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Impact on the radial distribution feeder with optimally located Electric Vehicle Charging Station and PV integrated Energy Storage System

Ananda Sapkota[a], Prabhat Kumar Pankaj [b]

[a] *Department of Electrical Engineering, Paschimanchal Campus, IOE, TU*
[b] *Nepal Electricity Authority, Nepal*
[a] anandsapkota2008@gmail.com, [b] pkp031@gmail.com

Abstract

With the increasing demand of EVs, requirement for the charging stations at the urban areas is undeniable. Due to the installation of the fast charging stations, the existing high loaded urban feeders can face the technical issues with higher voltage drop and losses. So, with the proper planning the optimal location for the installation needs to be determined. This paper studies the impact of the EVCS on the distribution feeder (11kV) with its optimal positioning and sizing with Particle Swarm Optimization (PSO) with the probabilistic evaluation of the EVCS load curve for Devinagar feeder of Yogikuti substation. With the placement of the EVCS on two areas: Highway area, and Sub-route area, there is decrease in the voltage profile from existing 0.95pu to 0.942pu and increase in the system loss by about 88.83kW at peak. Also, the system is analyzed with the optimal positioning for EVCS integrated with PV and ESS to reduce the impact of EVCS only. With the PV in the system, the peak load can be reduced with energy stored at ESS. With ESS the system loss decreased by 55.3% than with EVCS only. The results shows that technically the PV system with ESS is more viable, however the EVCS system without ESS is more financially profitable with IRR and payback period of 27.61% and 8.21years.

Keywords

EVCS, Forward/Backward Sweep, Monte-Carlo simulation, PSO, PVSyst

1. Introduction

With the progressive exhaustion of fossil fuels and increasing environmental concerns, the study and investment in renewable energy have soared exponentially. Moreover, the economic and political risks curtained by the scarcity of fuel and technological advances during the past decades as well, have promoted the imminent need for the usage of renewable sources as a substitution for fossil fuels. This sustainable energy has a wide area of penetration including electrical vehicles (EV) and distributed generations (DG).

The increasing demand for electrical vehicles has led many countries to set the foreseeable target of 100% Electrical Vehicles [1].With the increase in integration of EV, the demand gets increased and so does the power loss and voltage deviations in the system. It can also cause thermal limit violations of the lines and transformers. The demand side can show a considerable change due to the uptake of a new source of electric loads. So, the need for the optimal planning of electric vehicle charging stations (EVCS) has increased significantly. Installation of DG can be a way to mitigate the technical hindrances due to EV.

The installation of the DG with the charging station not only nullifies the adverse impact but also can support the distribution system with supply during the peak hours with energy storage systems (ESS). DG can also be an aid for the less reliable distribution systems as it can deliver power to the charging stations even during power outages and disturbance in the distribution systems too. So, a DG source can help to achieve a smooth voltage profile also reducing the power loss [2].To maximize the benefits of using DGs in power systems, it is crucial to find the best location and size of DGs simultaneously to improve the voltage stability and reliability of the grid [3].

Considering all the aforementioned elements the planning of investments in renewable-based DG units and the integration of new technologies, such as EVs and ESSs, at the demand side is a prevalent issue, and the need for distribution utilities to rely on optimal placement of the DGs and charging stations [4].

With the growing demand for EVs in our country too, the sole distribution utility, Nepal Electricity Authority (NEA) has been planning to develop charging stations in various parts of the valley and major cities to strengthen the EV infrastructure [5]. As support to the government's vision of a sustainable environmentally friendly transportation system, the NEA's electric vehicle charging infrastructure development project has aimed to install 50 numbers of 142kW fast-charging stations in the major cities and highways[5].

In this paper, the effect of the integration of EVCS in the existing distribution system is analyzed with its optimum placement. Also, the technical and financial analysis is performed for the same EVCS with PV generation and ESS. Forward Sweep Backward Sweep (FSBS) method is used to evaluate the technical parameters (voltage and loss) of the system with Particle Swarm Optimization(PSO) for the optimal selection of location and size.

2. Material and Methods

The major location of the charging station would obviously include the urban areas as the major use of EVs would be in this area. The main characteristics of the urban feeder would be higher loading and a short length. Having similar attributes, the Devinagar feeder of Yogikuti substation is considered for the study. The feeder has a total and radial lengths of 21.3km and 6.7km respectively composed of ABC, Dog, Rabbit and Weasel conductors with a peak demand of 4.2MVA for the wet season.Among the 81 transformers in the feeder, 48 of them belong to private consumers. The feeder has the peak load for 9pm in the month of Ashad. The methods and tools used in the study are described herewith.

2.1 Evaluation of Technical Parameters

For load flow analysis, the FSBS method is used [6] [7]. In this method, for the forward sweep, the voltage drop in the system is calculated with the update of current flow and for the backward sweep the bus voltages is updated.The method forms with the injection of bus in branch current matrix and branch current in bus-voltage matrix. In case of the distribution network, equivalent current injection based model is more practical [8] [9]. For i^{th} bus, the load S_i can be depicted as

$$S_i = (P_i + jQ_i)\ ,\ i = 1...N \tag{1}$$

The injected bus current [I] and branch currents [B] are expressed in general form with respect to bus-injection to branch-current (BIBC) matrix as in Eq.2. Also, the relationship between branch currents and bus voltages with branch-current to bus-voltage (BCBV) matrix is in Eq.3. From Eq.2 and Eq.3 , the bus voltage can be represented in accordance to the BIBC and BCBV matrices and bus current as in Eq.4.

$$[B] = [BIBC][I] \tag{2}$$

$$[\Delta V] = [BCBV][B] \tag{3}$$

$$[\Delta V] = [BIBC][BCBV][I] = [DLF][I] \tag{4}$$

where, [DLF] is a multiplication matrix of BCBV and BIBC matrices. And at the k^{th} iteration, the corresponding current injection can be expressed as:

$$I_i^k = I_i^r(V_i^k) + jI_i^i(V_i^k) = \left(\tfrac{P_i + jQ_i}{V_i}\right)^* \tag{5}$$

where V_i^k, I_i^k P_i and Q_i are the bus voltage, equivalent current injection, real and imaginary components of power associated with current injection of i^{th} bus at the k_{th} iteration respectively.Also, I_i^r and I_i^i are real and imaginary components of of the equivalent current injection of bus i at the k^{th} iteration respectively.

The voltage at each iterations are updated based on Eq.6. The voltage at each iteration is updated with the Eq.7

$$[\Delta V_i^{k+1}] = [DLF][I_i^k] \tag{6}$$

$$V_i^{k+1} = V_i^0 + \Delta V_i^{k+1} \tag{7}$$

The power loss of the line section connecting two buses i and i + 1 is computed as

$$P_{loss}(i, i+1) = R_{i,i+1} \times \frac{(P_i^2 + Q_i^2)}{V_i^2} \tag{8}$$

where, $R_{i,i+1}$ is resistance of line section, P_i and Q_i are active and reactive load at bus i. The total power loss of the feeder can be obtained by adding the loss obtained for each of the line sections.

2.2 Modeling of EV

The major uncertainties in the EVCS load characteristics would be due to the following causes [10]:

- Duration each EV is connected for charging
- Distance traveled by each EV
- SOC level of each EV at any given time

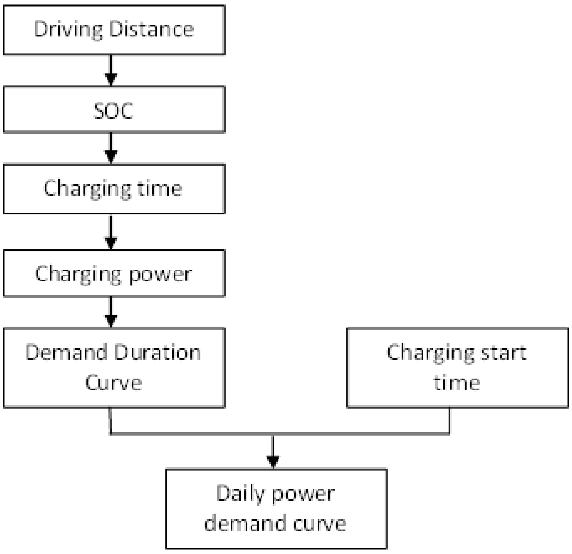

Figure 1: Battery modeling during its charging cycle

A logonormal distribution described by the mathematical equation in Eq. 9 [11] is used to evaluate probability of daily driving distance, D. The state of charge(SOC) provides the charge in the battery of the EV with the driving. The charge declines almost linearly in the EV and it is considered that the charge does not decline below 0.2, i.e. 20% of the rated capacity[11].So, within a maximum limit distance, X the SOC for the battery is calculated.

$$f_D(x) = \frac{1}{x\sigma_D\sqrt{2\pi}} e^{[-(lnx-\mu_D)^2/2\sigma_D^2]} \tag{9}$$

$$SOC = \left\{max\left\{0.2, 1-(D/Vehiclemileage)\right\}, D \leq X\right. \tag{10}$$

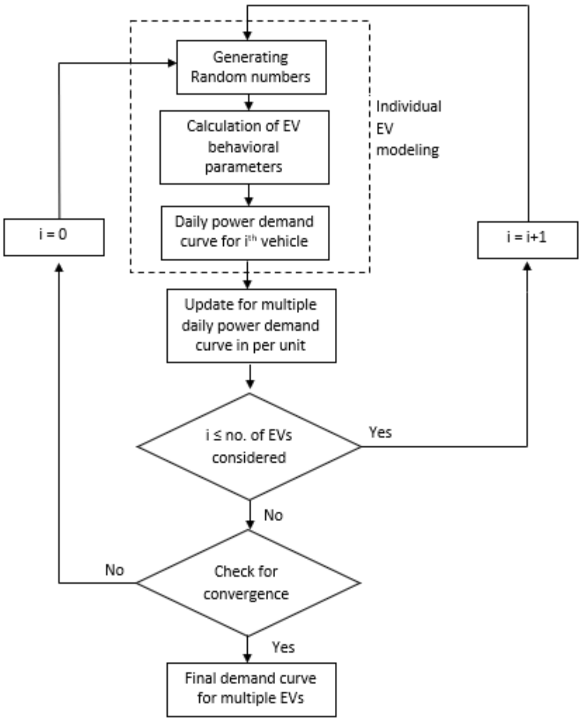

Figure 2: Modeling procedure for large no. of EVs [11]

For the formulation of power transaction, the load profile of single EV is formulated with the sequential modeling as shown in Figure 1 and is repeated for a large number of EVs assumed [11]. A Monte Carlo Simulation (MCS) method is used for the overall model by combining individual models as shown in Figure 2. First, the random numbers are generated for each EV to calculate their parameters using the distributions showed in Eq.9-11[11].

The power demand curve is obtained for each vehicle and the daily sequential loads for all the n vehicles are recursively aggregated to obtain the load curve for 24 hour time period as in Eq. 12.The simulation is repeated until the convergence criterion is met. For the convergence it is considered that the peak of EV curve obtained should not differ its previous by more than 2%.

$$f_{T_p} = \frac{1}{x\sigma_{T_p}\sqrt{2\pi}} e^{[-(x-\mu_{T_p})^2/2\sigma_{T_p}^2]} \tag{11}$$

$$L_h = \sum_{i=1}^{n} L_{PEV_{i,h}} \tag{12}$$

Table 1: Assumptions for EV modeling

Description	Public Bus	Medium Vehicle
Battery Type	Lithium-ion	
Battery Size (kWh)	144	71.1
Mean Driving distance (km)	87.09	44.79
Deviation in mean driving distance (km)	12.62	11.06
Capacity of Charger(kW)	135	40
Vehicle Mileage (km)	225	160
Charging Efficiency	0.88	
Minimum SOC	0.2	

2.3 Optimum Placement of EVCS

PSO is used for the optimum placement of the EVCS with the objective and constraints discussed here with. The methodology is shown in Figure 3

2.3.1 Objective Function:

The objective for the optimum placement of the EVCS would be the minimization of the total cost associated with the EV charging stations to be planned, which includes the investment cost, operation costs, maintenance costs and network loss cost in the planning period. The mathematical function can be expressed as:

$$\text{Minimize } f = \sum_{t=1}^{T} \frac{1}{(1+v)^t} \left[\sum_{i=1}^{N_{EVCS}} C_{EVCS_i}^{I}(t) + C_{EVCS_i}^{O}(t) + C_{EVCS_i}^{M}(t) + C_{PS}^{L}(t) \right] \quad (13)$$

where:
T = Number of Years included in the planning period
v = Discount Rate and used to transform the future cost to present value
N_{EVCS} = No.of EV charging stations in the distribution system
$C_{EVCS_i}^{I}$=Investment cost of i^{th} EVCS
$C_{EVCS_i}^{O}$=Operation cost of i^{th} EVCS
$C_{EVCS_i}^{M}$=Maintenance cost of i^{th} EVCS
C_{PS}^{L}=Network loss in the planning period

2.3.2 Constraints:

The equality and inequality constraints will be used for the optimizations. The equality constraints include the power flow equations and the inequality constraints are specified herewith.

Voltage The voltage at each bus must be within the lower and upper voltage limits specified.

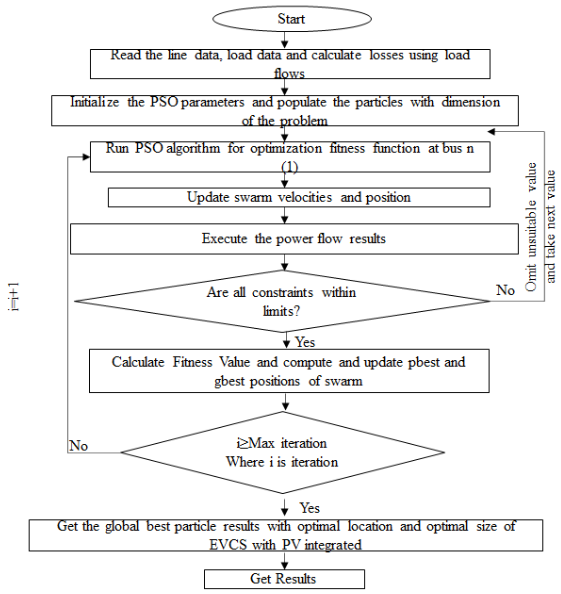

Figure 3: Methodology for optimization with PSO

$$0.9pu \leq V_i \leq 1.1pu, (i = 1,2,...N)$$

Loading The loading of each branch must be less than 100%.
$$\%Loading_{ij} \leq 100\%, (i, j = 1,2...N)$$

Area The area required for the placement of the charging station must be less than or equal to the area available.
$$|Area_i| \leq Area_{i_{available}}, (i = 1,2...N)$$

2.4 Placement of EVCS with PV

2.4.1 Objective Function

The objective function of the optimization model involves cost of power supplied by the grid, operating cost of PV and fixed battery storage, cost of unsupplied demand, cost of discharging PEVs and profits from charging PEVs and providing power back to the grid.

$$\min f = \sum_{t=1}^{T} \frac{1}{(1+\nu)^t} \left[\sum_{i=1}^{N_{EVCS}} C^I_{total_i}(t) + C^O_{total_i}(t) + C^M_{total_i}(t) + C^L_{PS}(t) - P^C_{EVs}(t) - P^G_{PVs}(t) \right] \tag{14}$$

where:
T = Number of Years included in the planning period
ν = Discount Rate and used to transform the future cost to present value
N_{EVCS} = No.of EV charging stations in the distribution system
$C^I_{total_i}$=Total investment cost
$C^O_{total_i}$=Total operation cost
$C^M_{total_i}$=Total maintenance cost
C^L_{PS}=Cost due to power Loss
P^C_{EVs}=Profit from charging EVs
P^G_{PVs}=Profit from supply to grid

2.4.2 Constraints

In addition to the constraints in subtopic 2.3.2, the following generation constraint the constraints for the placement of EVCS with PV.

For PV Generation The size of charging capacity is considered to be less than or equal to the power generation capacity of PV.
$P_{EVCS_i} \leq P_{PV_i}, (i = 1, 2...N)$

2.5 Tools

Python programming language is used for the process of load flow with FSBS method. Similarly, Monte-Carlo simulation in the modeling of EVCS, particle swarm optimization for determination of optimal sizing and location of EVCS and PV generation is performed with the same programming language.The detail modeling of PV is done with the aid of PVSyst software and financial feasibility is checked in MS Excel.

3. Result and Discussion

With the aforementioned methodology, the analysis for the Devinagar feeder was carried out the results obtained during the process are described herewith.

3.1 Base Case

For the existing system, the load flow parameters of voltage and loss was evaluated. In the Figure 4 the nodal voltages of the feeder are shown in descending order. The minimum voltage was obtained for the private transformer at Bhairab multi Engineering industry with 0.950pu voltage.

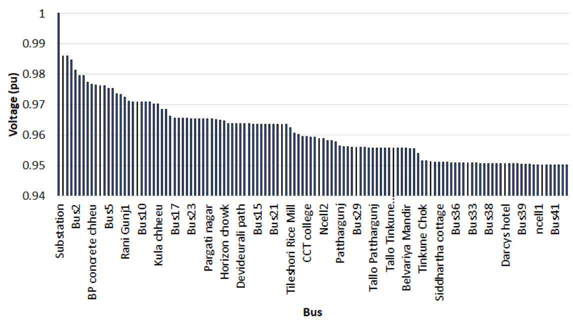

Figure 4: Voltage along the feeder

Also, the power loss for the feeder at the peak time is 170.74kW. Among the total loss, the 0.86km of the section just coming out from the substation is responsible for 61.54kW loss. Although the section comprises of the Dog conductor, due the higher demand of load, the loss is higher in the section.

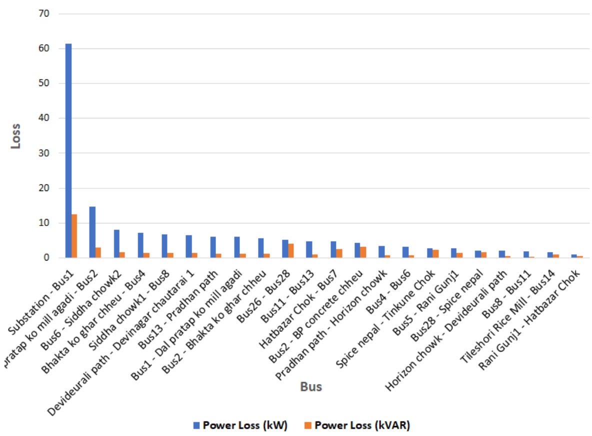

Figure 5: Loss along the major line sections in feeder

The loading along the major loss occurring sections is shown in Figure 6 with the maximum loading of 79.08

3.2 Modeling of EVCS Load

So, considering data obtained from the Lumbini CS for mean peak time and deviation from peak the load pattern of EVCS is to be modeled. 100 number of public bus and 200 medium-sized vehicles is considered. So, a unit of charging station for bus and

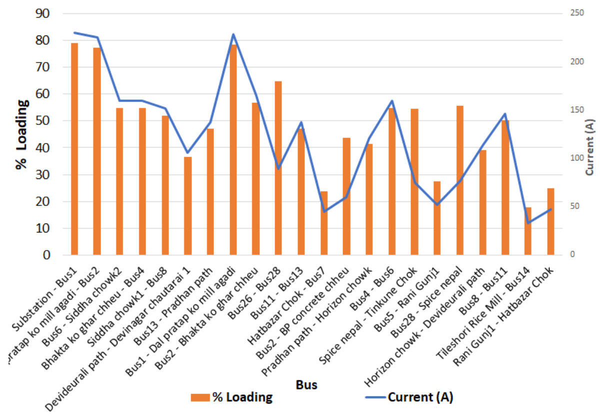

Figure 6: Loading along the major loss occurring sections

2 units for the medium-sized is considered.The data related to the distance and charging conditions is shown in Table 1. The load curve for a unit of charging station for a public bus and medium sized vehicles is evaluated and shown in Figure 7 and 8 respectively. The combined load demand from a 135kW and two units of 40kW charging station would have 161kW peak and the load at feeder peak would be 138kW, so this load needs to be considered for simulation at feeder peak.

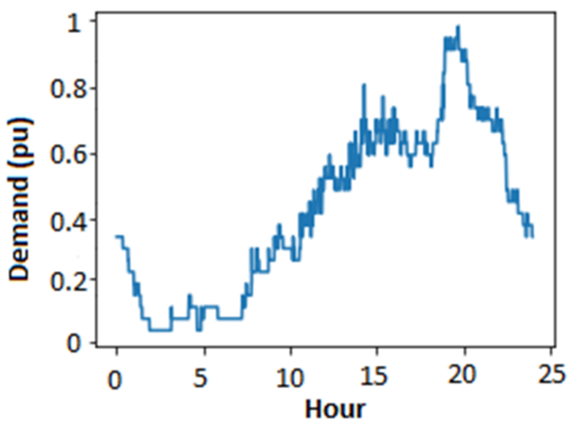

Figure 7: Average load pattern of charging public bus from a single unit at EVCS

3.3 Optimum Placement of EVCS

With the particle swarm optimization, the optimum location for the a single place of EVCS is determined.With the population size of 100 and 1000 iterations, the PSO program is run. The most optimum location for the placement of EV is at Devsiddha Khanepani with the 8*135kW and 16*40kW charging stations.

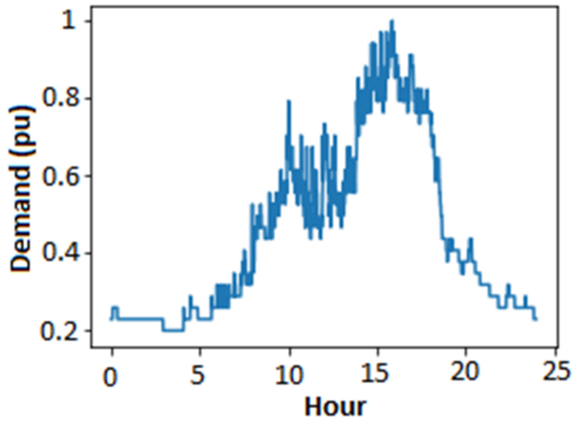

Figure 8: Average load pattern of charging medium sized vehicles from a single unit at EVCS

The minimum voltage location is determined as Murgiya Danda with the voltage of 0.945pu. Along with the drop in the voltage, the loss also has increased in the feeder. As comparison to the existing loss of 170.75kW, the loss with EVCS addition would be 244.80kW.The loading of the first section would increase to 98.59% as in Figure 9.

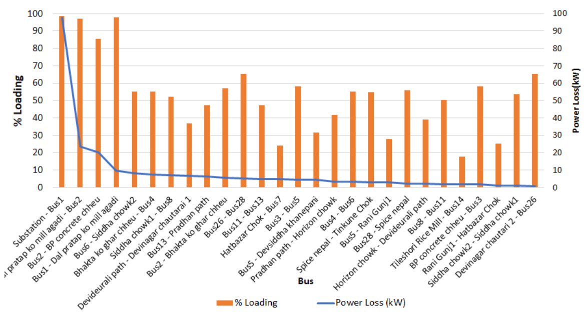

Figure 9: Major branch loss and loading with the placement of EVCS at one location

Moreover, two separate areas: Highway and Sub-Route was considered (shown in Figure 10)and optimal location for the placement of the EVCS is also determined for each of them. With the Sub-route area being 3 folds larger, in area, than the Highway area, the size of EV to be placed those are placed in same proportion. EVCS at the Highway area is found to be at Hotel namo Buddha agadi with the 2*135kW and 4*40kW fast charging chargers. Optimal location for Sub-route area is found to be at Devsiddha khanepani with 6*135kW and 12*40kW charging units. With the placement of the charger on those areas, the minimum voltage of the system at ”Sindur hotel pachhadi” dropped to 0.942pu and loss increased to 259.58kW.

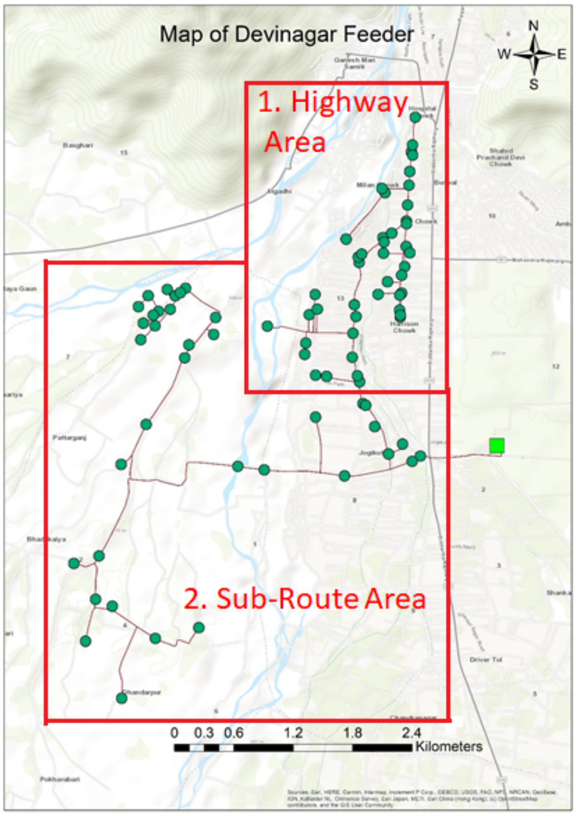

Figure 10: Residential and Commercial Area for Placement of EVCS

3.4 Placement of EVCS with PV and ESS

The size of the optimal charging station with PV integrated is determined for the areas. The optimal location for the placement in Highway area is found to be Hotel namo Buddha agadi with 1*135kW and 2*40kW stations with 226kW PV for the area. As, it could not fit the optimal number of charging station, second best location is determined at Banijya Campus with same size and 230kW of PV. The ESS that can store 1380kWh of the energy produced from PV is required. Also for the Sub-route area, the optimal is determined at Devsiddha Khanepani with the capacity of 4*136kW and 8*40kW CS. From the optimization, the 943kW sized PV can be placed in the area available with ESS of capacity 5,600kWh. Further, the second best location is Hatbazar chowk in which the 2*135 and 4*40kW station can be placed with the PV of 530kW with 3,050kWh ESS. Without PV and ESS, the loss and voltage would be almost similar to the previous case, but when the ESS is used to charge the EVs and the excess from the PV size is fed to the peak, the voltage along the feeder has improved to 0.956pu with the reduction in the loss to 116kW at peak. The daily energy that can be generated from the PV installed at Hotel namo Buddha agadi and Devsiddha Khanepani are shown in Fig. 11 and 12 respectively.

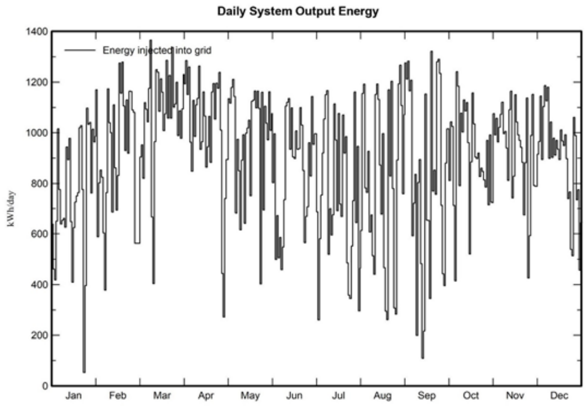

Figure 11: Daily output energy from PV at Hotel namo buddha agadi

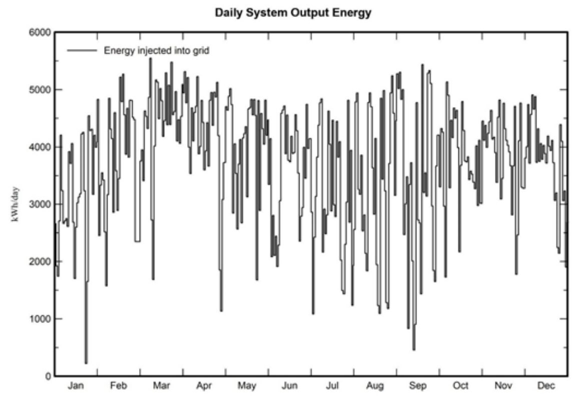

Figure 12: Daily output energy from PV at Devsiddha Khanepani

3.5 Financial Analysis

The financial analysis has been performed for the comparison of the financial parameters with the placement of EVCS only and PV integrated EVCS with ESS.

Table 2: Financial Results

Indicators	Scenarios		
	With EVCS only	EVCS and PV integrated without ESS	EVCS and PV integrated with ESS
NPV	354,404.49	1,960,574.68	1,501,959.84
BCR	1.21	1.57	1.70
IRR	17.80%	27.61%	16.94%
Payback Period (years)	15.55	8.21	12.73

4. Conclusion

With the placement of the EVCS, the loss and the voltage drop would increase in the feeder. With the integration of PV and energy storage system, the improvement in voltage profile can be obtained as compared to integration of EVCS only, and even than the existing case. A total of 1.93MW PV system can be injected to the feeder with the daily storage of 11.41MWh total capacity. The ESS system can be used to supply the grid at peak demand to nullify the effects due to load increase and can also be used in charging of the electrical vehicles at the time of system disturbances. The financial result indicate that the EVCS system with PV only is the most financial alternative with BCR, IRR and Payback period of 1.57, 27.61% and 8.21 years respectively.

The future recommendation for the study can include the analysis for monthly and hourly variations of the PV generation. The distance between the charging stations can be considered as constraint. Also, with the forecast of the future load conditions, the EV with home charging system can also be performed.

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