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TRANSMISSION-CONSTRAINED GENERATION EXPANSION PLANNING FOR A REAL-WORLD POWER INDUSTRY

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Transmission-constrained generation expansion planning (TC-GEP) problem for new generating units significantly involves location, capacity and type of fuel. This problem can be solved by adding Optimal Power Flow (OPF) constraints. This study renders an application of the Self-adaptive Differential Evolution (SaDE) algorithm to the TC-GEP problem for multiple horizons, at least cost, for the power generating system of Tamil Nadu, India. TC-GEP problem has been solved for 6-year (till 2022) and 12-year (till 2028) planning horizon by considering the least cost and reliable supply. The problem is solved for six different scenarios on an Indian utility 62 bus test system, and the results are validated with Dynamic Programming (DP). The results of the TC-GEP problem for the year 2028 are compared with the solutions of the GEP problem without transmission constraint. Finally, a comparison is made between the proposed solution and the practically implemented expansion plan for the year 2017 by the Tamil Nadu electricity sector.

Keywords: Electric Power Industry; Energy Conservation; Optimization Algorithms; Transmission Constrained Generation Expansion Planning.

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1. INTRODUCTION

Electricity is conceived to be a vital tool for socioeconomic growth, particularly in developing countries. Globalization has led to a rise in urbanization and population, which makes energy demand a serious problem on a global scale. Economic progress in Tamil Nadu has been evident and incurs needful efforts by the Government to expand energy supplies to overcome supply imbalance. Tamil Nadu imports about 80% of its fuel, and this is a grievous threat to Tamil Nadu's future energy supply security. Furthermore, the expansion of thermal power plants, gas reserves and oil to meet the demand could also completely exhaust in the future. While other energy sources such as hydro and nuclear are considered a remedy for the energy crisis, there are implications such as mass people displacement and hazards of nuclear materials that could hinder their utility. To overcome the aforementioned issues Tamil Nadu power sector needs a generation expansion plan by concentrating the renewable energy sources (RES).

GEP is the crucial step after estimating the demand. GEP aims to define the minimal cost expansion plans to satisfy the demand. Previously for solving the GEP problem, DP (Careri *et al*., 2011), Branch and bound technique (Meier 1990), and Benders-decomposition (Khodr *et al*., 2002) have been employed. The GEP problem has been solved using eight different optimization algorithms, and the outcomes are compared (Kannan *et al*., 2005). The comparative results have implied that Differential Evolution (DE) performed better than other methods. The GEP problem has been solved to analyze the effect of incorporating solar plants (Rajesh *et al*. 2016). The minimal cost GEP problem has been solved by integrating wind power plants to reduce overall costs and emissions (Bhuvanesh *et al*., 2014). GEP problems for Tamil Nadu were resolved by means of software, for instance, Long-Range Energy Alternative Planning (LEAP) and EnergyPLAN (Bhuvanesh *et al*., 2017; Bhuvanesh *et al*., 2018a). The applications DE and its variants have been executed to resolve the GEP problem. The comparative results revealed that SaDE performed better than other procedures (Bhuvanesh *et al*. 2018c). The GEP problem has been resolved with multiple objective functions using Multi-Objective Differential Evolution (MODE), where minimum cost and minimum Green emission are considered (Bhuvanesh *et al*., 2018b).

DE has been extensively used for solving GEP problems. Though it offers optimal results, it has some demerits. One of these demerits is that for a particular problem selecting the best amid various mutation strategies and its related control parameters, scaling factor F, and crossover rate (CR) is very challenging. Therefore, it wants a time-consuming trial-and-

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error procedure. So as to evade this extensive computational time, (Qin *et al*., 2009) proposed Self-adaptive Differential Evolution (SaDE).

After analyzing several literatures, it is recognized that a real-world TC-GEP is not considered previously. Henceforth, the TC-GEP problem for the Tamil Nadu power sector is resolved in this study using SaDE.

This study aims:

1) To frame the outcomes of the TC-GEP problem and determine the effect of incorporating Energy Conservation.
2) To investigate the influence of Energy Storage Technologies (EST) on the fuel mix ratio for the system under consideration.
3) To study the influence of emission penalty costs of high emission plants (HEP).
4) To choose new power plants with category, size, site and period of investment by sustaining the Optimal Power Flow restraints.

2. PROBLEM FORMULATION

2.1 Objective of TC-GEP problem

The GEP is a problem of finding a set of best decision vectors over a planning horizon that minimizes the investment and the operating costs by considering the constraints. The forecasted peak demand till the year 2022 for the Tamil Nadu power system is given in Table A.1 (Karunanithi *et al*., 2015). The technical and cost data of the candidate plants pumped storage power plant and the existing plants are given in Tables A.2 and A.3, respectively (CapitalCost, 2013; CostReport, 2012).

The following expression represents the cost objective

$$\text{Min.}\, Cost = \sum_{t=1}^{T} [I(U_t) + M(X_t) + O(X_t) - S(U_t)], \tag{1}$$

where

$$X_t = X_{t\text{-}1} + \mathrm{U}_t \qquad (t = 1,2,\ldots T) \tag{2}$$

$$I(U_t) = (1 + d)^{-t} \sum_{i=1}^{N} \left(CI_i \times \mathrm{U}_{t,i}\right) \tag{3}$$

$$S(U_t) = (1 + d)^{-T'} \sum_{i=1}^{N} \left(CI_i \times \delta_i \times U_{t,i}\right) \tag{4}$$

$$M(X_t) = \sum_{s'=0}^{1} \left((1 + d)^{1.5+\,t'+s'} \left(\sum (X_t \times \mathrm{FC}) + \mathrm{EC} + \mathrm{MC}\right)\right) \tag{5}$$

$$O(X_t) = \mathrm{EENS} \times \mathrm{OC} \times \sum_{s'=0}^{1} \left((1 + d)^{1.5+\,t'+s'}\right) \tag{6}$$

The outage cost calculation of (6), used in (1), depends on the Expected Energy Not Served (EENS). The equivalent energy function method is used to calculate the EENS and also used to calculate the loss of load probability (LOLP).

$$t' = (t\text{-}1) \quad \text{and}\, T' = \mathrm{T} - t', \tag{7}$$

where

Cost	total cost, $;
U_t	N-dimensional vector of the introduced units in stage *t*;
$U_{t,i}$	number of introduced units of type *i* in stage *t*;
X_t	cumulative capacity vector of the existing units in stage *t*, (MW);
$I(U_t)$	investment cost of the introduced unit at the *t*-th stage, $;
$M(X_t)$	total operation and maintenance cost of the existing and the newly introduced units, $;
s'	variable used to indicate that the maintenance cost is calculated in the middle of each year;
$O(X_t)$	outage cost of the existing and the introduced units, $;
$S(U_t)$	salvage value of the introduced unit at the *t*-th interval, $;
D	discount rate;
CI_i	capital investment cost of the *i*-th unit, $;
δ_i	salvage factor of the *i*-th unit;
T	length of the planning horizon (in stages);
N	total number of different types of units;
FC	fixed operation and maintenance cost of the units, $/MW;
EC	emission cost of the units, $/MW;

MC	variable operation and maintenance cost of the units, \$;
EENS	Expected Energy Not Served, MWhrs;
OC	value of the outage cost constant, \$/ MWhrs

2.2 Constraints

2.2.1 Upper Construction limit

Let U_t be the units to be committed in the expansion plan at stage t that must satisfy the maximum construction capacity.

$$0 \leq U_t \leq U_{\max,t} , \tag{8}$$

where $U_{\max,t}$ is the maximum construction capacity of the units at stage t.

2.2.2 Demand

The selected units must satisfy the minimum demand.

$$\sum_{i=1}^{N} X_{t,i} \geq D_t , \tag{9}$$

where

$X_{t,i}$	cumulative capacity of the ith unit at stage t;
D_t	demand at the tth stage in megawatts (MW).

2.2.3 Reliability criterion

The selected units and existing units must satisfy the reliability criterion and the LOLP.

$$LOLP\ (X_t) \leq \varepsilon , \tag{10}$$

where

ε is the reliability criterion expressed in the calculation of LOLP.

Furthermore, the energy produced by each unit and the EENS is calculated using the Equivalent energy function method. The EENS indices are used for estimating the outage cost.

2.2.4 Optimal Power Flow (OPF) constraints

The transmission line flow constraints are considered, such as real power flow, reactive power flow, and voltage magnitude at each bus. Finally, the Linear Programming based OPF algorithm is used to check whether all the power flow constraints are satisfied or not.
The various power flow constraints are:
Active power generation limit

$$P_{gi}^{\min} \leq P_{gi} \leq P_{gi}^{\max} . \tag{11}$$

Reactive power generation limit

$$Q_{gi}^{\min} \leq Q_{gi} \leq Q_{gi}^{\max} \tag{12}$$

Bus voltage limit

$$V_{i}^{\min} \leq V_{i} \leq V_{i}^{\max} \tag{13}$$

Active power balance equation

$$\sum P_{\mathrm{gi}} - \sum P_{\mathrm{Li}} - \mathrm{TL}_p = 0 \tag{14}$$

Reactive power balance equation

$$\sum Q_{\mathrm{gi}} - \sum Q_{\mathrm{Li}} - \mathrm{TL}_q = 0 \tag{15}$$

Apparent power flow limit

$$\tilde{S}_{ij} \leq S_{ij}^{\max}, \tag{16}$$

where

$\mathrm{P_{gi}}$	real power output of the generating unit at *i*th bus
$P_{gi}^{\min}$	minimum real power output of the generating unit at *i*th bus
$P_{gi}^{\max}$	maximum real power output of the generating unit at *i*th bus
$\mathrm{Q_{gi}}$	reactive power output of the generating unit at the *i*th bus
$Q_{gi}^{\min}$	minimum reactive power output of the generating unit at *i*th bus
$Q_{gi}^{\max}$	maximum reactive power output of the generating unit at *i*th bus
V_i	voltage at *i*th bus
$V_i^{\min}$	minimum voltage limit at *i*th bus
$V_i^{\max}$	maximum voltage limit at *i*th bus
$\mathrm{P_{Li}}$	real power demand at *i*th bus
$\mathrm{Q_{Li}}$	reactive power demand at *i*th bus
TL_p	total real power losses in the transmission lines
TL_q	total reactive power losses in the transmission lines
$\tilde{S}_{\mathrm{ij}}$	power flow (calculated) in MVA between bus *i* and bus *j*
S_{ij}^{max}	MVA limit of the transmission line between bus *i* and bus *j*

The selected units should satisfy all the constraints from equations (11) to (16).

2.3 Assumptions made in this study

Based on the previous research works, the following factors are considered in this study.

- The power plants proposed in "The Vision Tamil Nadu 2023" (Nadu, 2014) by the Tamil Nadu government are North Chennai thermal power station stage III & Uppur thermal power plant, Udangudi thermal power station stage I & II, PPN gas power generation Pvt. Ltd, GMR Vasavi oil power plant, Kudankulam nuclear power plant, Bhavani barrage, wind, Adani solar, biomass and Kundah pumped storage. In this study, they are termed as coal 1, coal 2, gas, oil, nuclear, hydro, wind, solar, biomass and pumped hydro, respectively.
- It is considered that the proposed power plants coal 1, coal 2, gas, oil, nuclear, hydro, wind, solar, biomass and pumped hydro will be fixed at Bus no. 1, 36, 22, 5, 33, 50, 34, 43, 47 and 51 respectively of 62 Bus Indian Utility system, which is given in Appendix. The generator data, load bus data, transmission line data and sites of different buses in Tamil Nadu (62 Bus Indian Utility system) are taken from (Gnanadass, 2005) and also given in Appendix.
- The salvage factor (δ) for coal 1, coal 2, gas, oil, nuclear, hydro, wind, solar and biomass are considered as 0.1, 0.1, 0.1, 0.15, 0.15, 0.2, 0.2, 0.2 and 0.2, respectively. The salvage factor for the pumped storage plants is assumed to be the same as that of the Hydro plants.
- The cost of EENS is fixed at 0.05 $/kW h.
- The discount rate is fixed at 8.5%.
- It is assumed that the date of accessibility of the new generation plants is from the year 2017. The capital investment cost is assumed to occur at the start of the project.
- The maintenance cost is presumed to experience in the middle of the year, and it is computed by using the equivalent energy function method.
- The salvage cost is valued at the end of the planning horizon.

3. DE AND ITS BEST PARAMETERS

In this work, the SaDE algorithm, a variant of DE, is employed to solve the TC-GEP problem. Brief descriptions of DE and SaDE algorithms are given in this section.

3.1 Differential Evolution (DE) algorithm

Price and Storn (Rainer Storn and Price 1997) proposed DE. It is a population-based stochastic direct search algorithm like GA but differs from GA with respect to the mechanics of mutation, crossover and selection.

DE employs mutation and crossover operations at each iteration J to produce a trial vector $V_{i,J}$ for each individual vector $X_{i,J}$, also named as the target vector, in the current population.

Based on the mutation rule, the DE has been categorized into 6 different strategies. They are:

i) DE/best/1

$$U_{i,J+1} = X_{best} + F \times (X_{r1,J} - X_{r2,J}) \tag*{17()}$$

ii) DE/rand/1

$$U_{i,J+1} = X_{r3,J} + F \times (X_{r1,J} - X_{r2,J}) \tag{18}$$

iii) DE/rand-to-best/1

$$U_{i,J+1} = X_{i,J} + F \times (X_{best} - X_{i,J}) + F \times (X_{r1,J} - X_{r2,J}) \tag{19}$$

iv) DE/best/2

$$U_{i,J+1} = X_{best} + F \times (X_{r1,J} - X_{r2,J} + X_{r3,J} - X_{r4,J}) \tag{20}$$

v) DE/rand/2

$$U_{i,J+1} = X_{r5,J} + F \times (X_{r1,J} - X_{r2,J} + X_{r3,J} - X_{r4,J}) \tag{21}$$

vi) DE/Current-to-rand/1

$$U_{i,J+1} = X_{r1,J} + F \times (X_{r1,J} - X_{r2,J}) + K \times (X_{r3,J} - X_{i,J}) , \tag{22}$$

where

X	is the set of population
$U_{i,J+1}$	is the mutated *i*-th individual for the next iteration
$X_{i,J}$	is the *i*-th individual of the current iteration
X_{best}	is the best individuals among the population X
F	is a constant [0, 2]
K	is a constant taken equal to F
J	is the current iteration

$X_{r1,J}$, $X_{r2,J}$, $X_{r3,J}$, $X_{r4,J}$, and $X_{r5,J}$ are the randomly selected populations in the current iteration.

After mutation, an exponential crossover is applied to the individuals by the following rule

$$V_{i,J+1} = \begin{cases} U_{k,i,J+1} & \text{if } (\text{rand}_j[0,1] \leq \text{CR}) \text{ or } (k = k_{\text{rand}}) \\ X_{\text{k,i,J}} & \text{otherwise} \end{cases} , \text{k} = 1,2,\ldots,\text{n} , \tag{23}$$

where CR is the crossover rate [0, 1].

The parents for the next iteration are selected based on a one-to-one greedy selection scheme for minimization problems as follows:

$$X_{i,J+1} = \begin{cases} V_{i,J+1} & \text{if } f(V_{i,J+1}) < f(X_{i,J+1}) \\ X_{i,J+1} & \text{if } f(X_{i,\rightleftarrows J+1}) > f(V_{i,J+1}) \end{cases} , \tag{24}$$

where

$f(V_{i,J+1})$ is the fitness function value of the *i*-th individual of the population in which the mutation and crossover operators are applied.

$f(X_{i,J+1})$ is the fitness function value of the *i*-th individual in the original population.

The loss of the best individuals in the subsequent iteration is avoided by this selection mechanism, as the best individuals replace the worst individuals.

3.2 Self-adaptive Differential Evolution (SaDE)

The SaDE automatically chooses one from the various available learning strategies for each individual in the current population, depending on their past understanding of generating the best results (Qin *et al*. 2009).

The initial probabilities p_i, i=1, 2…*numst* are considered to be equal so that all strategies will have an equal probability to be implemented for each individual in the initial population, where p_i is updated as:

$$\rho_i = \frac{ns_i}{ns_i+nf_i} \ , \tag{25}$$

where

numst	is the number of strategies considered
ns_i	is the number of trial vectors entering the next iteration successfully while generated by each strategy
nf_i	is the number of trial vectors rejected while generated by each strategy

From the previous experience, the author directly adopts SaDE for solving the TC-GEP problem. The user fixes the number of population NP according to the type of problem. The value of F is taken from the range of 0 to 2 with a standard deviation of 0.3 and normal distributions of mean 0.5 for each individual in the current population. The value of CR is considered with the normal distributions of mean $CR_{m,}$ and standard deviation 0.1 and CR_m is dynamically improved based on the past learning experience. The best parameters are selected through the trial and error method. The best control parameters for SaDE selected through 50 test simulation runs are given in Table 1.

Table 1. Best parameters for SaDE

S. No	Parameters	SaDE
1	Number of Population *NP*	10×n*
2	Maximum no. of function evaluations	10000×n
3	Mutation Strategy	Adaptive
4	Scaling Factor *F*	N (0.5, 0.3)
5	Crossover rate *CR*	Adaptive
6	Jumping rate Z_r	-

*where **n** is the number of a decision variable

3.3 Implementation of SaDE to TC-GEP problem

The significant steps for solving the TC-GEP problem can be summarized as follows:

Step 1: Read all the necessary test system data from the database for solving the TC-GEP problem. The data of load demand and cost values are considered at each planning stage;
Step 2: Set up all the required parameters of the SaDE optimization process by the user. Set up the control parameters of the SaDE optimization process, such as population size (N_P), mutation factor (F), crossover probability (CR), convergence criterion (ε), number of problem variables (D), lower and upper bounds of initial population ($x_j^{\min}$ and $x_j^{\max}$) and maximum number of iterations or generations ($G^{\max}$). Select a mutation operator strategy;
Step 3: Set iteration G = 0 for the initialization step of the optimization process;
Step 4: Initialize the population P of the individuals;
Step 5: Calculate and evaluate the fitness values of the initial individuals according to the problem fitness function and check the constraints for each individual;
Step 6: Rank the initial individuals according to their fitness;
Step 7: Set iteration G = 1 for the optimization step;
Step 8: Apply the mutation, crossover and selection operators to generate the new individuals. Apply the mutation operator to generate the mutant vectors ($V_i^{(G)}$) with an automatically selected mutation operator strategy in step 2. Apply the

crossover operator to generate the trial vectors ($U_i^{(G)}$). Apply the selection operator by comparing the fitness of the trial vector ($U_i^{(G)}$) and the corresponding target vector ($X_i^{(G)}$) and then select one that provides the best solution;

Step 9: Calculate and evaluate the fitness values of the new individuals according to the problem fitness function and check the constraints for each new individual;

Step 10: Rank the new individuals according to their fitness;

Step 11: Update the best fitness value of the current iteration and the best fitness value of the previous iteration;

Step 12: Check the termination criterion;
$IF\left|X_i^{best} - X_i\right| > \varepsilon$and the number of the current generation is not exceeding the maximum number of generations $G<G^{\max}$, set $G = G + 1$ and return to step 8 to search for the solution. Or else, stop to calculate the objective function and go to step 13;

Step 13: The output shows the least cost value of the TC-GEP problem with the capacity and locations of the candidate plants to be added in each stage.

4. RESULTS AND DISCUSSIONS

The model analysis is carried out for six different scenarios in the Tamil Nadu power system. The schematic diagram of the TC-GEP model analysis is shown in Figure 1. The first case is the base case scenario, wherein there is no inclusion of any considerable scenarios. The TC-GEP problem is solved with the technical details of existing power plants and the candidate plants proposed in “The Vision Tamil Nadu 2023” by the Tamil Nadu government. The second case is the EC scenario, wherein energy conservation is considered while planning. The actual average annual load growth rate is 6%, whereas, in the EC scenario, it is reduced to 5%. The third case is the emission cost scenario, wherein the impact of the emissions penalty cost from the HEP on the overall cost is studied. The emission penalty cost of all the power plants is given in Appendix. The fourth case is the EST scenario, wherein the replacement of oil plants by the pumped storage plants is considered. The fifth case is the combination of cases 2 and 3. The sixth case is the combination of cases 2, 3 and 4. Tables 2, 3, 4, 5, 6 and 7 show results of the least cost TC-GEP problem for 6-year (till 2022) and 12-year (till 2028) planning horizons for cases 1, 2, 3, 4, 5 and 6, respectively.

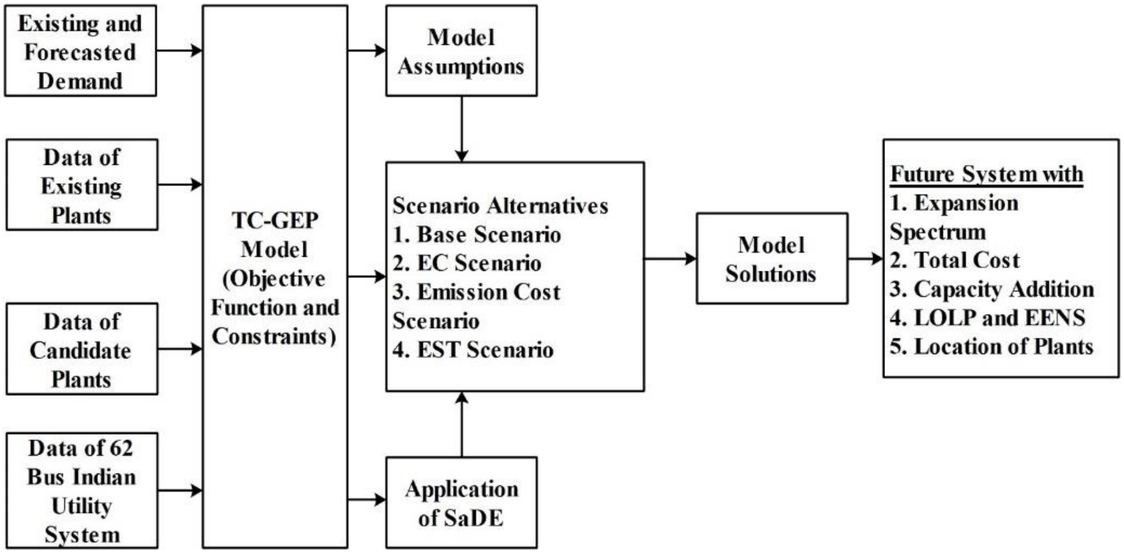

Figure 1. Process flow diagram for the TC-GEP model study

4.1 Case 1: Base scenario (TC-GEP without any considerable scenario)

For this case, the installation capacity is 29,118 MW for a 6-year planning period. Coal 1, coal 2, gas, oil, nuclear, hydro, wind, solar, and biomass plants contribute with the capacities of 6400 MW, 5200 MW, 3240 MW, 560 MW, 6650 MW, 30 MW, 1750 MW, 5000 MW and 288 MW respectively. The cumulative capacity becomes 56,415 MW with an overall cost of 7.6531 ×10^{10} \$. For a 12-year planning period, the added capacity is 54,925 MW. The contributions of coal 1, coal 2, gas, oil, nuclear, hydro, wind, solar, and biomass plants are 8800 MW, 9100 MW, 6480 MW, 1280 MW, 17,100 MW, 75 MW, 3250 MW, 7800 MW and 540 MW respectively. The cumulative capacity becomes 78,031 MW with an overall cost of 11.8143 $\times 10^{10}$ \$. The year-wise planning details have been provided in Table 2.

4.2 Case 2: EC scenario (TC-GEP considering Energy Conservation)

In this case, the installation capacity is 36,842 MW for a 6-year planning period. Coal 1, coal 2, gas, oil, nuclear, hydro, wind, solar, and biomass plants contribute 7200 MW, 5850 MW, 3600 MW, 880 MW, 10,450 MW, 55 MW, 2750 MW, 5625 MW and 432 MW, respectively. The cumulative capacity is 59,948 MW with an overall cost of 7.2816 $\times 10^{10}$ \$. The overall cost is reduced by 5% than the base scenario. For a 12-year planning period, the added capacity is 45,625 MW. The expansion capacities of coal 1, coal 2, gas, oil, nuclear, hydro, wind, solar, and biomass plants are 10,400 MW, 9100 MW, 2880 MW, 1200 MW, 12,350 MW, 55 MW, 3250 MW, 5850 MW and 540 MW respectively. The cumulative capacity becomes 68,731 MW with an overall cost of 11.3574 $\times 10^{10}$ \$. Due to the reduced demand, the overall cost is also reduced by 4% than the base scenario.

Table 2. Solutions of Tamil Nadu's TC-GEP problem for case 1

Planning Horizon	Year	Types of plants									Added Capacity (MW)	Cumulative Capacity (MW)	EENS $\times 10^6$ (MWh)	LOLP $\times 10^{-6}$ (Days/ Year)	Overall cost $\times 10^{10}$ (\$)
		Coal 1	Coal 2	Gas	Oil	Nuclear	Hydro	Wind	Solar	Biogas					
6 year	2017	1600	1300	720	160	1900	5	250	1250	72	7257	30363	0.5805	0.0147	7.6531
	2018	1600	1300	720	160	1900	0	500	1250	72	7502	37865			
	2019	1600	1300	720	0	0	5	500	1250	72	5447	43312			
	2020	800	650	720	80	950	10	250	1250	72	4782	48094			
	2021	800	650	360	160	1900	10	250	0	0	4130	52224			
	2022	800	650	720	160	950	0	250	625	36	4191	56415			
	Total	6400	5200	3240	560	6650	30	1750	5000	288	29118	-			
12 year	2017	800	1300	720	0	1900	10	250	650	36	5666	28772	0.0014	0.0010	11.8143
	2018	800	650	360	160	950	10	500	650	36	4116	32888			
	2019	800	650	360	160	950	5	250	1300	0	4475	37363			
	2020	800	1300	720	160	1900	0	500	0	72	5452	42815			
	2021	800	1300	360	80	1900	10	0	650	72	5172	41987			
	2022	1600	0	720	160	950	5	0	650	36	4121	52108			
	2023	800	1300	0	160	0	5	500	650	36	3451	55559			
	2024	0	1300	720	80	1900	5	500	650	36	5191	60750			
	2025	800	650	720	80	1900	5	250	0	72	4477	65227			
	2026	0	0	720	80	1900	5	500	650	0	3855	69082			
	2027	0	650	720	80	1900	5	0	650	72	4077	73159			
	2028	1600	0	360	80	950	10	500	1300	72	4872	78031			
	Total	8800	9100	6480	1280	17100	75	3250	7800	540	54925	-			

Table 3. Solutions of Tamil Nadu’s TC-GEP problem for case 2

Planning Horizon	Year	Types of plants									Added Capacity (MW)	Cumulative Capacity (MW)	EENS×10^6 (MWh)	LOLP ×10^{-6} (Days/ Year)	Overall cost ×10^{10} ($)
		Coal 1	Coal 2	Gas	Oil	Nuclear	Hydro	Wind	Solar	Biogas					
6 year	2017	1600	1300	720	160	1900	10	500	1250	72	7512	30618	0.2841	0.0545	7.2816
	2018	1600	1300	720	80	1900	10	500	625	72	6807	37425			
	2019	800	0	720	160	1900	10	500	1250	72	5412	48837			
	2020	800	1300	360	160	950	10	500	0	72	4152	46989			
	2021	1600	650	360	160	1900	10	500	1250	72	6502	53491			
	2022	800	1300	720	160	1900	5	250	1250	72	6457	59948			
	Total	7200	5850	3600	880	10450	55	2750	5625	432	36842	-			
12 year	2017	1600	1300	0	160	1900	10	250	650	36	5906	29012	0.0008	0.0001	11.3574
	2018	800	650	360	160	1900	0	0	0	36	3906	32918			
	2019	0	0	360	80	950	5	0	650	72	2117	35035			
	2020	800	650	0	160	0	0	0	1300	36	2946	37981			
	2021	800	650	360	160	950	0	250	0	36	3206	41187			
	2022	800	650	360	0	950	10	250	0	36	3056	44243			
	2023	0	650	360	80	0	5	500	1300	36	2931	47174			
	2024	800	1300	0	80	1900	5	500	0	72	4657	51831			
	2025	800	1300	360	80	0	5	250	1300	36	4131	55962			
	2026	1600	1300	0	80	950	5	500	0	36	4471	60433			
	2027	800	0	720	80	950	10	500	650	72	3782	64215			
	2028	1600	650	0	80	1900	0	250	0	36	4516	68731			
	Total	10400	9100	2880	1200	12350	55	3250	5850	540	45625	-			

Table 4. Solutions of Tamil Nadu’s TC-GEP problem for case 3

Planning Horizon	Year	Types of plants									Added Capacity (MW)	Cumulative Capacity (MW)	EENS×10^6 (MWh)	LOLP ×10^{-6} (Days/ Year)	Overall cost ×10^{10} ($)
		Coal 1	Coal 2	Gas	Oil	Nuclear	Hydro	Wind	Solar	Biogas					
6 year	2017	1600	1300	720	160	1900	5	500	1250	72	7507	30613	0.0402	0.0201	7.7416
	2018	1600	1300	720	160	1900	5	500	1250	36	7471	38084			
	2019	1600	1300	720	160	1900	10	500	1250	36	7476	45560			
	2020	1600	650	720	160	950	5	500	1250	72	5907	51467			
	2021	1600	650	720	160	950	10	250	625	72	5037	56504			
	2022	1600	650	720	160	950	10	500	1250	72	5912	62416			
	Total	9600	5850	4320	960	8550	45	2750	6875	360	39310	-			
12 year	2017	800	1300	360	80	1900	0	250	1300	72	6062	29168	0.0003	0.0001	11.9104
	2018	1600	1300	0	0	950	5	500	0	36	4391	33559			
	2019	800	650	720	80	0	5	250	0	72	2577	36136			
	2020	1600	650	720	0	950	5	500	650	72	5147	41283			
	2021	1600	1300	0	80	1900	0	500	1300	72	6752	48035			
	2022	800	650	360	80	0	10	250	650	72	2872	50907			
	2023	0	650	360	0	1900	10	500	1300	0	4720	55627			
	2024	0	1300	720	0	950	10	0	0	72	3052	58679			
	2025	800	650	720	80	0	0	250	1300	72	3872	62551			
	2026	800	1300	0	80	1900	10	500	1300	72	5962	68513			
	2027	800	1300	0	160	0	5	250	1300	36	3851	72364			
	2028	800	650	360	160	1900	0	250	1300	0	5420	77784			
	Total	10400	11700	4320	800	12350	60	4000	10400	648	54678	-			

Table 5. Solutions of Tamil Nadu's TC-GEP problem for case 4

Planning Horizon	Year	Types of plants									Added Capacity (MW)	Cumulative Capacity (MW)	EENS×10^6 (MWh)	LOLP ×10^{-6} (Days/ Year)	Overall cost ×10^{10} ($)
		Coal 1	Coal 2	Gas	EST	Nuclear	Hydro	Wind	Solar	Biogas					
6 year	2017	1600	1300	720	250	1900	10	500	1250	72	7602	30708	0.0874	0.0027	7.4236
	2018	800	1300	720	250	1900	10	500	1250	36	6766	37474			
	2019	800	650	720	125	1900	10	0	1250	36	5491	42965			
	2020	1600	1300	720	250	1900	10	500	625	72	6977	49942			
	2021	1600	1300	720	250	1900	5	500	1250	72	7597	57539			
	2022	800	1300	360	250	950	5	500	625	72	4862	62401			
	Total	7200	7150	3960	1375	10450	50	2500	6250	360	39295	-			
12 year	2017	800	1300	0	250	1900	5	500	650	36	5441	28547	0.0047	0.0012	11.5194
	2018	1600	650	360	250	1900	0	250	1300	36	6346	34893			
	2019	1600	650	0	0	1900	5	500	650	36	5341	40234			
	2020	1600	650	720	125	950	5	250	650	72	5022	45256			
	2021	1600	650	720	125	1900	0	250	650	36	5931	51187			
	2022	1600	650	360	250	950	10	500	650	72	5042	56229			
	2023	800	650	720	125	950	5	250	650	72	4222	60451			
	2024	1600	1300	360	125	950	5	0	1300	72	5712	66163			
	2025	1600	650	360	125	1900	5	250	1300	36	6226	72389			
	2026	800	0	0	125	1900	5	0	650	36	3516	75905			
	2027	800	0	0	250	1900	10	250	650	36	3896	79801			
	2028	800	650	720	125	0	0	250	1300	72	3917	83718			
	Total	15200	7800	4320	1875	17100	55	3250	10400	612	60612	-			

Table 6. Solutions of Tamil Nadu's TC-GEP problem for case 5

Planning Horizon	Year	Types of plants									Added Capacity (MW)	Cumulative Capacity (MW)	EENS×10^6 (MWh)	LOLP ×10^{-6} (Days/ Year)	Overall cost ×10^{10} ($)
		Coal 1	Coal 2	Gas	Oil	Nuclear	Hydro	Wind	Solar	Biogas					
6 year	2017	1600	1300	720	160	1900	10	500	1250	36	7476	30582	0.0140	0.0124	7.4112
	2018	1600	1300	720	80	1900	5	500	1250	72	7427	38009			
	2019	800	1300	360	160	1900	5	500	1250	72	6347	44356			
	2020	800	650	720	160	950	5	250	1250	72	4857	49213			
	2021	800	650	720	160	1900	10	250	625	36	5151	54364			
	2022	800	1300	720	160	1900	10	500	625	72	6087	60451			
	Total	6400	6500	3960	880	10450	45	2500	6250	360	37345	-			
12 year	2017	800	1300	720	80	1900	5	500	650	72	6027	29133	0.0009	0.0001	11.5714
	2018	800	1300	360	80	950	10	250	1300	72	5122	34255			
	2019	0	0	0	80	950	5	500	650	72	2257	36512			
	2020	800	1300	360	160	0	0	500	1300	0	4420	40932			
	2021	800	1300	720	160	950	5	0	0	36	3971	44903			
	2022	800	0	0	0	950	10	0	1300	72	3132	48035			
	2023	1600	0	360	0	1900	0	250	650	36	4796	52831			
	2024	1600	0	360	160	1900	5	500	0	36	4561	57392			
	2025	0	0	360	0	950	10	0	1300	72	2692	60084			
	2026	1600	650	360	80	950	10	0	0	36	3686	63770			
	2027	800	1300	360	80	950	5	500	0	36	4031	67801			
	2028	800	0	720	80	950	0	0	650	36	3236	71037			
	Total	10400	7150	4680	960	13300	65	3000	7800	576	47931	-			

Table 7. Solutions of Tamil Nadu’s TC-GEP problem for case 6

Planning Horizon	Year	Types of plants									Added Capacity (MW)	Cumulative Capacity (MW)	EENS×10^6 (MWh)	LOLP ×10^{-6} (Days/ Year)	Overall cost ×10^{10} ($)
		Coal 1	Coal 2	Gas	EST	Nuclear	Hydro	Wind	Solar	Biogas					
6 year	2017	1600	1300	720	250	1900	10	500	1250	72	7602	30708	0.0458	0.0040	7.7246
	2018	1600	1300	720	250	950	5	500	1250	72	6647	37355			
	2019	1600	1300	720	250	950	10	250	625	72	5777	43132			
	2020	1600	0	720	250	1900	10	500	1250	72	6302	49434			
	2021	1600	1300	720	125	950	5	250	1250	72	6272	55706			
	2022	1600	650	360	250	1900	10	250	1250	72	6342	62048			
	Total	9600	5850	3960	1375	8550	50	2250	6875	432	38942	-			
12 year	2017	1600	1300	720	125	950	10	0	650	36	5391	28497	0.0002	0.0001	11.6894
	2018	800	650	360	0	950	10	250	650	36	3706	32203			
	2019	0	0	360	250	1900	10	0	0	0	2520	34723			
	2020	1600	1300	720	250	950	5	250	650	36	5761	40484			
	2021	800	650	720	125	1900	10	0	650	72	4927	45411			
	2022	1600	0	360	250	950	5	500	1300	72	5037	50448			
	2023	1600	650	0	125	0	0	500	1300	0	4175	54623			
	2024	0	650	0	125	0	10	250	650	36	1721	56344			
	2025	0	650	360	250	1900	10	500	650	36	4356	60700			
	2026	0	650	360	125	950	5	500	650	0	3240	63940			
	2027	0	650	360	250	950	5	250	1300	36	3801	67741			
	2028	800	0	720	250	950	5	250	650	0	3625	71366			
	Total	8800	7150	5040	2125	12350	85	3250	9100	360	48260	-			

4.3 Case 3: Emission cost scenario (emission penalty cost is included for HEP)

The expansion capacity is 39,310 MW for a 6-year planning period. The contributions of coal 1, coal 2, gas, oil, nuclear, hydro, wind, solar, and biomass plants are 9600 MW, 5850 MW, 4320 MW, 960 MW, 8550 MW, 45 MW, 2750 MW, 6875 MW and 360 MW respectively. The cumulative capacity is 62,416 MW with an overall cost of 7.7416 ×10^{10} $. For a 12-year planning period, the expansion capacity is 54,678 MW. The fuel mix of coal 1, coal 2, gas, oil, nuclear, hydro, wind, solar and biomass plants are 10,400 MW, 11,700 MW, 4320 MW, 800 MW, 12,350 MW, 60 MW, 4000 MW, 10,400 MW and 648 MW respectively. The cumulative capacity becomes 77,784 MW with an overall cost of 11.9104 ×10^{10} $. Due to the emission penalty, the overall cost is increased by 1% than the base scenario.

4.4 Case 4: EST scenario (Oil plant is replaced by pumped storage plant)

The expansion capacity is 39,295 MW for a 6-year planning period. Coal 1, Coal 2, gas, pumped hydro, nuclear, hydro, wind, solar, and biomass plants contribute with capacities of 7200 MW, 7150 MW, 3960 MW, 1375 MW, 10,450 MW, 50 MW, 2500 MW, 6250 MW and 360 MW respectively. The cumulative capacity becomes 62,401 MW with an overall cost of 7.4236 ×10^{10} $. Similarly, the expansion capacity for the 12-year planning period is 60,612 MW. The expansion capacities of coal 1, coal 2, gas, oil, nuclear, hydro, wind, solar, and biomass plants are 15,200 MW, 7800 MW, 4320 MW, 1875 MW, 17,100 MW, 55 MW, 3250 MW, 10,400 MW and 612 MW respectively. The cumulative capacity is 83,718 MW with an overall cost of 11.5194 ×10^{10} $. Even though the investment cost of the pumped hydro plants is high, the overall cost does not increase substantially. Due to the low fuel cost of ESTs, the overall cost is reduced by 2% than the base scenario.

4.5 Case 5: Combination of cases 2 and 3

The added capacity is 37,345 MW for a 6-year planning period. The expansion capacities of coal 1, coal 2, gas, oil, nuclear, hydro, wind, solar, and biomass plants are 6400 MW, 6500 MW, 3960 MW, 880 MW, 10,450 MW, 45 MW, 2500 MW, 6250 MW and 360 MW respectively. The cumulative capacity becomes 60,451 MW with an overall cost of 7.4112×10^{10} $. For a 12-year planning period, the expansion capacity is 47,931 MW. The contributions of coal 1, coal 2, gas, oil, nuclear, hydro, wind, solar, and biomass plants are 10,400 MW, 7150 MW, 4680 MW, 960 MW, 13,300 MW, 65 MW, 3000 MW, 7800

MW and 576 MW respectively. The cumulative capacity is 71,037 MW with an overall cost of 11.5714 $\times 10^{10}$ \$. Therefore, even though the emission penalty is applied on HEP, due to the reduced demand, the overall cost becomes 2% lesser than the base scenario.

4.6 Case 6: Combination of cases 2, 3 and 4

The expansion capacity is 38,942 MW for a 6-year planning period. The added capacities of coal 1, coal 2, gas, pumped hydro, nuclear, hydro, wind, solar, and biomass plants are 9600 MW, 5850 MW, 3960 MW, 1375 MW, 8550 MW, 50 MW, 2250 MW, 6875 MW and 432 MW respectively. The cumulative capacity becomes 62,048 MW with an overall cost of 7.7246 $\times 10^{10}$ \$. For a 12-year planning period, the added capacity is 48,260 MW. The fuel mix of coal 1, coal 2, gas, pumped hydro, nuclear, hydro, wind, solar, and biomass plants are 8800 MW, 7150 MW, 5040 MW, 2125 MW, 12350 MW, 85 MW, 3250 MW, 9100 MW and 360 MW respectively. The cumulative capacity is 71,366 MW with an overall cost of 11.6594 $\times 10^{10}$ \$. Due to the low operating cost of the pumped hydro plants and reduced demand, the overall cost becomes 1% lesser than the base scenario.

The results of Tamil Nadu's TC-GEP problem for 6 different cases obtained for a 6-year planning horizon using the SaDE technique have been validated and compared with DP, which is given in Table 8. It shows that for most cases, the best results in terms of overall cost are obtained by SaDE. The mean execution time is also minimum in SaDE compared to DP. SaDE is better than DP, as DP struggles more to obtain the best results when the problem becomes more complex. The mean execution time in DP will increase several times based on the complexity involved.

Figure 2 shows the convergence characteristic of the SaDE technique of Tamil Nadu's TC-GEP problem for a 6-year planning horizon for case 1. The best result of 7.6531 $\times 10^{10}$ \$ has been obtained after 60 iterations. The overall work done has been graphically illustrated in Figure 3.

Table 8. Comparison of results for Tamil Nadu's TC-GEP problem for a 6-year planning horizon using SaDE and DP

Case No	Technique	Overall cost $\times 10^{10}$ (\$)	Mean execution time (min)
1	SaDE	7.6531	13.45
	DP	7.6600	28.10
2	SaDE	7.2816	11.00
	DP	7.2410	24.30
3	SaDE	7.7416	15.10
	DP	7.8007	27.35
4	SaDE	7.4236	14.15
	DP	7.4311	26.30
5	SaDE	7.4112	20.00
	DP	7.3998	38.45
6	SaDE	7.7246	23.30
	DP	7.7314	42.00

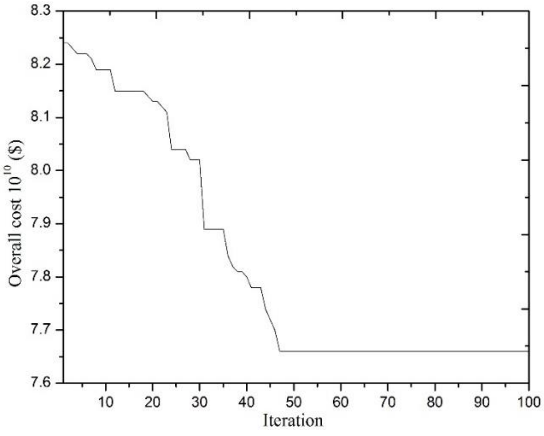

Figure 2: Convergence characteristic of SaDE technique applied for Tamil Nadu's TC-GEP problem for 6-year planning horizon for case 1

4.7 Highlights of the results

The highlights of the solutions obtained from different cases are presented below.

- The solution for the TC-GEP problem is obtained for a real-time test system (Tamil Nadu power system) for six different cases for a 6-year (till 2022) and 12-year (till 2028) planning horizon.
- The average annual demand growth rate in the EC scenario is reduced to 5% from 6%. So, the capacity that needs to be added will also be reduced. Therefore, the overall cost became low.
- The emission penalty costs of HEP are considered in the emission cost scenario. The increased emission cost results in increased overall cost.
- In the EST scenario, the high-emitting oil plants are replaced by the pumped storage plants. As a result, the overall cost is increased because of the high investment cost of EST.
- Case 5 combines cases 2 and 3, which results in an increased overall cost than the base scenario due to the emission penalty. But this scenario gave better results than the EC scenario.
- Case 6 combines cases 2, 3 and 4, which results in increased overall cost because of incorporating EST and the emission penalty. But this scenario gave better results than the EC scenario and EST scenario.

A comparison has been made between the estimated expansion capacity and the real-time expansion capacity of each power plant implemented by the power sector of Tamil Nadu for the year 2017 (CEA 2017). The case-wise comparison with the real-time values and the differences have been provided in Table 9 and Figure 4. Even though cases 3 and 5 have the least difference values, case 2 provides the best results in the context of cost. Moreover, the difference in expansion capacity is in an acceptable range (1.52 %). Hence, the author strongly proposes to follow the results of case 2.

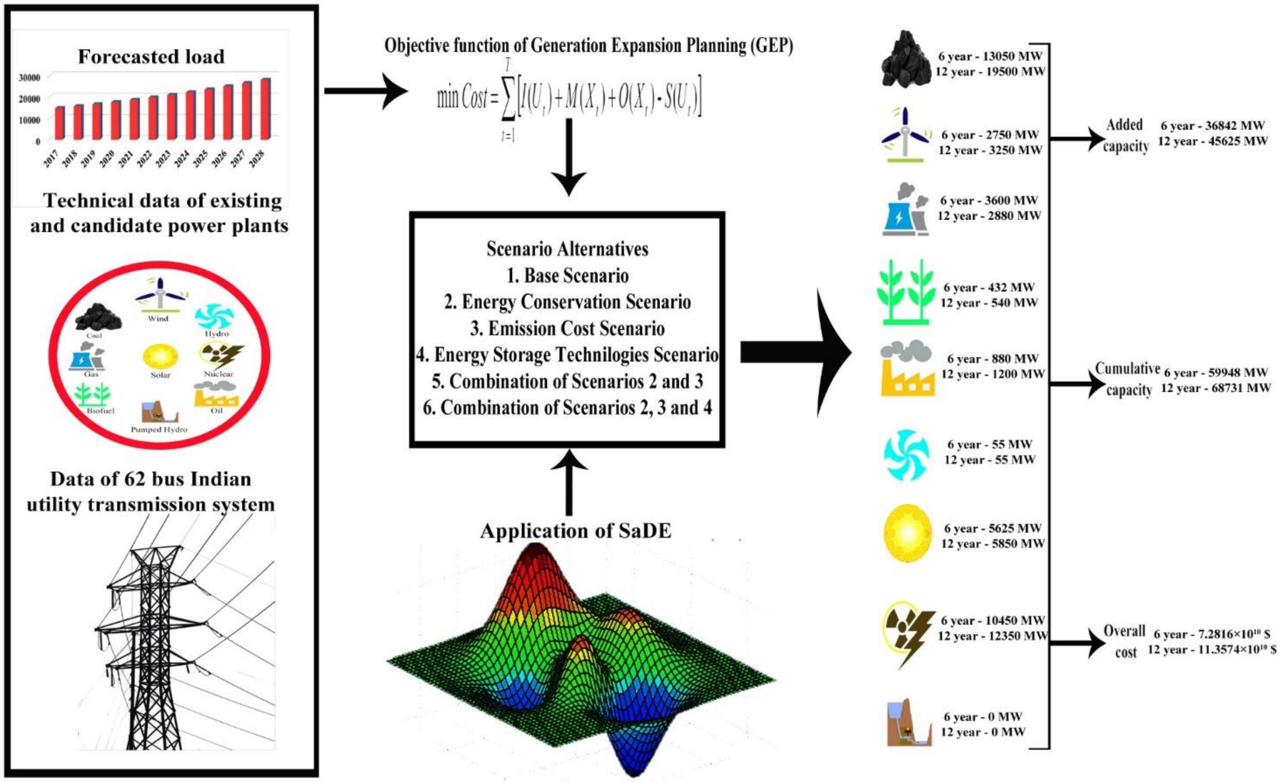

Figure 3. Graphical representation of overall work done

Table 9. Comparison between real-time and estimated expansion capacities for the year 2017 (CEA 2017)

Case	Coal	Gas	Diesel/EST	Nuclear	Hydro	RES	Total	Difference (MW)	Difference (%)
Real-time	13547	1027	412	1448	2203	10820	29457	-	-
1	12175	1746	412	2887	2192	9360	28772	685	2.35
2	12975	1026	572	2887	2192	9360	29012	445	1.52
3	12175	1386	492	2887	2182	10046	29168	289	0.98
4	12175	1026	662	2887	2187	9610	28547	910	3.13
5	12175	1746	662	2887	2187	9646	29303	154	0.52
6	12975	1746	537	1937	2192	9060	28447	1010	3.48

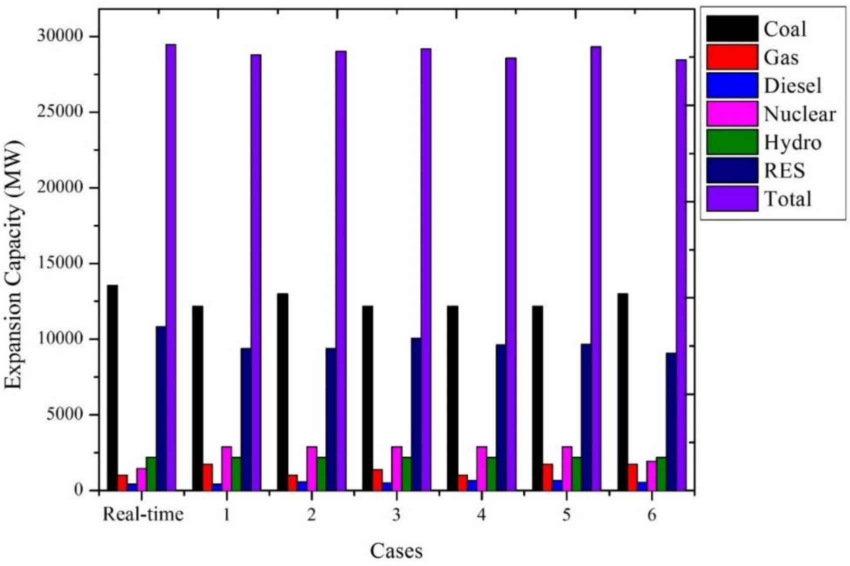

Figure 4. Comparative results of obtained results and executed plan

Table 10 compares the best plans proposed in GEP (Bhuvanesh *et al*. 2018d) and TC-GEP problems. The objectives of both problems are to minimize the overall cost and to increase reliability. Table 10 indicates that the overall cost is slightly increased in the TC-GEP problem, but the EENS and LOLP are considerably reduced. However, due to the consideration of transmission power losses as a constraint, the overall cost and the plan's reliability may increase.

This study has attempted to solve TC-GEP of Tamil Nadu, where the electricity demand is projected to elevate in 2028 twice the demand in 2017. The future generation mix is expected to have an essential change from the past due to the massive integration of RES. In order to connect the remote RES to the main power grid and prevents potential overloads, the additional transmission capacity is essential in the future power system. In this context, this real-world TC-GEP problem for Tamil Nadu has been modeled. The proposed TC-GEP model can avoid the overestimation or underestimation of the optimal capacities of different generation technologies and the required total cost subject to various constraints.

Table 10. Comparison of best results of GEP (Bhuvanesh *et al*. 2018d) and TC-GEP

Problem	Plant-wise expansion capacity (MW)						Cumulative Capacity (MW)	EENS×10^{6} (MWh)	LOLP ×10^{-6} (Days/ Year)	Overall cost ×10^{11} ($)
	Coal	Gas	Oil	Nuclear	Hydro	RES				
GEP	21875	6426	1452	6687	2267	10282	48989	0.0066	0.0861	1.0056
TC-GEP	29575	3906	1612	13337	2237	18064	68731	0.0008	0.0001	1.1357
Difference	7700	2520	160	6650	30	7782	19742	0.0058	0.086	0.1301

5. CONCLUSION

Previously, the GEP problems alone have been solved, and the transmission system is ignored in several power sectors, while the significance of transmission is inevitable for real-time planning. With the intention of constructing the GEP problems as realistic, this paper proposes a model to solve such problems by concurrently defining the site, category and size of every power plant needed to be expanded. The minimization of the overall cost is set as the main objective function by considering the transmission constraints. The reliability indices such as LOLP and EENS have been evaluated to ensure the reliability of the proposed plan. The SaDE technique is executed to solve the TC-GEP problem for six different cases. To validate the performance of SaDE, the outcomes have been compared with DP. The outcomes designate that SaDE is an operative process to solve the projected TC-GEP problem. Also, statistical outcomes express the adaptability of the projected model. The results demonstrated a notable decrement in the execution exertion, whereas the impartially preserving optimality of the extension results. After investigating the outcomes of six dissimilar cases, the authors decided that case 2 offers a minimal cost plan for both 6-year and 12-year planning spans and is easily adaptable for practical implementation. Furthermore, this study aids the power system planners to taking decisions while introducing the EC and EST into Tamil Nadu's TC-GEP problem. This study also offers the best results for the TC-GEP problem for different circumstances and permits the decision makers to choose a condition-precise solution.

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APPENDIX

Table A. Forecasted peak demand for Tamil Nadu (Karunanithi *et al*. 2015)

Year	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028
Demand (MW)	14786	15673	16614	17610	18667	19787	20974	22233	23567	24981	26480	28069
Demand (MW) for EC case	14586	15473	16414	17410	18467	19587	20774	22033	23367	24781	26280	27869

Table B. Technical details of candidate plants (CapitalCost 2013; CostReport 2012; Nadu 2014)(As proposed in Tamil Nadu vision 2023)

Candidate Type	Construction Upper limit	Capacity (MW)	FOR (%)	Operating Cost ($/kWh)	Fixed O&M Cost ($/kW-Mon)	Capital Cost ($/kW)	Emission Rate (kg/MW)	Emission Cost ($/kW-Mon)	Life Time (Years)
Coal 1-North Chennai TPS Stage III &Uppur TPP	3	800	20	0.02	3.15	3246	8.93	2.25	40
Coal 2-Udangudi TPS Stage I & II	4	650	20	0.025	3.15	3246	8.93	2.25	35
Gas-PPN Power Generation Pvt. Ltd	3	360	15	0.03	5.26	651	5.08	2.13	30
Diesel-GMR Vasavi Diesel Power Plant	4	80	14	0.03	3.67	1230	6.65	4.52	30
Nuclear- Kudankulam Nuclear Power Plant	1	950	4	0.035	7.77	6100	0.17	1.63	50
Hydro-Bhavani Barrage	4	5	5	0.005	1.17	5940	0.05	0	40
Wind	1	250	65	0.002	3.29	2231	0.17	0	25
Solar-Adani solar	1	625	70	0.001	2.31	3873	1.22	0	30
Biomass	1	36	10	0.007	8.8	4114	2.51	1	25
Kundah Pumped Storage	4	125	5	0.005	18	5288	0.05	0	40

Table C. Technical details of existing plants in Tamil Nadu (CapitalCost 2013; CostReport 2012) (As on January 2016)

Plant Type	Capacity (MW)	FOR (%)	Operating Cost ($/kWh)	Fixed O&M Cost ($/kW-Mon)	Emission Rate (kg/MW)	Emission Cost ($/kW-Mon)
Coal 1	5075	20	0.02	3.15	8.93	2.25
Coal 2	5000	20	0.025	3.15	8.93	2.25
Natural Gas	1026	15	0.03	5.26	5.08	2.13
Diesel	412	14	0.03	3.67	6.65	4.52
Nuclear	987	4	0.035	7.77	0.17	1.63

Hydro	2182	5	0.005	1.17	0.05	0
Wind	7861	65	0.002	3.29	0.17	0
Solar	173	70	0.001	2.31	1.22	0
Biomass	390	10	0.007	8.8	2.51	1

Table D. Generator Data

Bus. No	Pmax (MW)	Pmim (MW)	Qmax (MVAr)	Qmin (MVAr)	a	b	c
1	400	50	450	0	0.007	6.8	95
2	450	50	500	0	0.0055	4	30
3	450	50	500	-50	0.0055	4	45
4	100	0	150	0	0.0025	0.85	10
5	300	50	300	-50	0.006	4.6	20
6	450	50	500	-50	0.0055	4	90
7	200	50	250	-50	0.0065	4.7	42
8	500	50	600	-100	0.0075	5	46
9	600	0	550	-100	0.0085	6	55
10	100	0	150	0	0.002	0.5	58
11	150	50	200	-50	0.0045	1.6	65
12	50	0	75	0	0.0025	0.85	78
13	300	50	300	-50	0.005	1.8	75
14	150	0	200	-50	0.004	1.6	85
15	500	0	550	-50	0.0065	4.7	80
16	150	50	200	-50	0.0045	1.4	90
17	100	0	150	0	0.0025	0.85	10
18	300	50	400	-50	0.0045	1.6	25
19	600	100	600	-100	0.008	5.5	90

Table E. Load bus data

Bus No.	Load		Bus No.	Load	
	P(MW)	Q(MVAr)		P(MW)	Q(MVAr)
1	0	0	32	0	0
2	0	0	33	46	25
3	40	10	34	100	70
4	0	0	35	107	33
5	0	0	36	20	5
6	0	0	37	0	0
7	0	0	38	166	22
8	109	78	39	30	5
9	66	23	40	25	5
10	40	10	41	92	91
11	161	93	42	30	25
12	155	79	43	25	5
13	132	46	44	109	17
14	120	50	45	20	4
15	155	63	46	0	0
16	0	0	47	0	0
17	0	0	48	0	0
18	121	46	49	0	0
19	130	70	50	0	0
20	80	70	50	0	0
21	0	0	52	0	0
22	64	50	53	248	78
23	0	0	54	0	0
24	58	34	55	94	29
25	0	0	56	0	0
26	116	52	57	0	0
27	85	35	58	0	0

Bus No.	Load		Bus No.	Load	
	P(MW)	Q(MVAr)		P(MW)	Q(MVAr)
28	63	8	59	0	0
29	0	0	60	0	0
30	77	41	61	0	0
31	51	25	62	93	23

Table F. Sites of different buses in Tamil Nadu State

Bus No.	City	Bus No.	City
1	NMTPS	32	TTPS
2	ETPS	33	NAGERKOIL
3	MANALI	34	KAYATHAR
4	KORATUR	35	TTP AUTO
5	BBGAS	36	TUTICORIN(SPIC)
6	TONPET	37	MADURAI 1
7	PARRYS	38	ANNUPANKALAM
8	MYLAPORE	39	ALAGARKOIL
9	G POONDI	40	PUDUKOTTAI
10	MOSUR	41	TRICHI
11	TV ALAM	42	ALUNDUR
12	SPET	43	THANJAVUR
13	ARANI	44	PUGALUR
14	SPUDUR	45	SAMAYAPURAM
15	KOYAMBEDU	46	MADURAI 2
16	SPKOIL	47	SEMBATTY
17	MAPS	48	UDUMALPET 2
18	KADAPERI	49	KADAMPARAI
19	THARAMANI	50	UDUMALPET
20	TV MALAI	50	KUNDAH
21	VILLUPURAM	52	GOPI
22	CUDDALORE	53	ARASUR
23	NLC 1	54	THUDIYALUR
24	EACHENKADU	55	INGUR
25	N2 MIN4	56	MALCO
26	VILLIYANUR	57	MTRT
27	KADALANKUDI	58	MTPS
28	PERAMBALUR	59	UJANAI
29	TVARUR	60	SALEM 2
30	KARAIKUDI	61	SALEM 1
31	PARAMAKUDI	62	DEVAKURCHI

Table G. Transmission line data

Line No.	From Bus	To Bus	R (p.u)	X (p.u)	Susceptance (p.u)	Tap settings (p.u)
1	1	2	0.00305	0.01565	0.0289	0
2	1	4	0.00716	0.03678	0.06794	0
3	1	14	0.00548	0.02813	0.20784	0.9629
4	1	10	0.01569	0.08061	0.14886	0
5	1	9	0.00229	0.01174	0.02168	0
6	1	6	0.00411	0.02113	0.03902	0
7	2	6	0.00168	0.00861	0.0159	0
8	2	3	0.00289	0.01487	0.02746	0
9	3	4	0.00381	0.01957	0.03614	0
10	4	15	0.00411	0.02113	0.03902	0
11	14	15	0.0052	0.02669	0.04928	0.953
12	4	14	0.00411	0.02113	0.03902	1.0155
13	13	14	0.01315	0.06754	0.12474	1.0124
14	12	13	0.01537	0.07897	0.14584	0.9621

Line No.	From Bus	To Bus	R (p.u)	X (p.u)	Susceptance (p.u)	Tap settings (p.u)
15	12	11	0.01905	0.09783	0.18066	0
16	11	10	0.00686	0.03522	0.06504	0
17	4	5	0.00716	0.03678	0.06794	0
18	5	6	0.00575	0.01478	0.00618	0
19	6	7	0.0003	0.00157	0.01156	0
20	7	8	0.00049	0.00168	0.17224	0
21	5	8	0.00575	0.01478	0.00618	0
22	11	16	0.01406	0.07223	0.1334	0
23	16	17	0.00343	0.01761	0.13008	0
24	17	21	0.0185	0.09548	0.17632	0
25	21	22	0.01371	0.07043	0.13008	0
26	22	23	0.00396	0.02035	0.15032	0
27	23	24	0.00305	0.01565	0.0289	0
28	23	25	0.00126	0.0065	0.012	0
29	25	28	0.01062	0.05554	0.10074	0
30	25	26	0.00941	0.04828	0.08918	0
31	25	27	0.01173	0.06026	0.1113	0
32	27	29	0.00533	0.02739	0.05058	0
33	29	30	0.02058	0.10573	0.19526	0
34	20	23	0.02042	0.10487	0.19368	0
35	12	20	0.01981	0.10174	0.1879	0
36	13	17	0.0156	0.0803	0.1483	0
37	14	19	0.00707	0.03631	0.06706	0.963
38	14	18	0.00135	0.00693	0.05116	1.0121
39	14	16	0.00396	0.02035	0.03758	1.0135
40	24	45	0.01219	0.06261	0.11562	0
41	24	41	0.01554	0.07993	0.14742	0
42	41	45	0.00335	0.01712	0.0318	0
43	40	41	0.00609	0.0313	0.05782	0
44	41	42	0.00076	0.00391	0.0289	0
45	42	43	0.00914	0.04696	0.08672	0
46	42	44	0.01417	0.07278	0.13442	0
47	39	42	0.00686	0.03522	0.06504	0
48	39	37	0.00229	0.01174	0.02168	0
49	38	37	0.01044	0.05361	0.099	0
50	38	34	0.01076	0.05525	0.10204	0
50	34	37	0.0199	0.01022	0.18876	0
52	34	33	0.01737	0.08922	0.16516	0
53	34	35	0.00701	0.036	0.06648	0
54	35	32	0.00036	0.00184	0.01358	0
55	33	32	0.01676	0.08609	0.15898	0
56	32	31	0.01787	0.0918	0.16954	0
57	30	31	0.00992	0.05095	0.0941	0
58	40	30	0.00716	0.03678	0.06794	0
59	32	36	0.00305	0.01565	0.0289	0
60	32	37	0.022	0.111301	0.2087	0
61	32	34	0.00396	0.02035	0.15032	0
62	32	46	0.02095	0.10761	0.19874	0
63	36	46	0.01828	0.09391	0.17344	0
64	37	46	0.00104	0.00536	0.0396	0
65	46	44	0.01676	0.08609	0.15898	0
66	44	59	0.00884	0.04539	0.08382	0
67	59	61	0.00922	0.04735	0.08744	0
68	60	61	0.00244	0.01252	0.0925	0
69	61	62	0.01499	0.07701	0.14222	0
70	62	25	0.01383	0.07106	0.13124	0
71	58	61	0.00335	0.01722	0.12718	0
72	58	60	0.0041	0.02113	0.03902	0

Line No.	From Bus	To Bus	R (p.u)	X (p.u)	Susceptance (p.u)	Tap settings (p.u)
73	55	58	0.0067	0.03443	0.0636	0
74	57	58	0.00183	0.00939	0.01734	0
75	57	56	0.00152	0.00783	0.01446	0
76	56	58	0.00259	0.0133	0.02458	0
77	52	61	0.01127	0.05815	0.10738	0
78	52	53	0.01132	0.05815	0.10738	0
79	51	55	0.01417	0.07278	0.13442	0
80	51	53	0.0119	0.06112	0.11288	0
81	51	54	0.00407	0.0209	0.0386	0
82	48	54	0.01254	0.06441	0.11896	0.963
83	48	50	0.00066	0.00337	0.02484	1.0132
84	49	50	0.0067	0.03443	0.0636	0
85	49	48	0.00366	0.01878	0.13876	0.963
86	47	48	0.01371	0.07043	0.13008	0
87	47	46	0.00792	0.0407	0.07516	0
88	60	12	0.01365	0.07012	0.1295	0
89	58	12	0.01211	0.06222	0.1149	0