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Sustainable charging station allocation in the distribution system for electric vehicles considering technical, economic, and societal factors

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ABSTRACT

With a greater emphasis on achieving sustainable objectives, attention has switched to the electrification of the transportation sector. In the modern transportation industry, the burgeoning number of electric vehicles is progressively leading to the phase-out of petroleum-based cars. The quick deployment of electric vehicles, on the other hand, is heavily reliant on the coordinated and rapid construction of an electric vehicle charging ecosystem. The fusion of the electric vehicle charging ecosystem in today's distribution network with penetration of randomly dispersed photovoltaic systems is intricate since it might result in high power losses and voltage variances above permissible limits. This study employs the Grey Wolf Optimization to organize the charging ecosystem in the grid in order to maximize the profits while remaining within the legal bounds of limitations and maintaining user comfort in mind. The study incorporates the human inconvenience factor to provide the better results. The whole research is carried out using an IEEE 33 bus test system, which replicates a balanced radial distribution network for the deployment of electric vehicle charging ecosystems. It has been discovered that strong buses in the system can endure the installation of fast-charging ecosystem up to a certain point. In contrast, deployment of charging ecosystem on weak buses obstructs the functioning of the power system with increased losses, penalties and frequent blackouts.

1. Introduction

The ever-increasing need for energy, coupled with the limited nature of the natural fuel supply, increase in global warming and climate change, are the primary apprehensions in the 21st century. The transportation industry contributes significantly to CO_2 emissions., which play the primary role in climate change triggering significant concerns such as rising ocean water levels and droughts. As per the various research, it has been validated that electrification of the transport sector will prove to be very beneficial as it will phase out internal combustion engines, which will help in low tailpipe emission, less noise pollution, and better efficiency vehicles [1,2]. An electric vehicle is viewed as a viable solution to curb the global warming emissions and fuel dearth problem in the future. Even though electric vehicles in the past few years have increased their penetration in the transport market and are likely to expand in the future; fast adoption of electric vehicles is hampered by various factors such as high cost, limited charging ecosystem, an overloaded grid causing electric disruption. Penetration of electric vehicle charging ecosystem (EVCE) in the existing grid is accompanied by extra stress on the system, causing degradation, system temperature rises and extreme losses resulting in a power failure. Various literature have illustrated the harmful effects of penetration EVCE, such as voltage deviation, power factor loss, harmonics, and peak load [3–6]. To address the problem stated above few design parameters need to be considered, such as sizing the charging ecosystem and optimal placement of EVCE.

Although home charging is one option, the setup cost is high and provides slow charging. Therefore, EVCE with high power output is necessary for electric vehicle user convenience as charging time may vary from 10 min to 30 min depending on battery capacity and charging level. For optimal allocation of charging stations existing work is based on optimization models using different metaheuristic methods considering a different point of view and variables. One among the most emblematic metaheuristic methods Genetic Algorithm was used in [7] to optimally allocate the charging station without considering the losses in the system. This technique of installing the EVCS impacts the distribution system's stability and performance when connected to the grid. To ensure that charging ecosystem are situated most efficiently and

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Nomenclature

A_L	Area of land
$C_{Construction}$	Cost of construction
$C_{Charger}$	Cost of charger
C_{Elec}	Cost of electricity used
C_{EPV}	Energy cost from solar photovoltaic
$C_{Install}$	Cost of installation of charging ecosystem
C_{Land}	Cost of land
C_{Labour}	Cost of labour
$C_{O\&M}$	Operation and maintenance cost
C_{Salv}	Salvation cost of solar photovoltaic plant
Cap_{SPV}	Capacity of solar photovoltaic
CP_{Fast}	Fast charger power rating
CP_{Med}	Medium charger power rating
CF	Correction factor
CUF	Capacity utilization factor
D_t	distance travelled
$\overrightarrow{D}$	Distance vector
E_C	Energy consumed
G_t	Mean radiation
II	Inconvenience index
II_{min}	Minimum Inconvenience index value
II_{max}	Maximum Inconvenience index value
N_{Fast}	Number of fast chargers
N_{Med}	Number of medium chargers
N_{Slow}	Number of slow chargers
N_Y	Number of years
P_{jL}	Power demand by load
P_{ij}	Power flow between bus I and J
P_j^F	Active and reactive power flow beyond jth bus
P_j^{SPV}	Real power supplied by SPV
$\sum_{j=1}^{N_b} P_{loss,j,WSPV}$	Power loss with SPV
$\sum_{j=1}^{N_b} P_{loss,j,WOSPV}$	Power loss without SPV
pf	Power factor
pfp	Power factor penalty
pf_{min}	Minimum power factor
pf_{max}	Maximum power factor
PLP	Power loss penalty
$P_{loss}(i,j)$	Active power loss between i and j
Q_{ij}	Reactive power flow between i and j bus
Q_j^F	Reactive power flow beyond jth bus
Q_{jL}	Reactive power at j bus load
$Q_{loss}(i,j)$	Reactive power loss
r	depreciation rate
R_{ij}	Resistance between i and j bus
$\overrightarrow{R}$	Coefficient vectors
$\overrightarrow{S}$	Coefficient vectors
TDP	Travel distance penalty
T_{Cost}	Total charging ecosystem cost
T_Y	Time period
V_i^2	Voltage at ith bus
VDP	Voltage deviation penalty
V_i^{min}	Minimum voltage limit
V_i^{max}	Maximum voltage limit
W_P	Position vector of the prey
$\overrightarrow{W}$	Position vector of a grey wolf
X_{ij}	Reactance at bus i and j
$\overrightarrow{z_1}$	Random vectors
$\overrightarrow{z_2}$	Random vectors

productively, the authors take into account factors such as voltage, power factor, current, convenience and reliability indices [8–12]. An extra expense will be incurred to install charging stations, which the authors have taken into account when deciding the optimal location for the charging system [9,10]. It was studied that author of [9] performed a test study on 31 bus systems where he aimed to reduce the annual cost related to charging stations but discarded the electricity cost stating it inelastic and irrelevant in an optimal allocation of charging ecosystem.

Further, the authors in [13] extended the research by optimally placing the charging station based on profits for the distribution company with the help of a Genetic Algorithm. In [14], a bi-level approach is used for location charging station based on transportation congestion and energy demand. Authors in [15] provided an optimization model in which facility size and charging cycle scheduling are optimized in order to keep costs low and provide quality service. Furthermore, a turnover optimization challenge was presented in [16] for charging network operators looking to establish or extend their charging networks based on time-varying and location-dependent car needs and power grid restrictions. The authors used fast converging RMCL-E algorithm. Operators of fast-charging stations strive to optimise earnings while satisfying EV charging demand. The optimum functioning of external main grid power and internal electricity from solar photovoltaic (PV) systems and energy storage solutions (ESS) is critical to achieving this goal. To reduce the development and operational cost of PV-powered EV charging ecosystem, a research suggested a mixed-integer programming technique in [17]. Authors in [18], used hybrid genetic and particle swarm optimization to place electric vehicle charging station but considering only the technical and grid side stability while not ensuring the public convenience. A hybrid grey wolf optimization was introduced by authors in [19] to reduce the losses in IEEE 33 Bus system. The results also showed the outperformance with respect to exhaustive search of other algorithm and provided best results in global optima. While another research was conducted to place the energy storage system in a distributed network of 30 bus and 69 bus by authors in [20] with the help of grey wolf optimization. In [21], an optimization was introduced to site the distribution generation in IEEE 69 bus system with the help of grey wolf optimization and showed prominent results.

Studies have shown that the placement considerations for charging stations are driven by either profit maximization or the maintenance of technical characteristics essential to the reliability of the grid. Moreover, it has been also observed that the human factor such as inconvenience caused to customer for charging of EV is not considered. Human factor plays an important role when dispensing a technology to masses since if it's not suitable the charging infrastructure might not be utilized properly and cause losses to the system in terms of capital. Therefore this study considers both monetary and technical parameters with human behaviour for getting optimal location for the penetration of charging infrastructure in the existing grid.

This study extends the previous research by adding a few factors to make a robust framework for cost maximization while keeping minimum losses in the system. The critical contribution of this study is:

- Calculation of the number of ports required for the smooth operation of the charging ecosystem.
- Optimal planning of charging ecosystem placement for the minimum cost required to set up and maximize the profits while keeping in check the technical parameters and human behaviour.

Table 1
Power factor penalty range.

S. No.	Power factor range	Penalty
1	$0.895 \leq pf < 0.900$	0 %
2	$0.885 \leq pf < 0.895$	1 %
3	$0.875 \leq pf < 0.885$	1.5 %
4	$0.865 \leq pf < 0.875$	2 %
5	$0.855 \leq pf < 0.865$	2.5 %
6	$0.845 \leq pf < 0.855$	3 %
7	$0.835 \leq pf < 0.845$	3.5 %
8	$0.825 \leq pf < 0.835$	4 %
9	$0.815 \leq pf < 0.825$	4.5 %
10	$0.805 \leq pf < 0.815$	5 %

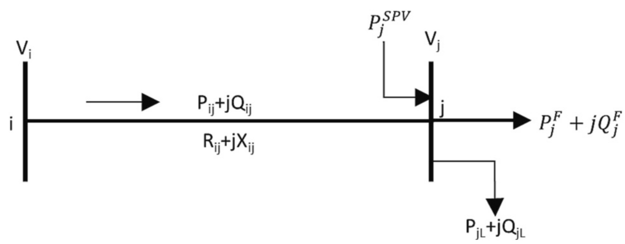

Fig. 1. Two-bus system.

2. Problem formulation and mathematical modelling

The optimal placement of the sustainable charging ecosystem is a multidimensional nature problem. In this study, the objective function considers the economical aspect and electric network stability, such as fixed capital cost, equipment cost, operation and maintenance cost, voltage deviation penalty, and user inconvenience penalty.

The average space required for parking space is assumed to be 25 m^2. In contrast, when including the electric equipment service area and other amenities, the average area per car in a charging station came out to be 45 m^2. The initial development and installation cost $C_{Install}$ is represented by Eq. (1).

$$C_{\mathrm{Install}}(i) = C_{\mathrm{Land}}(\mathrm{i}) + C_{\mathrm{Labour}}(\mathrm{i}) + C_{\mathrm{Construction}}(\mathrm{i}) + C_{\mathrm{Charger}}(\mathrm{i}) \tag{1}$$

where $C_{Land}(i)$ is the land cost, $C_{Labour}(i)$ is the cost associated with the labor charges, $C_{Construction}(i)$ is the cost associated with the development of the charging station, and $C_{Charger}(i)$ is the amount required as per the number of charging ports and type of charging incorporated in the station. $C_{Land}(i)$ can either be a constant value when purchasing land or based on a lease defined in Eq. (2). Cost/m^2 variable depicts the value of land per m^2 of area. Similarly, cost of charger is epitomized by Eqs. (3), and (4) explicates the construction cost for the setting up of building and solar photovoltaic plant. In Eq. (4) the value of ₹11,000/m^2 is the constant value which is being charged for construction of charging station per meter square where as the value of ₹60/Wh is the construction cost per Wh for solar photovoltaic plant.

$$C_{\mathrm{Land}}(i) = N_{\mathrm{Y}}*A_{\mathrm{L}}(\mathrm{i})*\left(\frac{Cost}{m^2}\right) \tag{2}$$

$$C_{\mathrm{Charger}}(i) = N_{Fast}(i)*C_{InstallF}(i) + N_{Med}(i)*C_{InstallM}(i) + N_{Slow}(i)*C_{InstallS}(i) \tag{3}$$

$$C_{\mathrm{Construction}}(\mathrm{i}) = \left(\frac{₹11000}{m^2}*A_{\mathrm{L}}(\mathrm{i})\right) + \left(\frac{₹60}{Wh}*Cap_{SPV}\right) \tag{4}$$

where, N_Y is the number of years if taking land on lease, $A_L(i)$ associated with the charging station area at bus *i*. $N_{Fast}(i)$, $N_{Med}(i)$, $N_{Slow}(i)$ represents the number of fast, medium, and slow chargers being installed, whereas $C_{InstallF}(i)$, $C_{InstallM}(i)$, $C_{InstallS}(i)$ represents the cost per charging port for fast, medium, and slow chargers respectively. The fast chargers also called as level 3 charging usually takes 15–20 min to charge from 20 % to 80 % of battery capacity with power output varying between 36 and 240 kW. Medium chargers or level 2 chargers can be used at commercial places with 400 V supply with power output touching 20 kW and charging time between 4 and 8 h. Slow chargers or level 1 chargers are home outlet chargers with 3.3 kW power outlet and charging time ranging between 8 and 16 h [22,23]. $Cap_{SPV}(i)$ in Eq. (5) illustrates the capacity of solar photovoltaic that can be installed on the charging station. Panel conversion efficiency was depicted by η_{PV} and G_t is the standard radiation available.

$$Cap_{SPV}(i) = \eta_{PV}*A_{\mathrm{L}}(\mathrm{i})*G_t \tag{5}$$

The total operation cost is illustrated in Eq. (6) by $C_{Operation}$, which is the sum of cost incurred due to electricity purchase, cost of energy for energy supplied by solar PV plant, operation and maintenance of charging ecosystem, and total salvation cost of PV plant after 25 years.

$$C_{\mathrm{Operation}} = C_{\mathrm{Elec}} - C_{\mathrm{EPV}} + C_{O\&M} - C_{\mathrm{Salv}} \tag{6}$$

$$C_{\mathrm{Operation}} = \Bigg\{ ((N_{Fast}(i)*CP_{Fast}(i) + N_{Med}(i)*CP_{Med}(i) + N_{Slow}(i)*CP_{Slow}(i))\, *P_{Elec}*T_Y*CF) - (Cap_{SPV}*P_{Elec}*T_Y*CUF) + C_{O\&M} - \left(Cap_{SPV}*60*\left(\frac{(100+r)}{100}\right)^{NY}\right)\Bigg\} \tag{7}$$

Eq. (7) represents the elaborative version of the cost of operation of the charging ecosystem. Where P_{Elec} is the tariff of electricity, T_Y is the time period, *CUF*, and Cap_{SPV} is associated with capacity utilization factor and capacity of solar photovoltaics, respectively.

The penalty cost is depicted in Eq. (8) by $C_{Penalty}$, which is the sum of penalty caused due to user inconvenience to traveling long distances for charging, penalty caused by voltage deviation in the system by electric vehicle penetration, and the penalty for extra power losses incurred when charging stations were installed in the electric network. Voltage deviation penalty (*VDP*), *Travel distance penalty* (*TDP*), and Power loss penalty (*PLP*) are explicitly explained in Eqs. (9), (10), and (11).

$$C_{Penalty} = VDP + TDP + PLP \tag{8}$$

$$VDP = E_C*\left(\frac{Energy\ Cost}{kWh}\right)*pfp*T_Y \tag{9}$$

$$TDP = D_t*number\ of\ vehicle*\frac{Travel\ Cost}{K.M.}*T_Y \tag{10}$$

$$PLP = (P_{Loss} - 202.7)*T_Y*\frac{Energy\ Cost}{kWh} \tag{11}$$

where, E_C is the energy consumed, *pfp* is the power factor penalty, D_t distance travelled. The value of *pfp* has been provided in Table 1 [24].

Considering the charging station is sustainable, it is installed with solar photovoltaic system. The Total carbon emission for station without solar (TCE_{NSS}) in Eq. (12) is calculated by adding the carbon emission from generating power for extra load on the grid and losses in the system. Whereas the Total carbon emission for station with solar plant (TCE_{SS}) in Eq. (13) is calculated by adding the carbon emission from generating power for extra load on the grid and losses in the system and adjusting the carbon emission saving from input power from the solar plant. The production of CO_2 during manufacturing the solar panel is neglected because the manufacturing and installation CO_2 emission of coal fire plant is neglected.

$$\mathrm{TCE}_{NSS} = \{1600*0.7*T_Y\} + \{(P_{Loss} - 202.7)*0.7*T_Y\} \tag{12}$$

$$\text{TCE}_{SS} = \{1600^*0.7^*T_Y\} + \{(P_{Loss} - 202.7)^*0.7^*T_Y\} - \left\{\frac{Cap_{SPV}(i)}{1000}{}^*0.7\frac{kg}{kW}{}^*T_Y{}^*CUF\right\} \tag{13}$$

The IEEE 33 bus system is used as the base network topology to calculate the voltage deviation for necessary penalty calculation and is subjected to a forward-backward sweep load flow algorithm [25]. Owing to the high R/X ratio, the usual techniques of load flow analysis, such as the Newton Raphson method, have limitations for determining the voltage of a radial distribution network. Consequently, the forward and backward sweep algorithm is used to determine the voltage of the distribution network's buses [26,27]. A basic 2 bus system is shown below in Fig. 1 to provide the information of load flow in the system. Eqs. (14) and (15) represents the active power and reactive power at point j, whereas Eqs. (16) and (17) represents active and reactive power to be supplied from point i to point j. Similarly, Eq. (18) represents the calculated voltage using load flow analysis.

$$P_{ij}^{'} = P_j^F + P_{jL} - P_j^{SPV} \tag{14}$$

$$Q_{ij}^{'} = Q_j^F + Q_{jL} \tag{15}$$

$$P_{ij} = P_j^F + P_{jL} - P_j^{SPV} + \frac{R_{ij}}{V_i^2}\left(P_{ij}^{'2} + Q_{ij}^{'2}\right) \tag{16}$$

$$Q_{ij} = Q_j^F + Q_{jL} + \frac{X_{ij}}{V_i^2}\left(P_{ij}^{'2} + Q_{ij}^{'2}\right) \tag{17}$$

$$V_j^2 = V_i^2 + 2\left(P_{ij}R_{ij} + Q_{ij}X_{ij}\right) + \frac{R_{ij}^2 + X_{ij}^2}{V_i^2}\left(P_{ij}^2 + Q_{ij}^2\right) \tag{18}$$

$$P_{loss}(i,j) = I_{ij}^2 R_{ij} \tag{19}$$

$$Q_{loss}(i,j) = I_{ij}^2 X_{ij} \tag{20}$$

3. Objective function and constraints

This aim of this study is to minimize the overall total cost of the charging station ecosystem; which included electrical equipment's, penalty if so any in terms of voltage deviation, user inconvenience, and installation cost. The objective function is given by Eqs. (21) and (22) which is expressed by the minimization of the total installation, operation cost of charging and penalty incurred while operating the plant.

$$F_1 = min\sum T_{Cost} \tag{21}$$

$$F_1 = min\left(C_{\text{Install}} + C_{\text{Operation}} + C_{Penalty}\right) \tag{22}$$

The above-mentioned target function is minimized in accordance with several operational limitations, ensuring that charging station infrastructure design does not jeopardize the electrical grid. In constructing the paradigm for optimum EVCS placement and size, the following inequality restrictions are imposed, represented by Eqs. (23)–(28).

- Voltage limits:

$$V_i^{min} \le V_i \le V_i^{max}\ i \in \text{n} \tag{23}$$

where, V_i^{min} and V_i^{max} represents the minimum and maximum permissible voltage deviation without any penalty.

- Power factor

$$pf_{min} \le pf \le pf_{max}\ i \in \text{n} \tag{24}$$

where, pf_{min} and pf_{max} represents the minimum and maximum permissible power factor deviation without any penalty.

- Power balance

$$P_{Gi} + \sum_{j=1}^{N_{SPV}} P_j^{SPV} = \sum_{j=1}^{N_l} P_{Dj} + \sum_{j=1}^{N_b} P_{Loss,j} \tag{25}$$

$$Q_{Gi} + \sum_{j=1}^{N_{SPV}} Q_j^{SPV} = \sum_{j=1}^{N_l} Q_{Dj} + \sum_{j=1}^{N_b} Q_{Loss,j} \tag{26}$$

The left-hand side in Eqs. (23) and (24) represents generated active and reactive power combinedly from conventional grid and solar PV system respectively; and the right-hand side represents required active and reactive power.

- Active power loss: System active power loss with SPV should be less than system loss without SPV

$$\sum_{j=1}^{N_b} P_{loss,j,WSPV} < \sum_{j=1}^{N_b} P_{loss,j,WOSPV} \tag{27}$$

The above equation demands the system with installed solar capacity should reduce the losses else, the system is not considered feasible.

- Inconvenience Index (II): This constraint restricts the charging station placement nearby. If a customer has to travel across 5 buses (locations), then it includes in inconvenience value.

$$II_{min} \le II \le II_{max} \tag{28}$$

4. Electric vehicle charging ecosystem infrastructure formulation

In India, the present market penetration is electric vehicles on the road is just 0.42 %, and as per the aim set up by the government by 2025 and 2030, India will observe a penetration of up to 40 % and 100 % by 2050 [28,29]. There are a total of 12,08,225 electric vehicles, and India's transportation sector caters to a total of 28,78,67,282 vehicles on the road [28]. India is a country where the economics of every product is seen as the first factor in purchasing; thus, as per reports in India, most of the vehicles sold are in the semi-luxury or utility range thus while designing the charging ecosystem medium charging ports are installed most rather than fast charging stations [30,31]. In India as per data there are 70,698 amount of fuel stations [32–34] which serves to 28,78,67,282 vehicle fuelling. On an average 4000 vehicle are being refuelled per day per station. If taking 40 % penetration of electric vehicle it accounts for 1600 vehicle being charged at single charging station per day. Considering the vehicle buying trend in India 10 % of the charging ports are fast chargers, 60 % medium chargers and 30 % are slow chargers. The total charging station capacity comes out to be 1600 kW. The total area for charging ecosystem development will spread across the area of 3060 m^2. The total solar capacity for the aforementioned region has been assessed to be 716.040 kW.

5. Methodology for objective function optimization

The objective function proposed above and the following constraints make it evident that it is a problem associated with Mixed Integer Non-Linear Programming (MINLP). Typical mathematical programming methodologies are impractical for dealing with this kind of problem. Therefore, Grey Wolf Optimizer, a metaheuristic algorithm, is being employed to solve it. A new optimization approach based on grey wolves was suggested by Mirjalili in 2014 [35]. They form a formidable social hierarchy. As the leader of the hierarchy, the Alpha (α) is in charge of a variety of duties, including hunting, resting, and determining when the pack is awake. The second tier of the grey wolf hierarchy is beta (β),

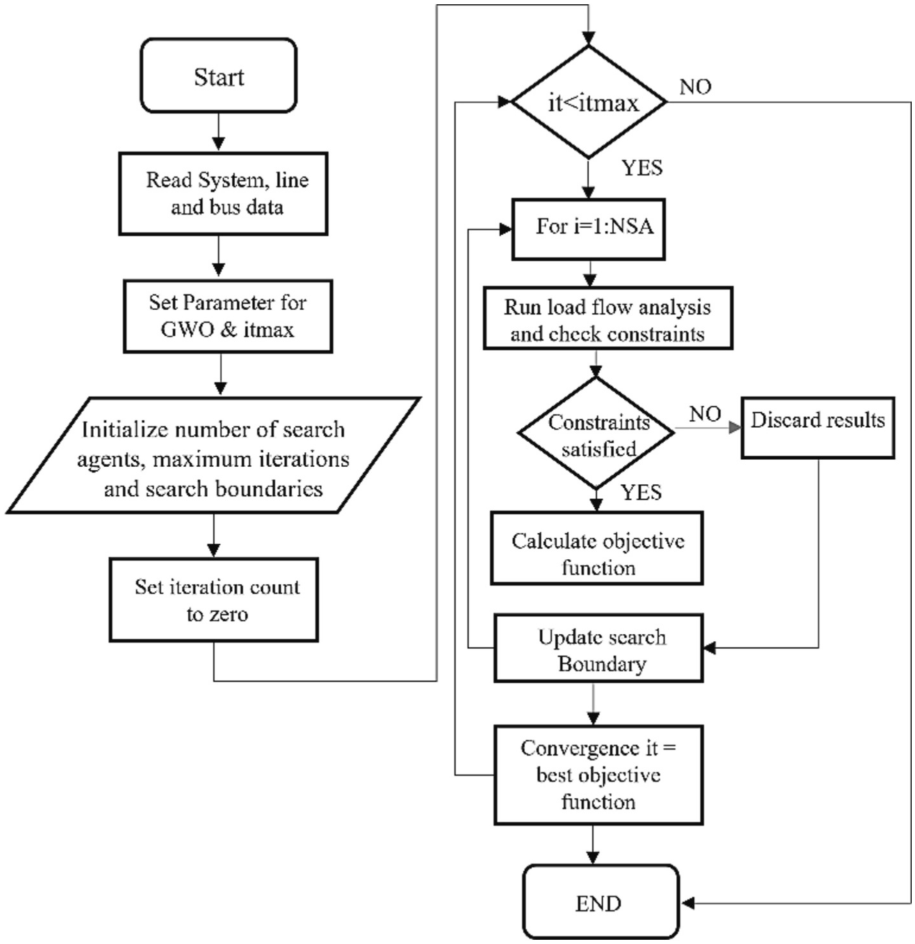

Fig. 2. Flow chart for GWO.

which serves as an advisor to alpha and is the best contender for the position of alpha. Beta wolf also works as a group organizer. Delta (δ) is the third runner in the hierarchy after alpha and beta and constitutes the younglings in the pack. The lowest level of the hierarchy is Omega (γ). The main phases of the grey wolf hunting mechanism are tracking, chasing, encircling, and finally attacking. The alpha (α) is considered as the fittest solution of the function and is used to quantitatively designate the social structure of wolves while constructing GWO. As a result, the second and third-best solutions are referred to as beta (β) and delta (δ). The remaining possible solution are labeled as omega (γ). Several benefits the Grey Wolf method (GWO) has over other popular algorithms have led to its recognition as a potent optimisation method. The capacity to balance exploration and exploitation, a critical component in optimisation issues, is a major benefit. The GWO algorithm promotes productive collaboration and communication among search agents by modelling their actions after the social structure and hunting techniques of grey wolves. The algorithm is able to rapidly explore complicated search spaces and find optimum or near-optimal solutions because of the cooperative behaviour of its components.

The GWO method is not only cooperative, but also remarkably resilient when put to the test against a broad variety of optimisation issues. It may be used for a wide variety of problems, both continuous and discrete, as well as those with constraints. Because of its adaptability, the GWO algorithm is a viable option for scientists and professionals in many fields [35]. Grey wolf encircling behaviour during hunt is expressed by Eqs. (29) and (30).

$$\overrightarrow{D} = |\overrightarrow{R} * W_P(i) - \overrightarrow{W}(i)| \tag{29}$$

$$\overrightarrow{W}(i+1) = \overrightarrow{W_P}(i) - \overrightarrow{S} * \overrightarrow{D} \tag{30}$$

where, $\overrightarrow{R}$ and $\overrightarrow{S}$ are coefficient vectors, i indicates the iteration, W_P represents the prey position vector, and grey wolf position vector is depicted by $\overrightarrow{W}$. The coefficients $\overrightarrow{R}$ and $\overrightarrow{S}$ can be obtained via Eqs. (31) and (32).

$$\overrightarrow{R} = 2\overrightarrow{r} * \overrightarrow{z_1} - \overrightarrow{r} \tag{31}$$

$$\overrightarrow{S} = 2\,\overrightarrow{z_2} \tag{32}$$

where, $\overrightarrow{r}$ is linearly reduced from 2 to 0 as the iteration advances and $\overrightarrow{z_1}$ and $\overrightarrow{z_2}$ are random vectors in [0,1]. Grey wolves, unlike other wolves, can detect and swiftly surround their target. The alpha is generally in charge of leading the pack on a hunt. It is possible that the beta and delta will sometimes assist in hunting. Consequently, the perfect location in an abstract search space (prey) is initially not known. In order to mathematically emulate grey wolf hunting behaviour, we assume that the alpha (best candidate solution), beta, and delta wolves have greater knowledge of potential prey locations. As a result, we keep the top three results and require the rest of the search agents (including the omegas) to adjust their rankings in accordance with them. In this respect, the following formulae have been presented from Eqs. (33)–(39).

$$\overrightarrow{D_\alpha} = |\,\overrightarrow{S_1} * \overrightarrow{W_\alpha} - \overrightarrow{W}| \tag{33}$$

$$\overrightarrow{D_\beta} = |\,\overrightarrow{S_2} * \overrightarrow{W_\beta} - \overrightarrow{W}| \tag{34}$$

Table 2
Initialization parameters for GWO.

S. No.	Parameters	Value
1	Number of search agents	100
2	Maximum number of iterations	100
3	Lower bound	2
4	Upper bound	33
5	Number of variables	4

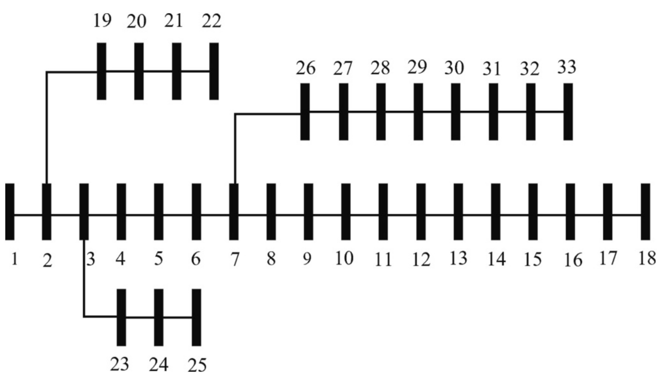

Fig. 3. IEEE 33 bus system.

Table 3
The value of defined parameters of objective function.

S. No.	Parameters	Value
Charging station		
1	Land cost per m^2 [36]	₹ 70,080
2	Fast charger cost [37]	₹ 3,25,000
3	Medium charger cost [38]	₹ 1,25,000
4	Slow charger cost [39]	₹ 80,000
5	Cost of construction per m^2 [40]	₹ 11,000
6	Cost of labour per m^2 [41]	₹ 2500
7	Fast charger rating [42]	50 kW
8	Medium charger rating [42]	25 kW
9	Slow charger rating [42]	10 kW
10	Unprecedented power interruption	10 %
11	Cost of energy per kWh	₹ 6
12	Travel cost per K.M.	₹ 0.8
Solar photovoltaic plant		
13	Capacity utilization factor [43]	20 %
14	Solar conversion efficiency [44]	23.4 %
15	Solar cell type	Mono-crystalline
16	Solar irradiance	1000 W/m^2
17	Operation and maintenance	₹ 0.5/watts
18	Plant depreciation rate	10 %/year
19	Plant type	Rooftop mounted
20	CO_2 emission saving per kW [45]	0.7 Kg of Co$_2$/kW

$$\overrightarrow{D_\delta} = |\overrightarrow{S_3} * \overrightarrow{W_\delta} - \overrightarrow{W}| \tag{35}$$

$$\overrightarrow{W_1} = |\overrightarrow{W_\alpha} - \overrightarrow{R_1} * \overrightarrow{D_\alpha}| \tag{36}$$

$$\overrightarrow{W_2} = |\overrightarrow{W_\beta} - \overrightarrow{R_2} * \overrightarrow{D_\beta}| \tag{37}$$

$$\overrightarrow{W_3} = |\overrightarrow{W_\delta} - \overrightarrow{R_3} * \overrightarrow{D_\delta}| \tag{38}$$

$$\overrightarrow{W}(i+1) = \frac{\overrightarrow{W_1} + \overrightarrow{W_2} + \overrightarrow{W_3}}{3} \tag{39}$$

The working of GWO is expressed in flow chart as represented in Fig. 2.

The pseudo-code for GWO is represented in the following steps.

The pseudo-code for GWO is represented in the following steps.

Step 1: Initialize the program via entering the Bus and Line data

Step 2: Compute the power loss through the forward, backward sweep load flow method.

Step 3: Initialize GWO

Step 4: Initialize the grey wolf population W_i

Step 5: Initialize R, S, r.

Step 6: Compute every grey wolf agent's objective function fitness value.

Step 7: Set: W_α = best outcome of the search agents
W_β = the second-best outcome of the search agents
W_δ = the third best outcome of the search agents

Step 8: While (t < max number of iteration)
Initialize z_1 and z_2 values
Update R, S, r in Equation (31) and (32)
For i
For j
Positions update of each grey wolf agent by means of Equations (33)–(39)
End j
End i
Compute the fitness of all agents with the new positions
i = i+ 1
End while
return W_α

Table 2 represents the initialization parameters used for the grey wolf optimization.

6. Case study

The objective function depicted in Eqs. (19) and (20) is processed using MATLAB 2019b software, and the hardware operated is 64-bit Windows 10 with a Ryzen 5 CPU and RX-560 GPU. The proposed framework for optimal electric vehicle charging ecosystem allocation is subjected to the IEEE 33 Bus radial distribution system. The total IEEE 33 bus system consists of 33 buses and 32 lines as shown in Fig. 3 with bus 1 considered as a slack bus. The system base voltage is 12.66 kV with a total base caseload is 3.715 MW. This research takes into account four charging stations, each with a capacity of 400 kW, increasing the overall load of the system by 1600 kW. As the load increases, so do the system's losses, resulting in voltage and power factor deviations. As per the objective defined in equation number 19 and 20 regarding cost minimization for allocation of charging stations, the charging stations are placed at different buses till we get the minimum value of the function, keeping in check the value defined by constraints. The pre-defined parameters used in this study are represented in Table 3. In this study following cases are considered:

Case 1. The base case where no charging station is connected.

Case 2. Charging ecosystem placement considering voltage limit constraints without the solar photovoltaic plant input.

Case 3. Charging ecosystem placement considering inconvenience index and voltage limit constraints without the solar photovoltaic plant input.

Case 4. Charging ecosystem placement considering location parameters, inconvenience index, and voltage limit constraints without input from the solar photovoltaic plant.

Case 5. Charging ecosystem placement considering voltage limit constraints with the solar photovoltaic plant input.

Case 6. Charging ecosystem placement considering inconvenience index and voltage limit constraints with input from the solar photovoltaic plant.

Table 4
Results as per different cases.

	Active power loss (kW)	Inconvenience Index (II)	Voltage (p.u.)	Power loss penalty (₹)	Voltage deviation penalty (₹)	Travel distance penalty (₹)	Total cost (₹)	Time (s)	Optimal location
Case 1	202.70		0.949		0.00			0.04	
Case 2	251.40	31.25	0.9420	6,39,91,800	0	7,56,02,304	2,31,76,20,393.23	15.80	2,7,19,20
Case 3	310.10	6.25	0.9375	14,11,23,600	35,04,000	48,77,568	2,32,75,74,802.01	15.62	2,12,19,27
Case 4	325.00	6.25	0.9343	16,07,02,200	35,04,000	48,77,568	2,34,71,22,902.68	16.20	2,12,23,27
Case 5	246.50	31.25	0.9432	5,75,53,200	0	7,56,02,304	2,17,17,95,165.65	16.54	2,7,19,20
Case 6	298.8000	6.25	0.9367	12,62,75400	35,04,000	48,77,568	2,17,33,47,517.13	16.62	2,12,19,27
Case 7	312.00	6.25	0.9356	14,36,20,200	35,04,000	48,77,568	2,14,54,33,624.10	16.81	2,12,23,27

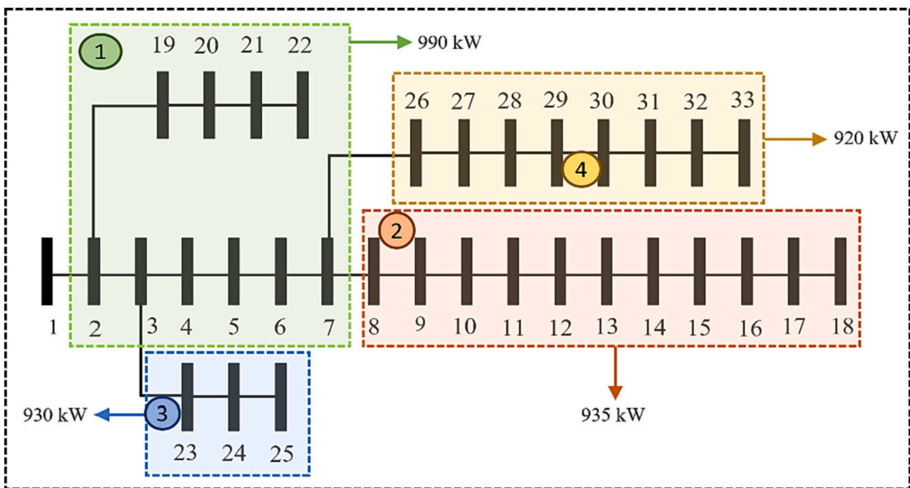

Fig. 4. IEEE 33 bus distribution system with defined segments.

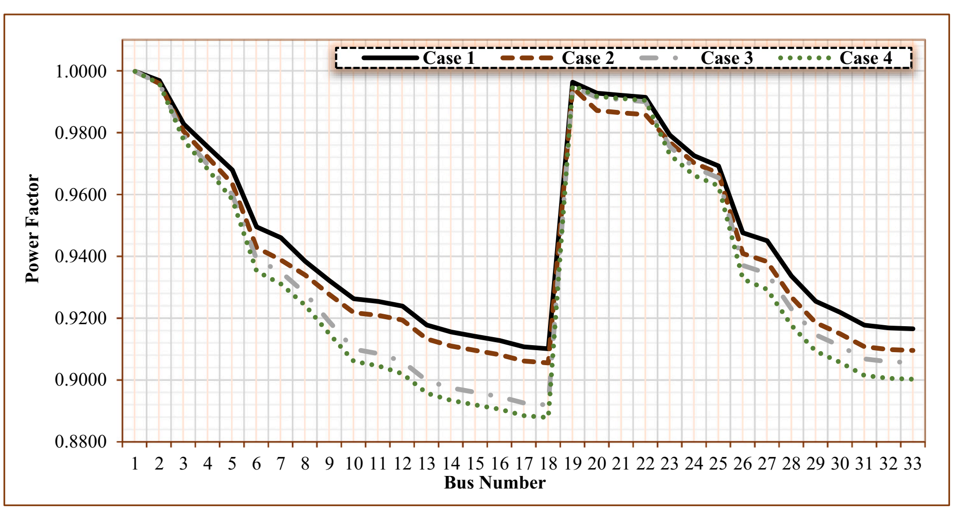

Fig. 5. Power factors output for Case-1 (Base Case), Case-2, 3 and 4 (without PV).

Case 7. Charging ecosystem placement considering location parameters, inconvenience index and voltage limit constraints with input from the solar photovoltaic plant.

The significance of the aforementioned cases lies in their capacity to establish a comprehensive understanding of the various factors contributing to the determination of the most advantageous and technically viable scenario. Each case under consideration entails distinct inputs, as certain instances prioritize the implementation of renewable energy sources for grid stabilization during periods of overloading, while others emphasize user convenience as the primary objective. By diligently comparing and contrasting the outcomes obtained from these diverse cases, we are able to discern the optimal configuration for installing a charging station within a given society.

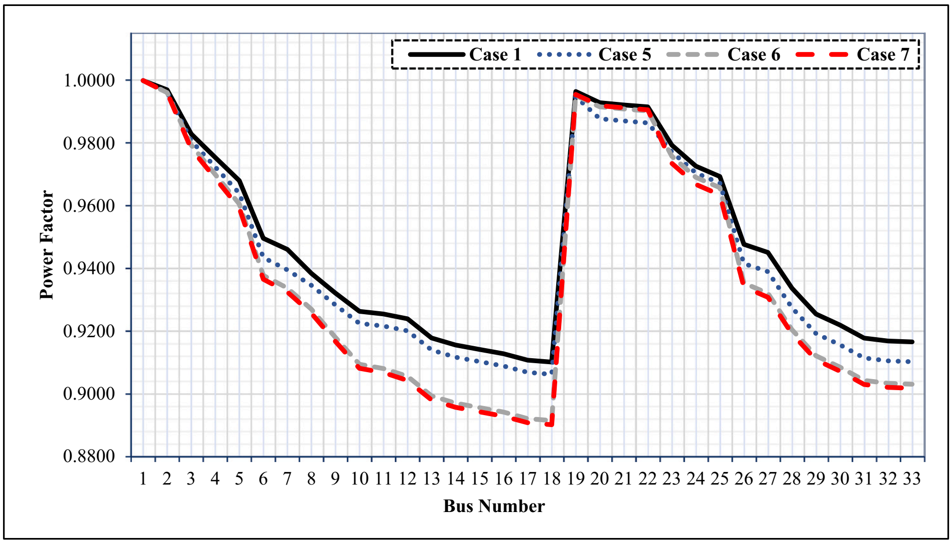

Fig. 6. Power factors output for Case-1 (Base Case), Case-5, 6 and 7 (with PV).

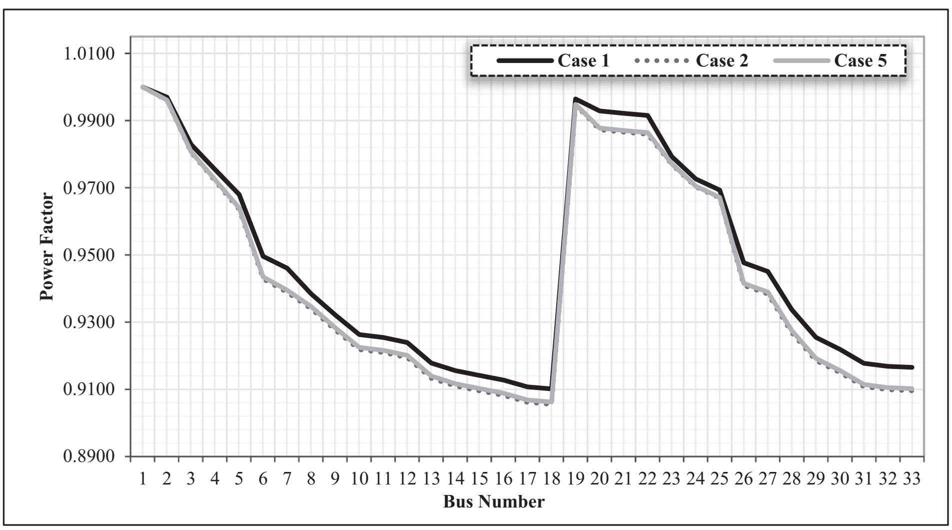

Fig. 7. Comparison of power factors output of Case1 (Base Case), Case-2 and 5 i.e., without and with solar PV.

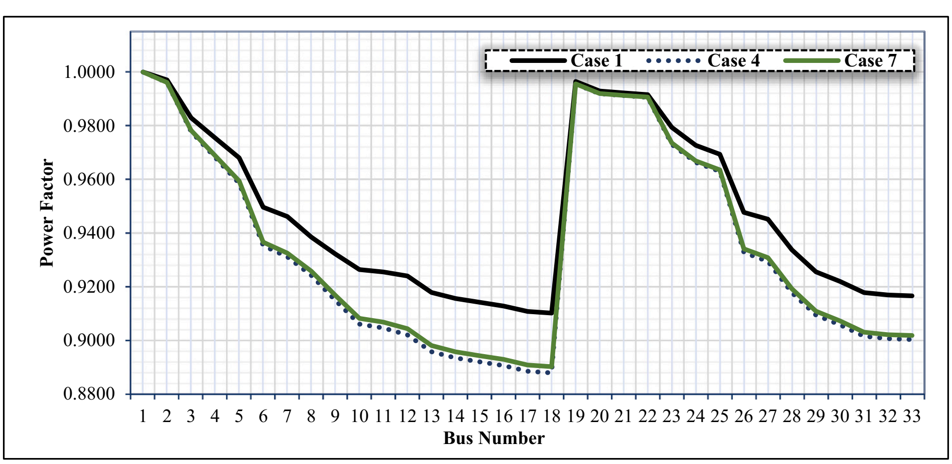

Fig. 8. Comparison of power factors output of Case1 (Base Case), Case-4 and 7 i.e., without and with solar PV.

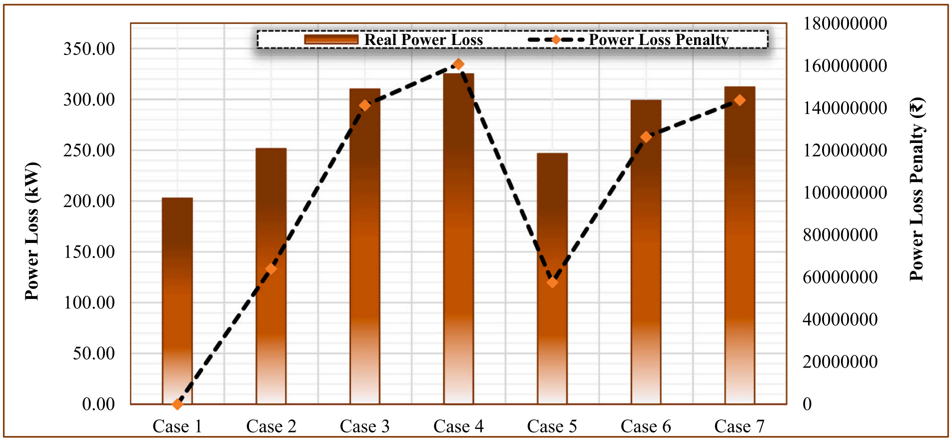

Fig. 9. Power loss and power loss penalty for all the considered cases.

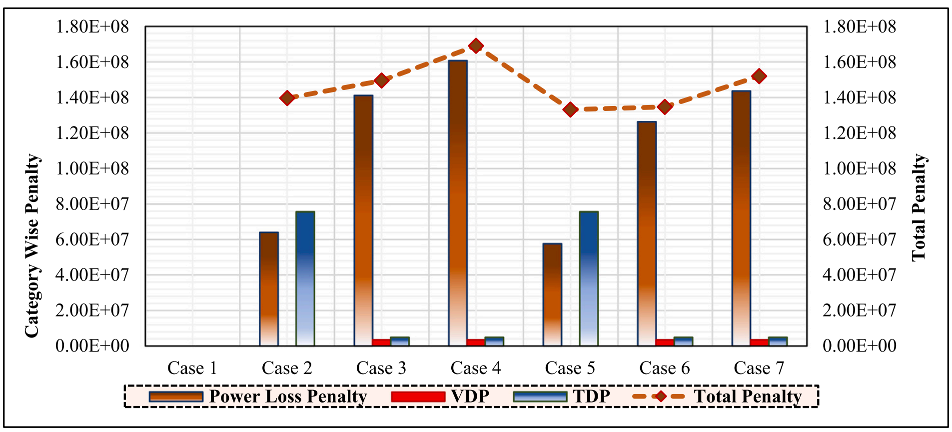

Fig. 10. Total penalty and penalty for different category.

Table 5
Comparison of CO_2 emission from conventional and electric vehicle.

Model	Range (a)	Battery capacity (b)	Average (c) = (a/b)	CO_2 emission/unit (d) [46]	CO_2 emission/K.M. (e) = (d/c)
Tata Nexon EV [47]	453 K.M.	40.5 kWh	11.185 K.M./kWh	0.7 kg of CO_2/kWh	0.06 kg/K.M.
Tata Nexon Petrol [48]	762 K.M.	Nil	17.33 K.M./liter (given)	2.77 kg of CO_2/liter [48]	0.159 kg/K.M.

Such a meticulous analysis aids in identifying the most favourable course of action, accounting for both technical feasibility and societal benefits.

As depicted in Table 4, the losses in the base case i.e. *Case-1* of 33 bus radial distribution system, is calculated as 202.7 kW. In Case-2 when charging ecosystem planning is done with just power factor constraints the optimal bus location came out to be at bus number (2,7,19,20) with total cost of ₹ 2,31,76,20,393.23 over the span of 25 years and total power loss increased to 251.40 kW. It was observed that considering placement of charging ecosystem as per Case-2, 31.25 % of the consumer have to travel outside their comfort zone for charging of their electric vehicle and more over single station was being overloaded i.e. at bus 7. In Case-3 when we introduced user inconvenience index for charging ecosystem, the location came out to be at buses (2,12,19,27) with the total cost of station be ₹ 2,32,75,74,802.01 and increased loss of 310.10 kW. As per the constraint of inconvenience index not more than 20 % of consumer in a system should have to face long distance travel for charging of their vehicle. Inconvenience index was introduced to sought out the overloading of single station but did not justify the objective as desired. Therefore, as shown in Fig. 4, 33 bus system was divided into 4 parts based on load, Section 1 with 990 kW load is considered as office area, Section 2 with a load of 935 kW is considered as housing load, Section 3 with load of 930 kW is considered as industrial load and Section 4 with total load of 920 kW is set as commercial load. In Case-4, after introducing the segments the optimal bus came to be (2,12,23,27) with accounting for total cost of ₹ 2,34,71,22,902.68 and total loss of 325 kW.

To further improve the system stability and better model of shifting and use of sustainable energy, this work has introduced generation from solar photovoltaic plant on each charging station which accounts for 716.040 kW generation capacity. Case-5, when solar generation was included was see a reduction is power loss of 4.9 kW as compared to Case-2 and total cost came out to be ₹ 2,17,17,95,165.65 which was 6.29 % less than Case-2. Similarly, when Case-6, and Case-7 were optimized they fashioned a total cost of ₹ 2,17,33,47,517.13 and 2,14,54,33,624.10 respectively, which are less than what we observed in Case-3 and Case-4. Figs. 5, 6, 7, and 8 represents different cases of power factor variation for various cases studied. Fig. 5 represents the variation of power factor when the charging station are installed according to Case-1, Case-2, Case-3, Case-4 while Fig. 6 represents the variation of power factor when the charging station are installed according to Case-1, Case-5, Case-6, Case-7. Graph in Fig. 7 represents the comparison

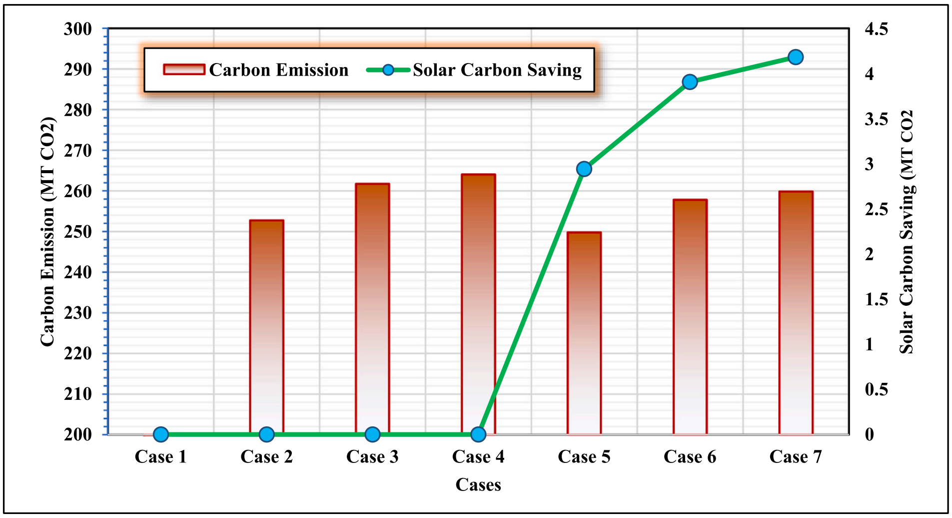

Fig. 11. Carbon emission data.

between Case-1, Case-2, and Case-5. It can be clearly seen when solar is added to the normal installation of charging station the improvement in the power factor can be seen compared to Case-2. While in Fig. 8 the comparison between Case-1, Case-4, and Case-7 have been published. The power factor noticeably improves from Case-4 to Case-7 when solar is added included with the consideration of inconvenience index and location constraints. Whereas, Fig. 9 explains the relation between the power loss incurred in different cases and power loss penalty relative to it. In Fig. 9 it can be clearly seen that when solar photovoltaic plant is installed in Case-7 compared to Case-4 with same variables the power loss is minimized thus attaining better power running power factor. Whereas, Fig. 10 briefly shows the plot between total penalty incurred over each case vs value of different type of penalty for each case. It can be clearly viewed that the total penalty in case-4 is substantially more than penalty incurred by charging station in case-7.

7. Carbon emission saving

In the context of transitioning from conventional to *E*-Transportation, carbon emissions play a crucial role in determining the viability and benefits of such a shift. The calculation of Total Carbon Saving, a pivotal formula, takes centre stage in this endeavour. This formula considers the impact of solar photovoltaic systems and their interplay with the grid, factoring in carbon emission savings derived from the utilization of solar power as discussed in Eqs. (12), (13). This approach ensures a formal and meticulous assessment of the environmental impact and potential advantages of embracing sustainable practices in the realm of transportation. The Table 5 below shows the difference in the carbon emissions of same vehicle when run 1 K.M. in distance under same test conditions. It can be seen that a conventional model of same vehicle emits nearly 2.5 times more CO_2 to run 1 K.M. distance than and EV version of same vehicle.

In this study different cases have different emission based on power loss, loading and solar installation. Data on each case is being depicted in Fig. 11 below. Cases 1, 2, 3, considers the charging station without solar power integration while Cases 5, 6, 7 considered charging station with solar power integration. Case 7 shows the most significant carbon saving as compared to every other case with savings of 4.188 MT CO_2.

8. Conclusion

This study presents to provide a sustainable solution for shifting toward *E*-Transportation with an aim to foster sustainable development goals. This study, with the help of fast converging GWO helps to find the optimal location for placement of the electric vehicle charging ecosystem as to minimize the losses and keeping in mind the comfort of customer. There were multiple cases that were studied, with constraints being added in every new case to make the solution more realistic and user-friendly. As in Case-5 and Case-6, though power system losses are low in Case-5, but travel penalty is much more, thus causing user inconvenience. And if the user is not convenient, he won't use that station for charging unless it's an emergency thus, Case-6 was introduced to foster user needs which can bear a little more power losses but cater to user needs and better utilization of charging ecosystem. It was seen in Case-7 that both TDP and VDP were the same as in Case-6 and the power loss penalty was more. But still Case-7 is introduced because the placement of the charging ecosystem in Case-6 i.e., at buses 2,19,12,17 was very close to a single segment of society/location and creating a higher load on two charging ecosystems causing much waiting time for charging. Carbon emission calculation also provided an insight on how a shift will be useful from conventional to E-transportation. Results showed a significant reduction of 2.5 times in carbon emission and addition of solar provides a boost in carbon reduction to fulfil sustainable development goals. Thus, to distribute the charging ecosystem thoroughly throughout the network, Case-7 is introduced with network segmentation and thus yielded optimal locations at buses 2,12,23,27. The use of solar power generation in the charging ecosystem also helps to provide stability to the system in terms of improved voltage profile and reduced losses.

CRediT authorship contribution statement

Rudraksh S. Gupta: Conceptualization, Methodology, Writing - Original draft preparation, Data Curation.
Y. Anand: Reviewing and Editing.
Arjun Tyagi: Supervision, Investigation, Reviewing, Validation.
S. Anand: Supervision, Writing: Reviewing and 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.

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