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Power Grid Impact Analysis for Future Expansion of EV Charging Stations in Kathmandu Valley: A Case Study of Sanepa Feeder

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Abstract
Increasing concerns over the fuel consumption and to achieve the sustainable development goals, the interests over battery operated vehicles EVs are increasing. From developed to developing countries, electric vehicles as major means of road transportation are being welcomed throughout the globe. While the primary infrastructure to flourish this technology is charging stations, the impact of such load on distribution network is somehow being shadowed. When additional load is added to the existing power system, the voltage fluctuations and power loss is imminent. This study emphasizes on analyzing the impact caused by addition of EV charging load on Sanepa distribution network. The system modelling is performed using DigSILENT PowerFactory tool. Several cases are considered for observing the impact in operational parameters. The placement of EV charging load on weaker bus and concentration of EV chargers in one bus has shown higher severity of impact. Voltage stability is the least affected and power loss is most affected parameter in the analysis. The range of change in power loss extends from 5 to 31 percent for different cases considered for analysis. And the change in reliability indices ranges from 3 to 14 percent making it the secondmost vulnerable paramter of the network. Addition of upto five number of EV charging stations in the feeder line causes 54% change in power loss, total of 43% change in reliability indices and only 3% change in voltage stability.

Keywords
Electric Vehicle, Charging Station, Distribution, Power loss, Voltage Stability

1. Introduction

With the increasing concern over the climate change and global warming, the need of changes on mobility and power sector has been realized. The fuel powered transportation sector is realized to be one of the most contributors to CO_2 emissions with 22 percent of CO_2 emission in the year 2020 [1]. As per the UN data, between 2010 and 2015 only. The transport sector was responsible for consumption of 28 percent of annual final energy and 60 percent of oil products in global scale as presented on the Policy Briefs in support of the first Sustainable Development Goals (SDG) 7 review at the United Nations (UN) high-level political forum 2018. This has led the world to step forward with the renewable energy sources for sustainable mobility. Nepal being the country blessed with hydro resources, has realized this opportunity to contribute in achieving the electric mobility targets [2].

The interest on Electric Vehicle (EV) has gained much popularity in Nepal with introduction of electric-two wheelers and cars. Charging is of major concern when it comes to electric vehicle. And currently most of the EVs require hour or more for complete charging. As being said, the charging infrastructure is not enough for the rising customer. The major requirement for flourishing EV business in Nepal is the availability of Charging infrastructure. To provide public EV charging facilities, Nepal Electricty Authority (NEA) is building several charging stations throughout the country. Each charger will have 142 kW capacity with 3 points (2DC and 1AC charging) providing the power of 60 kW for DC and 22kW for AC charging [3]. However, the adverse effect of EV charging loads on the distribution network and its operational parameters must be addressed and minimized. The load due to EV charging is high enough to cause fluctuations on voltage profile and reliability. If neglected, it may severely decrease the reliability of the system causing the outage of the network. There have been investigations carried out by researchers on the impacts potentially caused by the charging station loads on the distribution network. The different scenarios for EV penetration were studied on Low Volatge (LV) distribution network in which it was found that the node voltage profile was degraded due to placement of multiple charging stations and also the weak buses went through degradation of their voltage profile due to high EV charging loads [4]. So, it becomes very necessary to find out the optimal placement of EV charging stations (EVCS) in a distribution network.

Currently, NEA installed 51 and few charging stations across the country [5]which were forecasted and placed as per the EV density in highways, so the concerns related with the effect of charging station load on power networks is less. However, NEA plans to install 500 and more charging stations across the country through private partnerships. This can take a toll on the existing distribution Network. The effects are seen in voltage profile, stability, efficiency and on other critical factors of power system. When the load of high capacity of this extent is added in the system, the system operating factors fluctuates causing system outage on worst case scenarios as it forces additional burden on the power network.

That's why it is necessary to plan the addition of the charging station on the distribution network so that the operational parameters of the network are least or not affected. In this study, a distribution network inside Kathmandu Valley is taken into consideration for supporting and facilitating the addition of EV charging stations across the network. The feeder distribution network is analyzed before and after the EV charging load conditions with the calculation and analysis of operational parameters (Voltage Stability, Reliability and Power Loss). EV charging station are modelled in the distribution network for analysing the operational parameters. The main objective of the study is to analyze the impact of EV charging stations on distribution grid operational parameters in Sanepa distribution network in Kathmandu valley. Sanepa feeder being the feeder that has Sajha EVCS integrated on its line makes it the qualified candidate feeder for this study.

2. Literature Review

2.1 Voltage Stability

The voltage stability gives the voltage conditions in the line considering the voltage drop and fluctuations. For a system to be stable, it's voltage levels should be within the acceptable limits under any load conditions [6]. For the analysis of voltage stability, the computation of Voltage Stability Index (VSI) and Voltage Sensitivity Factor (VSF) are carried out in this study.

2.1.1 Voltage Sensitivity Factor (VSF)

VSF denotes the ratio of voltage change (dV) to the change in active load(dP). It is the measure sensitivity of the system voltage with step-wise loading increment. Mathematically, it is expressed as:

$$VSF = \left|\frac{dV}{dP}\right| \forall P < P_{max} \tag{1}$$

High value of VSF indicates lesser voltage stability, that means even with small changes on loading behavior, there is significant change in voltage drop [7]. The analysis of voltage stability suggests all voltage drop to be within 6% of their nominal value. The calculation of VSF is done directly through modelling in PowerFactory with the determination of PV curve.

2.1.2 Voltage Stability Index (VSI)

For the determination of this index, its mathematical formulation is presented through illustration of 2 bus system as shown in the Figure 1. The elaboration of mathematical

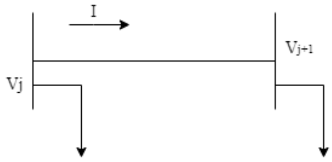

Figure 1: 2-bus system single line diagram

formulation is done as in [6]. VSI value can be determined through the Equation 2:

$$2V_j^2V_{j+1}^2 - V_j^4 - 2V_{j+1}^2(P_{j+1}r + Q_{j+1}x) - |Z|^2(P_{j+1}^2 + Q_{j+1}^2 \geq 0 \tag{2}$$

Where V = Voltage at bus, P = Active Power, Q = Reactive Power, I = current through the branch, r = resistance of the branch, x = impedance of the branch, j = bus number

2.2 Reliability

From engineering point of view, reliability refers to the system's capability to achieve its function for its anticipated lifetime under different conditions of operation. While, from consumer's point of view, the uninterrupted power supply in their homes and offices is regarded as reliability. In both cases, the duration and frequency of interruption at load point acts as important elements for determination of reliability indices[8].The indices under consideration are: System Average Interruption Frequency Index:

$$SAIFI = \left|\frac{\sum_{\lambda N}}{\sum_{N}}\right| \tag{3}$$

System Average Interruption Duration Index:

$$SAIDI = \left|\frac{\sum_{UN}}{\sum_{N}}\right| \tag{4}$$

Customer Average Interruption Duration Index:

$$CAIDI = \left|\frac{\sum_{UN}}{\sum_{\lambda N}}\right| \tag{5}$$

2.3 Power Losses

Addition of EV charging load on a distribution line raises serious concerns over power loss. In simpler terms, power loss is the I2R loss of a system or line. Mitigation of power loss is necessary for ensuring grid stability and efficient operation, The power loss of the network can be calculated by mathematical modelling. Total power loss is given by Equation 6:

$$P_t = \sum_{j=1}^{n} P_j \tag{6}$$

3. Methodology

Impact analysis emphasizes on determining operational parameters or VRP index (i.e. voltage stability, reliability and power loss) using two scenarios. Each of the index are computed and analyzed separately considering before and after loading conditions. Voltage Sensitivity Factor (VSF) is determined before EVCS load addition. This section is formulated in Figure 2.

The main methodology for the workflow of this study is illustrated in Figure 3.

3.1 Data collection

The EV charging stations are to be provided with 3-phase, 400V, 50 Hz AC supply through the distribution transformers connected at 11 kV feeder line as per the specifications on (NEA, 2020). In support with the decision to add more EV charging stations across the country, this study conducts the study of Sanepa distribution feeder of Kathmandu valley for EV charging station placement in view of the fact that the valley being densely populated city in terms of EV customers as well as EV charging stations. The radial feeder under study is Sanepa feeder supplied by Thapathali Switching Station.

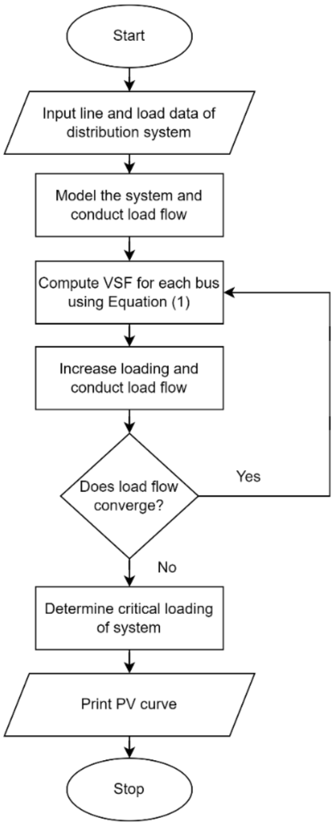

Figure 2: VSF methodology

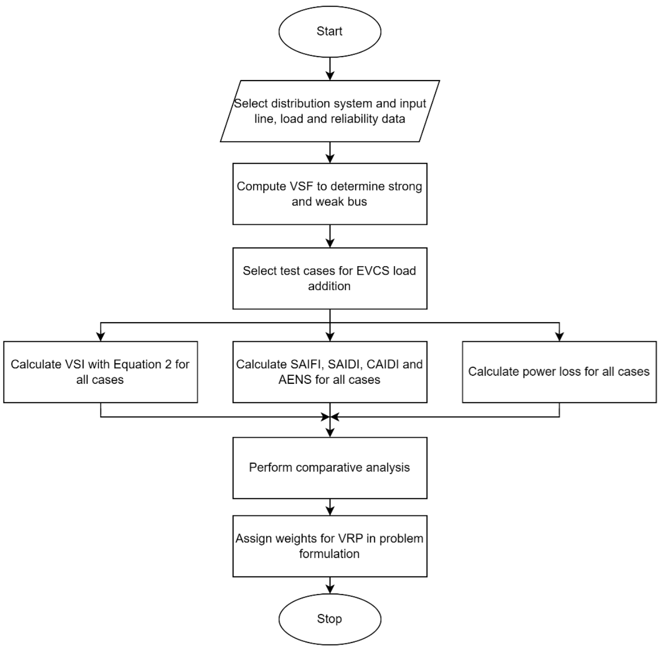

Figure 3: Impact Analysis Methodology

The feeder consists of 21 buses and 20 lines. This 11 kV system caters commercial as well as residential loads. The transformers are taken as the buses or load points on the system. 11kV lines are taken as distribution lines with the grid substations feeding the line as source and transformers as load points or buses. This study involved primary as well as secondary method of data collection. The primary data is collected from NEA substation which includes line and load data of 21 bus system. The assumptions are also made to accommodate for the unavailability of the data. The physical nature of feeder is studied using Geographic Information System (GIS) software. The GIS image of the feeder is shown in the Figure 4:

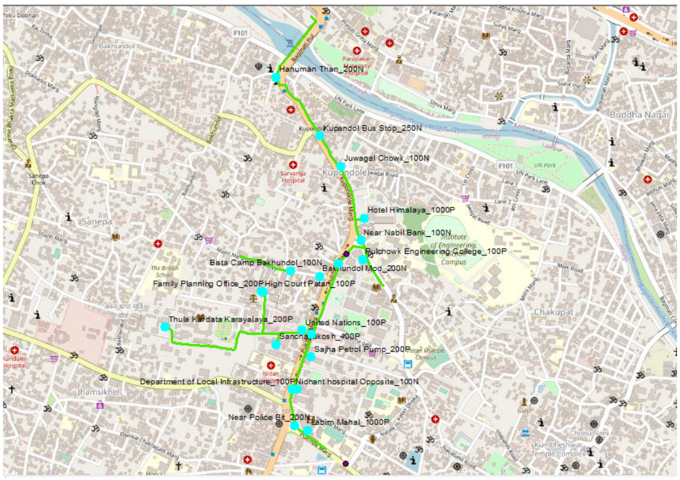

Figure 4: Sanepa feeder GIS map

3.2 System Modeling

The standard model is derived using DIgSILENT PowerFactory. The base case modelling is done first using the data. In this case, no loads are added in the system. The feeder components and lengths are obtained from GIS mapping. The data of this study consists of load data (active and reactive power), line data (resistance and reactance) and reliability data (failure rate, outage hours and number of consumers) associated with the considered feeder. The single line diagram depicting the 21-bus system is shown in Figure 5:

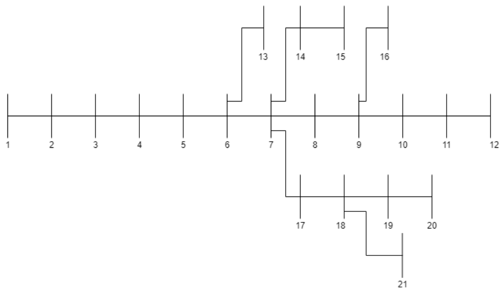

Figure 5: 21 bus Sanepa Feeder Network

First of all, the base case system is modelled at the base conditions of load and no external loads added to the system. The load flow calculation is executed using Newton-Raphson power equation method. The voltage sensitivity factor is calculated in different loading conditions for the determination of strongest and weakest bus to exist in the system with the help of PV curve

3.3 System Modeling with EV charging load

After the study of system in base case and different loading, the impact on system due to addition of EVCS load is analysed. The modelling of EVCS load on the existing system is carried out through consideration of different cases. The cases are considered such that one bus from the lower VSF group or strong group, one bus from average group and two buses from weaker group are included. The reason for this is to create diverse platforms for modelling the EVCS load in the network composed of high as well as less sensitive load points. The cases can be summarized in the Table 1.

Table 1: Cases considered for impact analysis of EV charging load addition

Cases	Description	Load Increment (kW)
1	1 charger in strong bus group: Bus 5	142
2	5 chargers in strong bus group: Bus 5	710
3	2 chargers each in strong bus group and average group: Bus 5 and Bus 8	568
4	1 charger in weak bus group: Bus 12	142
5	2 chargers each in weak bus group: Bus 12 and Bus 21	568

4. Results and Discussion

4.1 Determination of strong and weak buses

The load flow analysis of the system was carried out and the voltage on base case were recorded. PV curve of the system was plotted at step increase of the load. PV curve shows the behavioral patter of the power system with step addition of load. The critical margin of loading was determined. PV curve is shown in Figure 6. Voltage sensitivity factor was calculated for the determination of strong and weak buses in the line. The higher value of VSF denotes the higher sensitivity in load addition while the lower value of VSF denotes resistance to fluctuation due to load addition. The VSF values were tabulated and plotted for two different loading factors which is shown below. The weakest bus was found out to be Bus 12 and strong bus was Bus 2.

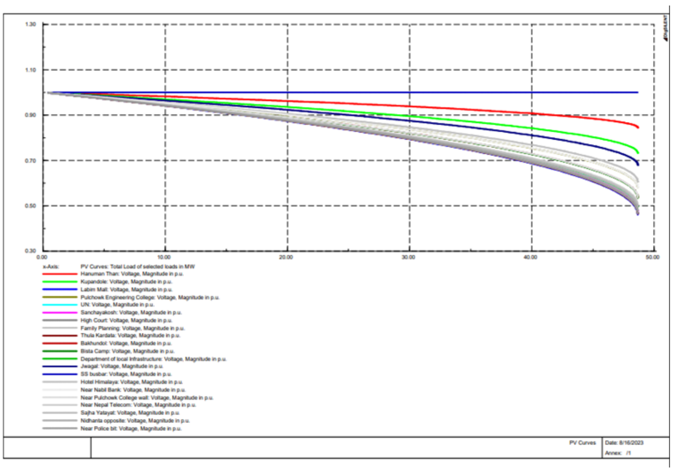

Figure 6: PV curve of 21 buses with step increase in loads

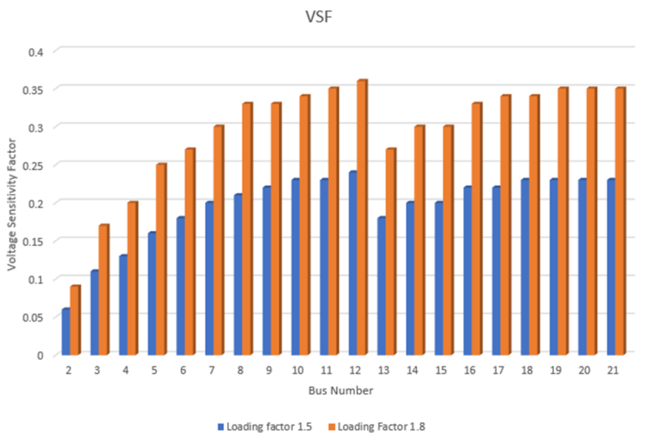

Figure 7: Voltage Sensitivity Factor for two different loading

4.2 Impact of EV charging load in VRP parameters

The EV charging load was modelled in to the system. Each charger has capacity of 142kW that is facilitated with 3-point charging; 2 DC charging (60kW) and 1 AC charging (22kW). The chargers were modelled according to the cases in Table 1. And the changes in VRP due to load addition were analysed and studied.

4.2.1 Impact on voltage stability index

Voltage Stability Index is calculated after load flow analysis using Equation 2 for base case and different cases of EVCS load addition. It is observed that that the value of VSI gradually decreases with the load addition in the system. In Table 2, the voltage deviation on all the buses due to the load addition is summarized. It is observed that the voltage gradually decreases in case 2, 3, 4 and 5 in comparison to the base case, case 1.

Table 2: VSI on different cases

Bus	Base	Case 1	Case 2	Case 3	Case 4	Case 5
1	1.000	1.000	1.000	1.000	1.000	1.000
2	0.9767	0.9761	0.9733	0.9743	0.9764	0.9743
3	0.8994	0.8960	0.8848	0.8855	0.8968	0.8862
4	0.9187	0.9175	0.9058	0.9113	0.9175	0.9113
5	0.8989	0.8934	0.8841	0.8845	0.8934	0.8851
6	0.9190	0.9153	0.9078	0.9106	0.9146	0.9090
7	0.9032	0.8995	0.8921	0.8898	0.8981	0.8880
8	0.9059	0.9022	0.8948	0.8927	0.9009	0.8927
9	0.9147	0.9109	0.9035	0.9035	0.9106	0.9027
10	0.9080	0.9081	0.8989	0.8980	0.9046	0.8966
11	0.9068	0.9024	0.8952	0.8952	0.9014	0.8933
12	0.9080	0.9081	0.8972	0.8972	0.9040	0.8965
13	0.9293	0.9254	0.9179	0.9179	0.9254	0.9179
14	0.9211	0.9175	0.9101	0.9101	0.9176	0.9101
15	0.9210	0.9174	0.9101	0.9101	0.9176	0.9101
16	0.9144	0.9144	0.9030	0.9030	0.9105	0.9030
17	0.8973	0.8935	0.8861	0.8861	0.8935	0.8777
18	0.9101	0.9064	0.8990	0.8990	0.9064	0.8939
19	0.9072	0.9072	0.8998	0.8996	0.9072	0.8975
20	0.9110	0.9110	0.8999	0.9036	0.9110	0.8999
21	0.9053	0.9053	0.8979	0.8979	0.9053	0.8884

4.2.2 Impact on reliability indices

The reliability indices SAIFI, SAIDI, CAIDI and AENS are calculated for studying the impact of EVCS load addition. The calculation is carried out for all cases mentioned in Table 1. The computation of reliability indices for different cases were carried out using unitary method for the failure rate and outage duration which is shown in Table 3.

Table 3: Reliability indices on different cases

Cases	SAIFI	SAIDI	CAIDI	AENS
Base	51.85473	9.605894	0.185246	85.63526
Case1	50.17746	9.295178	0.18524	85.29758
Case2	44.43704	8.231762	0.185245	84.14189
Case3	55.94136	10.36504	0.185284	85.30057
Case4	50.18052	9.295757	0.185246	85.78920
Case5	45.89162	8.501293	0.185247	86.19609

From above table, it is observed that the value of SAIFI and SAIDI decreases in cases 1, 2, 4 and 5, whereas, there is increment case 3. The decrement in the value of reliability indices like SAIFI, SAIDI and CAIDI can be because of following reasons:

- Load balancing
- Load diversity

The more reliable system has almost constant line of SAIFI and SAIDI indicating the constant failure rate as well as outage duration during loaded conditions. Hence, it is seen that SAIFI and SAIDI are significantly affected with the EVCS load addition. Further, the value of CAIDI remains almost same in all of the test cases that means it is almost constant for all test cases denoting, this parameter of reliability is least or not affected due to the EVCS load addition.

4.2.3 Impact on power loss

The power loss is calculated directly through load flow analysis in this study. The active power loss on each bus are summed up to calculate total power loss in the case. The total active power loss for the several cases are tabulated in Table 4 below.

Table 4: Impact on power loss

Case	Power loss in MW
Base	0.076029
Case 1	0.080328
Case 2	0.099032
Case 3	0.096435
Case 4	0.08192
Case 5	0.099743

With the addition of EV charging station load, the power loss of the system was increased. The power loss is highest in Case 5 where EV chargers were added to each of two weakest bus in the model. The concentration of load on one bus, even though the bus is strong one produces higher power loss. So, distributing the load among the buses significantly reduces power loss. This has been proved in [9], where the system under study is standard IEEE33 bus system.

4.2.4 Comparative Analysis

After studying the impact of EVCS load placement in the system, the comparative analysis is conducted. The change in each parameter from base case to different considered cases are calculated and tabulated in following Table 5.

Table 5: Changes in VRP indices

Cases	Δ VSI	Δ Ploss	Δ SAIFI	Δ SAIDI	Δ CAIDI
Case 1	0.00264	0.05655	0.03234	0.03234	7.81E-07
Case 2	0.01187	0.30256	0.14304	0.14305	3.9E-06
Case 3	0.01135	0.26840	0.07880	0.07903	0.00021
Case 4	0.00352	0.07749	0.03228	0.03228	4.19E-07
Case 5	0.01333	0.31190	0.11499	0.11499	5.01E-06

From this analysis, it is observed that the placement of EV charging station in weaker bus created highest impact on operational parameters as case 5 has the highest changes in VRP index. The parameter which is severely affected due to placement of EVCS is power loss. Power loss ranges from 5 percent increment on least affected case to 31 percent on severely affected case. It is then followed by reliability indices SAIFI and SAIDI and finally voltage stability. SAIFI and SAIDI change ranges from 3 percent at the least to 14 percent at the most. In case of SAIFI and SAIDI, case 2 with 5 EVCS placed on strong bus has the severe impact. The impact on voltage stability index is also not severe in comparison to Power loss, SAIFI and SAIDI. CAIDI is least to not affected due to the load increment. The percentage change in VRP parameters due to EVCS load addition is shown in Figure 8.

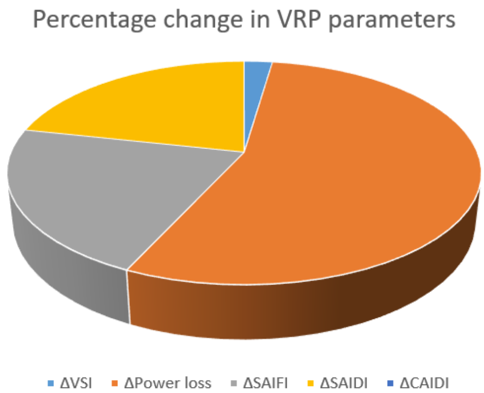

Figure 8: Percentage change in VRP parameters

With the integration of upto five number of EV charging stations in the feeder line, 54% change is observed in power loss, total of 43% change in reliability indices and only 3% change is seen in voltage stability.

5. Conclusion

The VSF calculation gave the strong and weak bus of the system. Bus number two is strongest and bus number 12 is the weakest bus on feeder. The integration of EVCS in weak bus has higher impact on the system. The number of EVCS load addition is also restricted to 5 to prevent the worse condition of the power loss. The change in VSI, reliability indices and power loss on the considered cases concluded that, the weak buses are to be provided with least number of charging stations to improve the system stability, reliability and efficiency. The major parameter to be considered during the placement of EV charging stations in distribution feeder is observed to be power loss then reliability indices and then voltage stability. The least impact on VRP paramters due to EVCS load addition can be realized with optimal placement rather than random placement of EV chargers to which the future work can be deviated to.

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