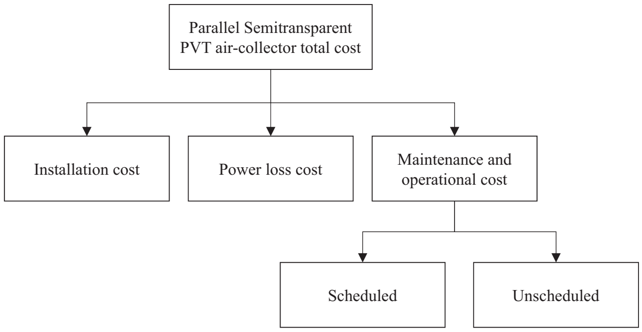

FIGURE 2 Cost components of semitransparent PV/T air collector

power loss cost of the system, maintenance and operational costs, and scheduled and unscheduled costs, which are shown by a block diagram in Figure 2.

4.1 | Cost optimization for single system operation

In a single system operation, components for the semitransparent PV/T air collector are installed. At that time, the installation cost is calculated from the individual component costs. Table 2 lists the total cost of each component (in Indian Rupees) of the semitransparent PV/T air collector (under study) along with the quantity used and their unit costs.

The levelized cost of energy (LCOE) can be calculated as the unit cost of energy over the entire useful life of the PV system. The unit cost of energy can be calculated as the ratio of total annual cost in the nth year to the net annual useful energy generated in the nth year by using the queuing theory of optimization. In this process, the individual component life and cost are considered to optimize the cost of the entire system. The results of cost optimization are shown in Figure 6.

4.2 | Cost optimization for a two-state model of architecture *N* module + *X* redundancy in parallel

Two-state model cost is calculated with the assumption that, after failure, the component is replaced by a new one within specified time, that is, the downtime cost is not included. The total cost of semitransparent PV/T air collector includes the installation cost, power loss cost, and maintenance and operational cost. The installation cost (C_{inst}) of a semitransparent PV/T air collector with power generation P(kW) and cost per unit power A(Rs/W) having N parallel collectors and X redundant modules can be calculated using (24) as follows:

$$C_{\text{inst}} = A \times P \times \left(1 + \frac{X}{N}\right). \tag{24}$$

The maintenance and operational cost of a system consists of two parts, namely scheduled and unscheduled cost. Scheduled cost is always referred to as an annual average value, which is 5%–10% of the installation cost with the warranty period. The unscheduled cost ($C_{\text{m\&o,u}}$) consists of the cost of replaced components (C_{part}) and labor cost (C_{labor}), and can be calculated using (25) as follows:

$$C_{\text{m\&o,u}} = \lambda_{N+X} \times (C_{\text{part}} + C_{\text{labor}} \times \text{MTTR}). \tag{25}$$

The scheduled cost is calculated with the help of (26) as follows:

$$C_{\text{m\&o,s}} = C_{\text{inst}} \times (5\% - 10\%) \times \text{warranty period} \tag{26}$$

where C_{inst} is the cost of installation.

The cost of power loss (C_{loss}) with power generation capacity ($P \times$ duration) and efficiency (η) is calculated with the help of (27) as follows:

$$C_{\text{loss}} = (1 - \eta) \times P \times \text{duration}. \tag{27}$$

The total cost of semitransparent PV/T air collector (C_{total}) can be calculated by adding the abovementioned cost expressed in (24)–(27) using (28) as follows:

$$C_{\text{total}}(N, X) = C_{\text{inst}} + C_{\text{m\&o,s}} + C_{\text{m\&o,u}} + C_{\text{loss}}. \tag{28}$$

The $N + X$ parallel semitransparent PV/T air collector architecture can be optimized using fault detection and bypassing algorithm for all components [37]. By implementing the optimal structure of semitransparent PV/T air collector, the total cost of the system can be minimized. Markov analysis shows that system availability will not change when X redundant modules are greater than 3 for any value of N.

TABLE 2 Components of glazed semitransparent PV/T air collector with their respective unit cost, quantity, and total cost [39]

Components with their unit cost in Indian Rupees (Rs.)	Quantity	Total Cost in Indian Rupees (Rs.)
The support structure (made up of mild steel) at Rs 50/kg	32 kg	1600/-
Semitransparent PV module at Rs 12,000/, 75 Wp	03 nos.	36 000/-
DC fan at Rs 380 (12 V, 1.8 A)	01 nos.	380/-
Paint at Rs 80/kg	01 kg	80/-
Charges for the fabrication process	N/A	1200/-
Total investment cost	N/A	39 260/-
Cost for regular operation and maintenance	N/A	500/- per year

5 | METHODOLOGY

The following methodology has been adopted for overall efficiency enhancement and cost optimization of semitransparent PV/T air collector:

- Initially, thermal efficiency and electrical efficiency are calculated for different types of semitransparent PV/T air collector using data [4].
- The electrical efficiency is fixed in the developed algorithm [37].
- The thermal efficiency is calculated based on the availability and found to decrease with time (10 years), which in turn results in decrease in the overall efficiency, as shown in Figure 4.
- Markov model has been developed with *N*-module and *X*-redundant architecture using *K* out of *n*: *G*-system algorithm with five-state and two-state.
- This developed Markov model offers maximum availability of semitransparent PV/T air collector with all components. It has also been observed that the availability remains constant after the specific values of *N* and *X* are reached.
- The complete cost of semitransparent PV/T air collector has also been calculated using the developed cost modeling algorithm with a single system operation [37].
- ANN-1 has been developed to ensure the minimum cost for different types of semitransparent PV/T air collector (unglazed, glazed with single duct, and glazed with double duct). The *N*-module + *X*-redundant architecture of semitransparent PV module is considered as the input parameters with the total cost as the output parameter. The cost can be optimized by optimizing the values of *N* and *X*.
- The complete system architecture (*N*-module + *X*-redundant) volume for two-state has also been calculated and compared with that for a different number of redundant modules. The results have been displayed in Figure 7.
- ANN-2 has been developed for obtaining the minimum temperature of semitransparent PV/T air collector where the total cost and types of semitransparent PV/T air collector are considered as the input parameters and the semitransparent PV/T air collector temperature is considered as the output parameter. With the optimized cost of different types of semitransparent PV/T air collectors, the minimum temperature could be attained.
- ANN-3 has been developed for obtaining the maximum thermal efficiency of semitransparent PV/T air collector where solar radiation and semitransparent PV/T air collector temperature are considered as the input parameters and thermal efficiency is considered as the output parameter. In this way, the overall efficiency has been found to be enhanced with optimized cost.

The complete workflow of the developed methodology has been illustrated in a block diagram in Figure 3.

6 | ANN MODEL

Artificial neural network (ANN) analysis is becoming a very effective approach to solving complicated practical problems and is being incorporated in conventional techniques in various areas. ANN can acquire knowledge from its environment through a learning process. Synaptic weights are used to store the acquired knowledge. The use of ANN offers many capabilities like nonlinearity, input-output mapping, evidential response, contextual information, fault tolerance, and uniformity of analysis. In this research, three generalized ANN models have been used, which are already described in [29]. The relation between the input and output parameters for the ANNs model has been described as follows:

The input vector $\mathbf{x}$ = [type of semitransparent PV/T air collector, Number of semitransparent PV module ($N + X$ architecture)] is applied to the input layer and the net input of the hidden unit can be calculated from (29) as given below:

$$n_j^1 = \sum_{i=1}^{2} w_{ji} x_i + b_j^1, \tag{29}$$

where w_{ji} is the weight on the connection from the *i*th input and *b* is the bias for hidden layer neurons. The hidden layer output can be calculated from (30) as

$$a_j^1 = f_1\left(\sum_{i=1}^{2} w_{ji} x_i + b_j^1\right). \tag{30}$$

In this way, the hidden layer output will be considered as input for the output layer, which can be estimated using (31) as follows:

$$f_1(n) = \tan\text{sig}(n) \tag{31}$$

and the output parameters of the ANN model have been calculated using (32) as follows:

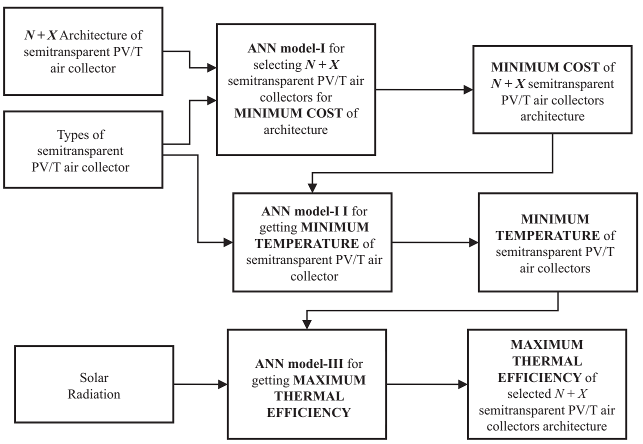

FIGURE 3 Complete work flow of developed methodology

$$a_k^2 = f_2\left(\sum_{j=1}^{10} w_{kj} a_j^1 + b_k^2\right). \quad (32)$$

Therefore, the ANN model outputs are a_k^2 and it can be considered as $f_2(n)$.

ANN-1 is used for determining the optimized cost for different types of semitransparent PV/T air collectors and N-module + X-redundant architecture. In this model, the parameters N and X are optimized with respect to the desired cost. After obtaining the desired cost, it is used as an input in ANN-2 for various types of semitransparent PV/T air collectors. ANN-2 is used for determining the minimum temperature of semitransparent PV/T air collector as an output. In ANN-3, solar radiation and semitransparent PV/T air collector temperature are considered as inputs for determining the maximum thermal efficiency of semitransparent PV/T air collector. With enhanced thermal efficiency, the overall efficiency is also enhanced.

7 | RESULTS AND DISCUSSION

In this research, the module/cell temperature, effective temperature, equivalent temperature, and acceleration factor for semitransparent PV/T air collector have been calculated. The electrical efficiency is found to decrease by less than 5% in 10 years, which can be considered as negligible; the electrical efficiency can be considered as constant with maximum availability throughout the analysis. The thermal efficiency reduces by approximately 25% in 10 years, which in turn reduces the overall efficiency. Therefore, to improve the overall efficiency, the thermal efficiency decrement should be minimized by maximizing the availability of semitransparent PV/T air collector.

The thermal efficiency depends on the cell temperature of semitransparent PV/T air collector. The electrical and thermal efficiency of semitransparent PV/T air collector with respect to time in years has been estimated using an analytical model, as shown in Figure 4. It can be observed from Figure 4 that the thermal efficiency decreases by up to 50% on the basis of availability of semitransparent PV modules calculated by Markov analysis. The decrement in thermal efficiency can be minimized using ANN-3, in which the temperature of semitransparent PV/T air collector and solar radiation are considered as input parameters.

The total levelized cost of energy (LCOE) of semitransparent PV/T air collector can be calculated using the developed algorithm [37]. In this research, the total cost is calculated for 10 years based on component life and individual cost knowledge by using queuing theory for single system operation cost. In this way, the conventional cost, that is LCOE, is decreased. The results have been shown in Figure 5.

The Markov availability model has been developed for five-state and two-state semitransparent PV/T air collectors. The repair rate, failure rate, component availability, and system availability for two set of values of N and X, that is, $N = 6$, $X = 3$ and $N = 10$, $X = 2$ have been calculated and the results are shown in Table 3. The results in Table 3 show that, with 10 modules and two redundant components, a component availability of 99.52% and a system availability of 99.99% can be achieved. It is also observed that with six modules and three redundant components, a component and system availability of 93.58% and 99.58%, respectively, can be achieved. It can be seen from Table 3 that redundant (X) has lesser effect on the component and system availability as compared to module (N). However, the failure and repair rates do not usually follow exponential distributions for a semitransparent PV/T air collector.

The total cost of semitransparent PV/T air collector has been calculated for a two-state model with N-module and X-redundant architecture for a fixed duration. The variation in the total cost of semitransparent PV/T air collector with module-N for redundant $X = 2$ and 3 is shown in Figure 6. It can be observed that, initially the cost decreases at a very fast rate but after $N = 6$, the slope of the curve reduces almost to zero, which means that the total cost becomes constant.

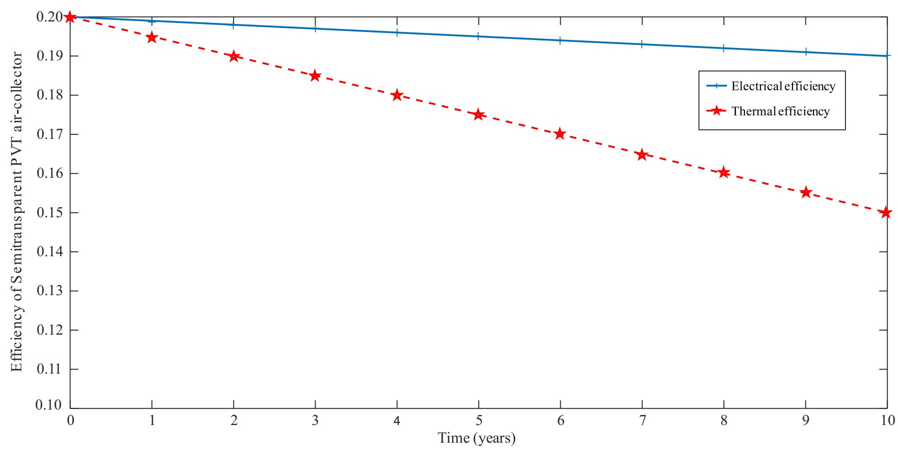

FIGURE 4 Efficiency (electrical and thermal) of semitransparent PV/T air collector with respect to time (years)

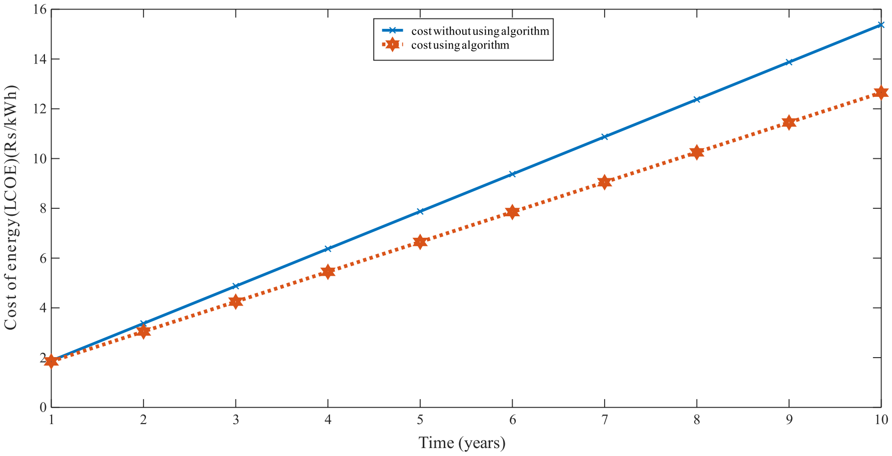

FIGURE 5 Levelized cost of energy (LCOE) with respect to time

TABLE 3 Repair rate, failure rate, component availability, and system availability for two set of values of N and X ($N = 6$, $X = 3$, and $N = 10$, $X = 2$)

S. No.	Case	Repair rate (μ)	Failure rate (λ)	Component availability A_i (%)	System availability A_s (%)
1	$N = 6$ $X = 3$	8.33×10^{-3} h^{-1}	5.71×10^{-4} h^{-1}	93.58	99.58
2	$N = 10$ $X = 2$	4.17×10^{-3} h^{-1}	2.85×10^{-5} h^{-1}	99.52	99.99

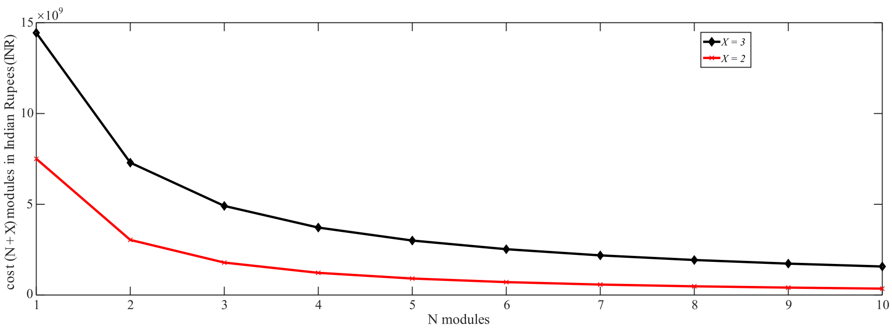

FIGURE 6 Total cost of semitransparent PV/T air collector with N-module + X-redundant architecture

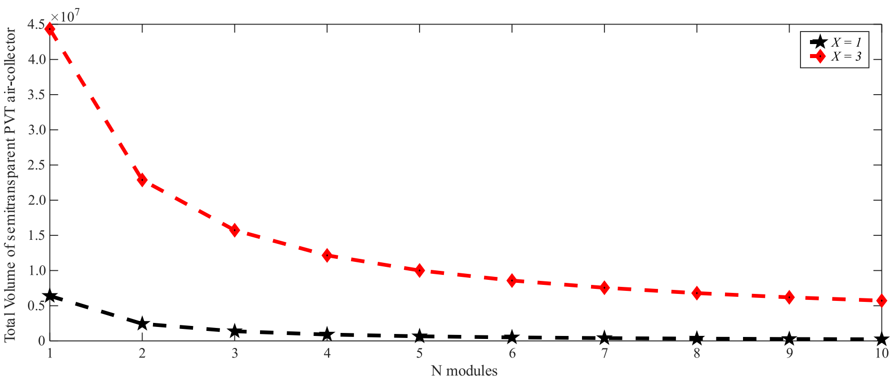

FIGURE 7 Variation of volume of two-state semitransparent PV/T air collector with modules (N) for $X = 1$ and 3

The total volume of semitransparent PV/T air collector with N-module and X-redundant architecture was also estimated for two-state. The variation in the total volume of semitransparent PV/T air collector with N-modules for $X = 1$ and 3 has been shown in Figure 7. It can be observed from Figure 7 that the volume of semitransparent PV/T air collector can be minimized using a lesser number of modules (N) and low value of redundancy (X).

8 | CONCLUSIONS

In this research, the authors have drawn the following conclusions:

- It is observed that electrical efficiency almost remains constant for a period of 10 years but thermal efficiency decreases by up to 50% in 10 years on the basis of availability of semitransparent PV modules calculated by Markov analysis. Therefore, it is deduced that the overall efficiency decreases due mainly to the reduction in thermal efficiency.
- ANN modeling is found to be an effective approach to minimize cost and temperature and also to maximize the thermal and overall efficiency of semitransparent PV/T air collector.
- The developed Markov model can increase the availability of $(N + X)$ semitransparent PV/T air collectors up to 100%, which together with ANN, can be considered as an efficient method to enhance the thermal and overall efficiency.
- Levelized cost of energy for semitransparent PV/T air collectors has been reduced using the developed algorithm.
- Markov model for five-state and two-state has been found suitable to select the optimized number of modules (N) and redundants (X) of semitransparent PV/T air collector, which in turn result into their minimum cost.
- It is observed that the volume of semitransparent PV/T air collector decreases fast initially and then becomes constant, with variation in module (N) and redundant (X). Therefore, the volume of semitransparent PV/T air collector can be reduced to minimum by optimizing the number of module (N) and redundant (X).
- It can also be concluded that a semitransparent PV/T air collector is a better device than a semitransparent PV system in terms of the overall efficiency.

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