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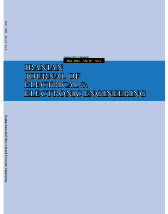

Multi-Stage Framework for Analyzing Penetration of Stochastic Distributed Energy Resources and Storage

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Abstract: This paper presents a multi-stage planning framework for analysis of stochastic distributed energy resources (DERs) comprising of solar, wind, and battery storage. The existing models do not consider penetration level analysis in conjunction with sizing, placement, and economic assessment. The main objective of this research is to embed all these dimensions of system planning in one structure. The first stage involves reliability constrained component sizing. The second stage pertains to placement of DERs based on loss minimization and voltage profile. The third stage is the main thrust of this work which provides exhaustive economic evaluation and cost-benefit analysis. The novelty of this work lies in the consideration of penetration level in backdrop of all three stages. The proposed formulation is implemented on a 33-Bus radial distribution feeder located in Jaisalmer, Rajasthan, India. Four penetration levels viz. 10, 20, 40, and 60 percent have been investigated and analyzed under different planning scenarios. The results facilitate the determination of optimum penetration level.

Keywords: DER Penetration, Economic Evaluation, Optimal Placement, Optimal Sizing, Planning Scenarios.

Nomenclature

Notations:

DERs	Distributed energy resources.
$EENS_{DER}$, $EENS_{base\ case}$	Expected energy not served with and without DER integration respectively, [MWh].
$LCOE$	Levelized cost of energy, [$/kWh].
N_{Bus}	Number of buses in distribution network.
N_{BR}	Number of branches in distribution network.
N_P	Number of planning years.
$N_{G\min}$, $N_{G\max}$	Minimum and maximum values respectively of generating units.
$N_{B\min}$, $N_{B\max}$	Minimum and maximum values respectively of battery storage unit.
PS-I	Planning Scenario-I.
PS-II	Planning Scenario-II.
$Pen_{\min}$	Minimum percentage of load that DERs must supply.
$Pen_{\max}$	Maximum percentage of load which DERs are allowed to supply.
RES	Renewable energy sources.
$R(i,j)$	Resistance of branch between bus i and j.
$SOC_{\min}$, $SOC_{\max}$	Minimum and maximum values respectively of battery state of charge.
$TLCC$	Total life cycle cost, [k$].
$V_{\min}$, $V_{\max}$	Minimum and maximum permissible voltage magnitude respectively, p.u.

Variables:

$I_{i,j}^{t}$	Current through branch between bus i and j during t-th time segment.
L^t	Load during t-th time segment, [kW].

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L_{DER}^{t}	Load supplied by DERs for *t*-th time segment, [kW].
$L_{DER_{\min}}^{t}$, $L_{DER_{\max}}^{t}$	Minimum and maximum load respectively which must be supplied by DERs for *t*-th time segment, [kW].
P_{G}^{t}	Power from grid during *t*-th time segment, [kW].
$P_{G\max}^{t}$	Maximum permissible power from grid during *t*-th time segment, [kW].
P_{loss}^{t}	Energy loss for *t*-th time segment, [kWh].
P_{DER}^{t}	Output power available from DERs during *t*-th time segment.
$P_{BSS_{ch}}^{t}$, $P_{BSS_{dis}}^{t}$	Power flow through battery during charging and discharging mode respectively.
Q_n	Energy supplied from DERs in *n*-th year, [kWh].

1 Introduction

DISTRIBUTED energy resources comprising solar and wind-based generators have experienced a significant evolution over the last few years. These sources have emerged as mainstream options in the power sector and have succeeded in establishing themselves on a global scale. The commitment to clean energy transition is the most important driver for renewable energy integration [1]. The increasing share of renewable energy sources (RES) is justified in the following contexts:

- Reducing environmental emissions
- Increasing energy security by diversification of resources;
- Increasing self-reliance by reducing import dependence;
- Hedging against price volatility of conventional fuels.

Though integration of RES based DERs such as solar and wind offer an array of benefits [2], there are two major concerns associated with their large scale deployment:

i. Stochastic nature of these resources and its wide impact on system parameters;
ii. Capital intensive structure.

In a significant work presented by Michas *et al.* [3], research priorities related to the intermittency of RES have been identified. In order to counteract the effect of intermittency, storage units have been widely employed. The storage cost has a direct impact on integration of RES [3]. The high cost remains a major hindrance in their adoption in several countries. The management of integrating higher penetration of renewable energy has to be backed by efficient planning to reinforce their economic viability.

1.1 Literature Survey

System planning involving RES-based DERs is an intricate task and requires comprehensive analysis. The literature survey pertaining to planning studies can be broadly classified under two groups viz. planning methodology and planning objectives which are discussed as follows.

1.1.1 Planning Methodology

The methodology reported in the literature is based either on optimal sizing, optimal location, or a combination of both. Amongst the studies involving optimal sizing, Akram *et al.* [4] have carried out two-stage planning. In the first stage, the sizes of generators are determined. The second stage involves battery sizing. Farag and Elnozahy [5] have determined optimum micro-grid configuration considering renewable and non-renewable technologies. Askari and Ameri [6] have conducted a techno-economic feasibility analysis of standalone systems in Iran. Different resource mix was investigated and PV/Battery system was found to be the most optimum configuration. Identifying the need for storage integration with stochastic resources, Dong *et al.* [7] have focused on storage reserve sizing. Mao *et al.* [8] have proposed a micro-grid design model comprising of solar-battery system. The determination of optimal size is carried out in association with scheduling strategy. Paliwal [9] has proposed a reliability constrained formulation for determining optimal component size for a solar-wind-battery-based isolated power system.

In addition to consideration of sizing, optimal placement models have also been widely reported in the literature. Alarcon-Rodriguez *et al.* [10] have put forward a multi-objective planning framework considering PV and wind. It was suggested that though DER integration facilitates improved grid performance, their intermittency remains a challenge. A scenario based planning model considering uncertainties associated with wind and solar generators has been proposed by Ehsan *et al.* [11]. The optimal location and capacities of DG units have been determined. The determination of sizing and location have also been presented by Kestane and Koray [12]. In a recent work proposed by Sannigrahi *et al.* [13] a bi-level planning problem with solar, wind and DSTATCOM has been formulated. However, in all above analyses, storage

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units have not been considered. There are only few papers that deal with a combination of PV, wind, and storage units [4], [14-17]. However, none of these papers provide a procedure for embedding penetration level analysis in the planning framework.

1.1.2 Planning Objectives

The objectives targeted by researchers for DER planning can be broadly classified into the following categories:

i. *Technical objectives:* Maximization of system reliability, Minimization of losses, improvement in voltage profile.
ii. *Environmental objectives:* Reduction in emissions.
iii. *Economic objectives:* Minimization of cost, Maximization of utility's profit.

Majority of planning problems are multi-objective formulation and involve a combination of the above objectives. Alarcon-Rodriguez *et al.* [10] have considered multiple objectives comprising line losses, DER energy, environmental emissions, voltage stability index, and penetration level. Akram *et al.* [4] have considered reliability and cost as prime objectives. Farag and Elnozahy [5] have proposed a bi-objective formulation considering economic and environmental factors. An analysis based on net present cost and unmet load fraction has been conducted by Askari and Ameri [6]. Dong *et al.* [7] have deeply analyzed the reliability indices in presence of storage units. Mao *et al.* [8] have considered levelized cost of energy, emission reduction benefits, and payback period as indicators for micro-grid sizing. Som and Chakraborty [18] have proposed an economic evaluation framework based on real valued cultural algorithm. The focus is on the determination of cost competitiveness of micro-grid configurations under different load scenarios. Ehsan *et al.* [11] have considered maximization of benefits to distribution network operator. The evaluation of payback period has been done by Kestane and Koray [12]. Ramli *et al*. [19] have used multi-objective optimization to analyze system reliability and energy cost.

Based on the above literature survey, it has been observed that the majority of planning studies have been focused on multi-objective formulation based on optimal sizing and/or optimal location. A very important aspect that is lacking in system planning is the analysis of penetration level along with sizing and location issues. The planning involving a combination of PV and wind-based DERs with storage is a complex problem. The benefits offered by DER integration should be markedly assessed and quantified concerning penetration level. There are few papers that assert the importance of penetration level. Amongst the literature discussed above, Alarcon-Rodriguez et al. [10], Wang and Singh [16], Ajlan [14], Dong *et al.* [7], Kanwar *et al.* [20], Ehsan *et al.* [11] have dealt with penetration level. However, none of these papers provide a comprehensive framework that involves planning of RES-based DERs and storage considering sizing, placement along penetration level. Besides, technical, environmental, and economic objectives have also not been dealt simultaneously in the majority of papers. This can be readily assessed with a quick visualization of the broad review presented in Table 1.

1.2 Research Gaps

Based on the literature survey, the following research gaps can be identified:

i. Due to intermittent nature of RES based DERs, it

Table 1 Literature survey.

Ref. No.	Type of technology			Objective			Methodology		Penetration level analysis
	PV	Wind	Storage	Technical	Environmental	Economic	Sizing	Placement	
[4]	✓	✓	✓	✓	×	✓	✓	×	×
[5]	✓	✓	×	×	✓	✓	✓	×	×
[6]	✓	✓	✓	×	×	✓	✓	×	×
[7]	×	×	✓	✓	×	✓	✓	×	✓
[8]	✓	×	✓	×	✓	✓	✓	×	×
[10]	✓	✓	×	✓	✓	✓	✓	✓	✓
[11]	✓	✓	×	×	×	✓	✓	✓	✓
[12]	×	✓	×	×	×	✓	✓	✓	×
[13]	✓	✓	×	✓	✓	✓	✓	✓	×
[14]	✓	✓	✓	×	✓	✓	×	×	✓
[15]	✓	✓	×	✓	✓	×	×	×	×
[16]	✓	✓	✓	✓	✓	✓	✓	×	✓
[17]	✓	✓	✓	✓	✓	✓	✓	✓	×
[18]	✓	×	✓	×	×	✓	✓	×	×
[20]	✓	✓	×	×	×	✓	✓	✓	✓
[21]	×	✓	×	✓	✓	✓	✓	✓	×
[22]	✓	✓	×	×	✓	✓	✓	✓	×
[23]	✓	✓	×	✓	✓	✓	✓	×	×
Proposed work	✓	✓	✓	✓	✓	✓	✓	✓	✓

is imperative that planning formulation should incorporate penetration analysis of DERs. However, there are very few papers that consider penetration level in planning strategy.

ii. Some of the papers which do consider penetration analysis, do not provide a suitable correlation between penetration level and stochastic behavior of DERs.

iii. There are several papers asserting the importance of storage integration with DERs. However, a planning formulation that facilitates the evaluation of battery storage sizing and placement as a function of penetration level has not been presented.

Economic evaluation has been incorporated as one of the most important components of the majority of planning formulations reported in the literature. However, to the best of the author's knowledge, none of the papers have organized economic evaluation considering optimal sizing, placement, and penetration level in one structure.

1.3 Contributions and Organization

In order to address the research gaps discussed in Section 1.2, this paper proposes a multi-stage comprehensive economic evaluation framework considering optimal sizing and optimal placement problems under the chassis of different penetration levels. The RES-based DERs considered in this paper comprise PV and wind generators. In order to negate the effect of intermittency, storage units have been interspersed at each penetration level. The novel contributions of work reported in this paper can be summated as follows:

i. A probabilistic framework for analyzing the impact of DER penetration on system planning has been presented. This adds a new dimension to planning methodology where, in addition to optimal sizing and placement, optimum DER penetration level can also be determined.

ii. The penetration level in this work is correlated with the meteorological parameters on hour by hour basis. The formulation proposes the concept of analyzing the DER penetration through $Pen_{\min}$ and $Pen_{\max}$. This adequately addresses the intermittent behavior of DERs.

iii. A three-stage methodology has been developed to addresses the assessment of DER penetration level. The intermittent nature of DERs may pose up technical issues such as system reliability problem and voltage fluctuation. Thus, in this planning framework, technical problems are given due consideration while simultaneously handling the economic front. In order to enable in-depth economic evaluation, the technical and environmental objectives have been expressed as cost functions.

iv. Different planning scenarios have been investigated in order to have an understanding of prioritizing objectives and penetration level from an economical perspective.

The proposed formulation is a generalized one and can be extended to any type of technology combinations. The remainder of this paper is organized as follows.

Section 2 explains penetration level as defined in this work. A brief discussion on the modeling of PV and wind resources has also been presented. Section 3 presents a multi-stage planning formulation. In Section 4, a case study on 33-bus radial distribution feeder has been presented. The obtained results have been critically analyzed. In Section 5, important conclusions drawn from work have been discussed.

2 Modeling and Penetration Level of DERs

With the purpose of acknowledging the stochastic behavior of PV and wind-based DERs, the study period is divided into time segments [24]. Corresponding to each time segment, the modeling of DERs and penetration level is briefly discussed in the following sub-sections.

2.1 Modeling of DERs

The output from RES-based sources such as solar and wind is a function of meteorological conditions. Based on high and low periods of wind or sun, the generation from these sources largely varies. In order to address the effect of intermittency, for each time segment, wind speed and solar irradiance are modeled using Weibull and Beta probability density function respectively [24-26]. The hardware availability of generators is modeled based on their forced outage rate (FOR). In order to establish the correlation between intermittent DERs and battery storage, a probabilistic battery state model has been used in this paper [25]. Fig. 1 presents the block diagram for DER modeling and system state evaluation.

2.2 Penetration Level of DERs

In this paper, DER penetration is defined so as to ensure that they provide a minimum amount of power even during adverse meteorological conditions. The existing literature does not provide adequate treatment to intermittency associated with stochastic DERs. In the majority of papers, DER penetration is defined as the ratio of power/energy supplied by DER to total power/energy demanded over the study period. This definition is not suitable in the context of stochastic DERs [26]. In this paper, the following two definitions of penetration levels are considered [26]:

2.2.1 $Pen_{\min}$

$Pen_{\min}$ is defined as the minimum percentage of load that DERs must supply for each time segment regardless

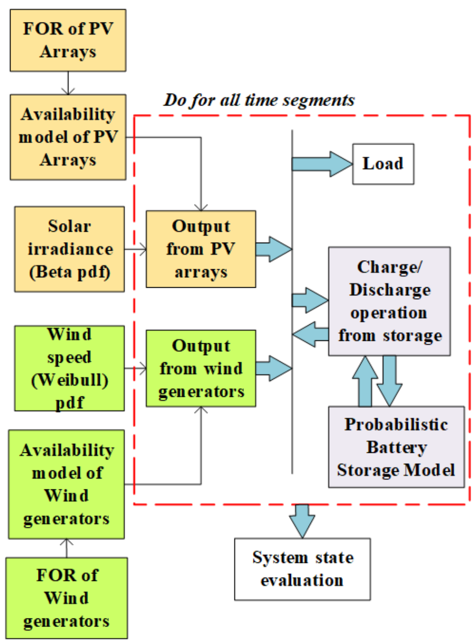

Fig. 1 DER modeling and system state evaluation.

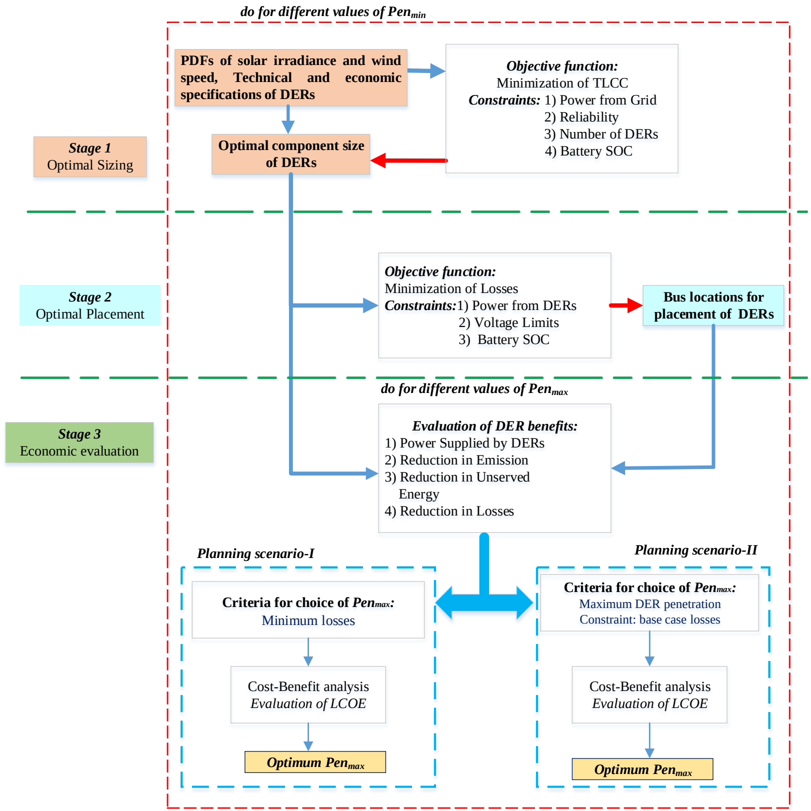

Fig. 2 Multi-stage planning framework.

of wind speed and solar irradiance. This imposition on Pen_{min} makes the deployment of storage units an essential component of planning with stochastic DERs. For time segment t

$$\text{Total power supplied from DERs} \geq Pen_{min} \tag{1}$$

Due to the highly stochastic nature of RES, a system designed to ensure Pen_{min} considers low and high periods of wind speed and solar irradiance. However, the system can definitely deliver much higher amount of power during favorable meteorological conditions. Thus, economically it makes all sense to allow a higher amount of penetration than Pen_{min} whenever it is feasible to do so.

2.2.2 Pen_{max}

Pen_{max} is defined as the maximum percentage of load which DERs are allowed to supply for each time segment. Allowing a higher amount of power from DERs can adversely affect system losses and voltage profile [27]. The Pen_{max} puts an upper limit to the amount of power that DERs are allowed to supply so that system losses and voltage profile are constrained within specified limits. For time segment t,

$$\text{Total power supplied from DERs} \leq Pen_{max} \tag{2}$$

The penetration levels of DERs affect system performance in multiple ways. A thorough analysis of the impact of Pen_{min} and Pen_{max} is essential in order to come up with a well-designed system.

3 Multi-Stage Planning Formulation

In this paper, a multi-stage planning formulation is proposed. The framework is depicted in Fig. 2 and comprises three stages: (i) Optimal sizing (ii) Optimal placement and (iii) Economic evaluation. The first two stages i.e. optimal sizing and placement are well reported in the literature and are not the focus of this work. The emphasis of this paper is on the third stage i.e. economic evaluation. Nevertheless, since the first two stages form the basis of analysis, they are briefly discussed in the following sub-sections.

3.1 Stage 1: Optimal Sizing

This stage involves the determination of optimal component sizes of RES-based DERs and storage capable of maintaining defined reliability standards. This is carried out for different penetration levels. The corresponding impacts in terms of improvement in reliability and reduction in emissions are analyzed. The objective function and constraints corresponding to this stage are presented in the following sub-sections.

3.1.1 Objective Function: Sizing

$$\text{Minimize} \quad TLCC \tag{3}$$

where, *TLCC* is total life cycle cost over the planning horizon. The *TLCC* can be calculated as follows:

$$TLCC = CC + MC + RC - SV \tag{4}$$

The cost components involved in (4) can be calculated as follows [24]:

(1) *Capital Cost* (*CC*)

$$CC = \sum_{\forall i} N_i \, \alpha_{CC_i} \, C_i \tag{5}$$

where, N_i, α_{CCi}, C_i are number of units, per unit capital cost, and capacity, respectively, of *i*-th component.

(2) *Maintenance cost* (*MC*)

$$MC = \underbrace{\sum_{i=1}^{N_G} \sum_{n=1}^{N_p} O_i . \alpha_{M_i} \left(\frac{1+E_{M_i}}{1+r} \right)^n}_{\text{Generating Units}} + \underbrace{\sum_{n=1}^{Np} \frac{\alpha_{M_B} . N_B . C_B}{(1+r)^n}}_{\text{Battery Storage unit}} \tag{6}$$

where, N_G is number of generating units, N_P is number of planning years, O_i is energy output from *i*-th generator [kWh/year], α_{Mi} and E_{Mi} are per unit maintenance cost and escalation rate of maintenance cost respectively of *i*-th generator, α_{M_B} is maintenance cost of battery storage units, [$/kWh/year], N_B is number of battery storage, C_B is battery capacity, [kWh], *r* is nominal discount rate.

(3) *Replacement Cost* (*RC*)

$$RC = \sum_{\forall i} \alpha_{CC_i} N_i C_i \sum_{m=1}^{N_{R_i}} \left(\frac{1+E_{C_i}}{1+r} \right)^{m \times L_i} \tag{7}$$

where, N_{R_i}, E_{C_i} and L_i represent number of replacements required over planning years, capital cost escalation rate, and lifetime respectively of *i*-th component.

(4) *Salvage Value* (*SV*)

$$SV = \sum_{\forall i} \frac{S_i}{(1+r)^{N_p}} \tag{8}$$

where, S_i is salvage value of *i*-th component.

3.1.2 Constraints

(1) *Constraint on power from utility grid*:

The maximum power that can be obtained from the utility grid for *t*-th time segment is dependent on $Pen_{\min}$ as follows:

$$P_G^t \le P_{G\max}^t \tag{9}$$

$$P_{G\max}^t = \left(1 - Pen_{\min}\right) L^t \tag{10}$$

(2) *Constraint on system reliability*:

The stochastic nature of RES-based DERs can raise reliability issues; particularly at higher penetration levels. Under no circumstances, reliability of the system should worsen with DER integration. Thus optimal sizing problem of DERs corresponding to different $Pen_{\min}$ is subjected to constraint on system reliability as follows:

$$EENS_{DER} \le EENS_{base\,case} \tag{11}$$

(3) *Constraint on number of units*:

The numbers of generating and storage units are constrained by minimum and maximum values.

$$N_{G\min} \le N_G \le N_{G\max} \tag{12}$$

$$N_{B\min} \le N_B \le N_{B\max} \tag{13}$$

(4) *Constraint on battery parameters*:

In order to ensure optimum life, battery is subjected to constraints on battery state of charge as follows:

$$SOC_{\min} \le SOC \le SOC_{\max} \tag{14}$$

(5) *Constraint on power flow*:

For all time segments, the power balance must be maintained as follows:

a) Battery discharging mode

$$P_{DER}^t + P_G^t + P_{BSS_{dis}}^t = L^t \tag{15}$$

b) Battery charging mode

$$P_{DER}^t = L^t + P_{BSS_{ch}}^t \tag{16}$$

3.2 Stage 2: Optimal Placement

This stage involves determination of the optimal placement of DERs on the distribution feeder with the objective of minimization of system losses. The placement problem is solved for different penetration levels. This enables system planners to analyze the impact of penetration of RES-based DGs and storage on line losses and voltage profile. The objective function and constraints corresponding to the optimal placement problem are presented in the following sub-sections.

3.2.1 Objective Function

The objective function for DER placement can be stated as [28-29]:

$$\text{Minimize} \sum_{t=1}^{T} P_{loss}^t \tag{17}$$

where $$P_{loss}^{t} = \sum_{i,j=1}^{N_{BR}} R(i,j).\,|\,I_{i,j}^{t}\,|^{2} \tag{18}$$

3.2.2 Constraints

(1) *Constraint on load supplied by DERs*:
The load which is to be supplied by DERs for any time segment is dependent on $Pen_{\min}$ and $Pen_{\max}$. It is subjected to the following constraints:

$$L_{DER_{\min}}^{t} \le L_{DER}^{t} \le L_{DER_{\max}}^{t} \tag{19}$$

$$L_{DER_{\min}}^{t} = Pen_{\min} \times L^{t} \tag{20}$$

$$L_{DER_{\max}}^{t} = Pen_{\max} \times L^{t} \tag{21}$$

(2) *Constraint on voltage limits on each bus*:
The magnitude of voltage at all buses in the network must comply with the defined voltage limit. Thus, voltage magnitude at i-th bus V_i is subjected to strict voltage constraints.

$$V_{\min} \le V_i \le V_{\max} \quad \text{for } i = 1, 2, \ldots, N_{Bus} \tag{22}$$

(3) *Constraint on battery parameters*:
Same as discussed in Eq. (14).

3.3 Stage 3: Economic Evaluation

Based on the above two steps, a comprehensive economic evaluation is carried out considering different planning scenarios. Having determined optimal sizing and placement of DERs for each $Pen_{\min}$, the impact on system losses and voltage profile is investigated by varying $Pen_{\max}$. From economic considerations, it is desirable to utilize the capacity of DERs completely. However, this may not be suitable from technical considerations. Increasing DER penetration beyond a certain level can result in degradation of line losses and voltage profile [27]. A cost/benefit analysis is performed in order to have a thorough study of different penetration levels. The economic evaluation parameters can be classified into two groups *viz.* costs incurred in DER integration and benefits offered by DER integration. The mathematical modeling of economic evaluation parameters is briefly discussed in the following sub-sections.

3.3.1 Cost Parameters

There are two cost parameters used in this work which are as follows:

i. Total life cycle cost: The costs incurred in DER integration are expressed as Total life cycle costs (TLCC) and explained in Section 3.1.1.
Levelized cost of energy (LCOE): *LCOE* is defined as the cost which if allocated to every unit of energy over the planning period will equal to *TLCC* of the system discounted to base year [30].

ii. *LCOE* can be calculated as:

$$LCOE = \frac{TLCC}{\left(\sum_{n=1}^{N_p} Q_n\right) \Big/ (1+r)^n} \tag{23}$$

3.3.2 Benefit Evaluation Parameters

The mathematical formulation of DER benefits is discussed as follows.

(1) *Benefits offered due to power supplied by DERs*:
The integration of DERs can significantly cut down the cost of buying power from the utility grid. Due to the scarcity of fossil fuel resources, there has been a sharp rise in their cost. This has resulted in an increase in the cost of power generated from these resources. Increasing integration of RES can reduce reliance on fossil fuel-based plants. This is seen as free hedging mechanism against the price volatility of fossil fuels leading to increased energy security. The present worth of benefit offered due to the energy supplied by DERs can be expressed as:

$$B_{E_{DER}} = \sum_{n=1}^{N_p} E_{DER}.\psi.\left(\frac{1+E_{\psi}}{1+r}\right)^{n} \tag{24}$$

where, $B_{E_{DER}}$ presents worth of benefit offered due to energy supplied by DERs, [\$], E_{DER} is energy supplied by DERs, [kWh/year], ψ is per unit cost of energy purchased from the grid, [\$/kWh], E_{ψ} is escalation rate of cost of energy purchased from the grid.

(2) *Benefits offered due to reduction in emissions*:
Integration of DERs to the grid reduces the social cost of carbon (SCC) and represents the competitive advantage of RES. As per Demirbas *et al.* [31], nearly 98% of carbon emissions are attributed to fossil fuel combustion. On the utility side, reducing SCC is becoming increasingly important due to environmental regulations worldwide. From the consumer's perspective, these costs are likely to gain importance in the future if consumers are charged for the indirect cost of environmental clean-up and health effects. The present worth of benefits offered due to reduction in emissions can be expressed as:

$$B_{E} = \sum_{n=1}^{N_p} (E_{G}^{WO_{DER}} - E_{G}^{W_{DER}}).C_{E}.\left(\frac{1+E_{C_E}}{1+r}\right)^{n} \tag{25}$$

where, B_E presents worth of benefit offered due to reduction in emissions, [\$], $E_{G}^{W_{DER}}$ and $E_{G}^{WO_{DER}}$ are energy supplied by the grid with and without DER integration respectively, [kWh/year], C_E is social cost of carbon emission/unit of energy produced from fossil fuel, [\$/kWh], E_{C_E} is escalation rate of social cost of emissions.

(3) *Benefits offered due to reduction in utility outage cost*:

The reliability benefits can be greatly improved if operation of DERs is permitted in islanded mode [26]. This leads to a reduction in system unserved energy. The present worth of benefits offered due to reduction in utility outage cost can be expressed as:

$$B_{UOC} = \sum_{n=1}^{N_p} (EENS^{WO_{DER}} - EENS^{W_{DER}}).C_{ENS}.\left(\frac{1+E_{C_{ENS}}}{1+r}\right)^n \quad (26)$$

where, B_{UOC} presents worth of benefit offered due to reduction in utility outage cost, [\$], $EENS^{W_{DER}}$ and $EENS^{WO_{DER}}$ are expected energy not served with and without DER integration respectively, [kWh/year], C_{ENS} is cost of energy not served, [\$/kWh], $E_{C_{ENS}}$ is escalation rate of cost of unserved energy.

(4) *Benefits offered due to reduction in losses*:

Integration of DERs can significantly facilitate line loss reduction by supplying power to a section of the feeder. The present worth of benefit offered due to reduction in energy losses can be expressed as:

$$B_L = \sum_{n=1}^{N_p} (E_{loss}^{WO_{DER}} - E_{loss}^{W_{DER}}).C_L.\left(\frac{1+E_L}{1+r}\right)^n \quad (27)$$

where, B_L presents worth of benefit offered due to reduction in losses, [\$], $E_{loss}^{W_{DER}}$ and $E_{loss}^{WO_{DER}}$ are active energy losses with and without DER integration respectively, [kWh/year], C_L is cost of losses, [\$/kWh], E_L is escalation rate of cost of losses.

3.3.3 Planning Scenarios (PS)

The system is designed to supply at least Pen_{min} from DERs. In order to choose Pen_{max}, the following two planning scenarios are considered:

(1) *Planning Scenario-I(PS-I)*:

Pen_{max} is chosen from the objective of minimizing losses. The benefits offered from DERs are calculated corresponding to this value of Pen_{max}.

(2) *Planning Scenario-II((PS-II)*:

Pen_{max} is chosen from the objective of maximizing DER penetration. The selection of Pen_{max} is constrained so that system losses do not exceed the losses without DER penetration. The benefits offered from DERs are calculated corresponding to this value of Pen_{max}.

4 Case Study: Results and Discussion

The proposed planning framework based on economic parameters has been applied to a 12.66 kV, 33-bus distribution system [32] presented in Fig. 3. The site of the distribution system is assumed as Jaisalmer, Rajasthan, India. The meteorological parameters for the considered site have been acquired from [33, 34]. The load data has been derived from [35]. The simulation is carried out for a period of one year comprising of 8760 time segments. The economic parameters used for calculating TLCC have been obtained from [24]. The planning horizon is considered as 20 years.

India's SCC is highest at 86 \$/tCO_2 [36]. Also, due to coal dominance, per unit electricity emissions in India is quite high. The cost of purchasing power from the utility grid and expected escalation in cost have been obtained from [37]. The cost of unserved energy and cost of losses is assumed to be equal to the cost of power supplied by the grid. The parameters used for evaluating DER benefits are presented in Table 2.

As discussed in Section 3, the evaluation framework proposed in this paper comprises three stages. Four different penetration levels viz. 10, 20, 40, and 60 percent have been analyzed in this work. The results corresponding to each stage are discussed in the following sub-sections.

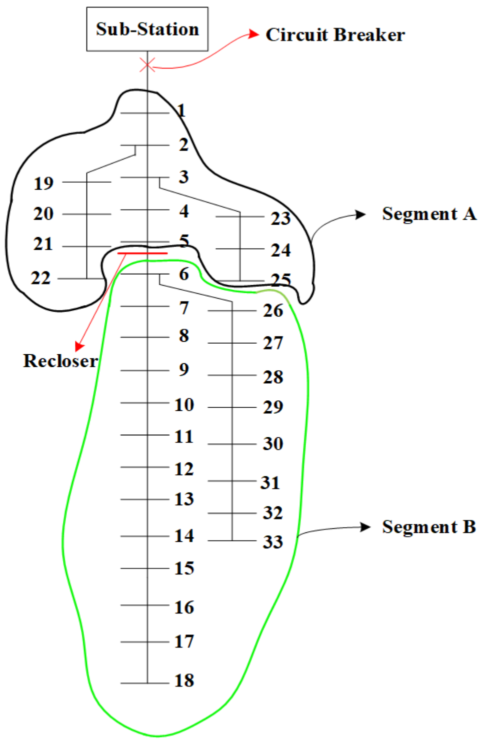

Fig. 3 33-bus radial distribution feeder.

Table 2 Cost evaluation parameters.

Parameter	Values
Project lifespan [years]	20
Social cost of emission [\$/kWh]	0.077
Cost of power purchased from grid [\$/kWh]	0.08
Cost of energy not served [\$/kWh]	0.08
Cost of losses [\$/kWh]	0.08
Escalation in cost of power purchased from grid, cost of energy not served, cost of losses, social cost of emission	5%

4.1 Results of Stage 1: Optimal Sizing

The improvement in reliability is one of the major benefits offered by DER integration. Thus, a reliability constrained optimal sizing formulation (Section 3.1) has been used in this work. In the event of fault, the system can be operated in islanded mode [26]. This leads to a reduction in outage costs. In order to acknowledge the effect of DER integration on system reliability, the radial distribution feeder presented in Fig. 3 is divided into two segments. Segment A has active and reactive load of 1.66 MW and 0.82 MVAR respectively. Segment B has active and reactive load of 2.095 MW and 1.48 MVAR respectively. Table 3 presents the base case reliability indices for respective segments as well as the whole system before DER integration. The reliability indices used in this work are loss of load expectation (LOLE) and expected energy not served (EENS). Reliability evaluation has been carried out using the segmentation concept [26].

The optimal sizing problem has been solved using the Butterfly Particle Swarm optimization algorithm [38]. Table 4 presents the optimal sizing results for different penetration levels. With respect to component sizes in Table 4, the impact of DERs on system reliability is assessed.

Table 5 presents the reliability indices obtained after DER integration.

On comparing base case results shown in Table 3 with Table 5, it can be clearly observed that irrespective of penetration level, integration of DERs reduces *EENS* and *LOLE* of both segments A and B.

4.2 Results of Stage 2: Optimal Placement

This stage is focused on determining optimal placement of DERs obtained from Stage 1. The objective of the placement problem is loss minimization as discussed in Section 3.2. Table 6 presents the real and reactive power losses without DER integration.

In order to critically analyze the impact of DER penetration, placement is carried out for four different levels of $Pen_{\min}$. The optimal placement problem has been solved using the Butterfly Particle Swarm optimization algorithm [38]. The results of the optimal placement problem have been presented in Table 7.

Table 3 Base case reliability indices.

Segment	Base Case Results	
	EENS [MWh/Yr]	*LOLE* [Hours/Yr]
A	3.534	3.4692
B	15.177	11.8044
Entire feeder	18.711	15.2736

Table 4 Optimal sizing results for different $Pen_{\min}$.

Penetration level ($Pen_{\min}$)	Capacity		
	PV [MW]	Wind [MW]	Battery storage [MWh]
10%	0.375	Two generators of 1 MW each	Not required
20%	0.525	One generator of 3 MW	4.752
40%	1.5	One generator of 3 MW, Two generators of 1.5 MW each	11.088
60%	1.5	One generator of 4.1 MW, Two generators of 2.05 MW each	29.658

Table 5 Reliability indices after DER integration.

$Pen_{\min}$ [%]	Segment A		Segment B		Entire feeder	Entire feeder
	$EENS^{A}_{DER}$ [MWh]	$LOLE^{A}_{DER}$ [Hours/yr]	$EENS^{B}_{DER}$ [MWh]	$LOLE^{B}_{DER}$ [Hours/yr]	$EENS_{DER}$ [MWh]	$LOLE_{DER}$ [Hours/yr]
10	3.5290	3.4622	12.7353	10.8586	16.264	11.797
20	3.3936	3.3302	10.727	8.3563	14.126	11.752
40	3.3868	3.3244	10.713	8.3359	14.128	11.762
60	3.3868	3.3244	10.700	8.3353	15.153	11.803

Table 6 Base case losses for 33-bus system.

Real losses [MWh/yr]	Reactive losses [MVArh/yr]
691.78	464.19

Table 7 Optimal placement results for different $Pen_{\min}$.

Penetration level ($Pen_{\min}$)	PV generator	Wind generator	Battery storage
10%	Bus No. 17	Bus No. 17, Bus No. 32	Not required
20%	Bus No. 32	Bus No. 15	Bus No. 32
40%	Bus No. 32	Bus No. 14 (3 MW), Bus No. 15 and Bus No. 32 (1.5 MW)	Bus No. 14
60%	Bus No. 32	Bus No. 14 (4.1 MW), Bus No. 15 and Bus No. 32 (2.05 MW)	Bus No. 14

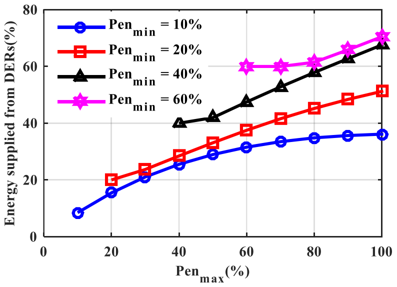

Fig. 4 Energy supplied from DERs for different levels of Pen_{max}.

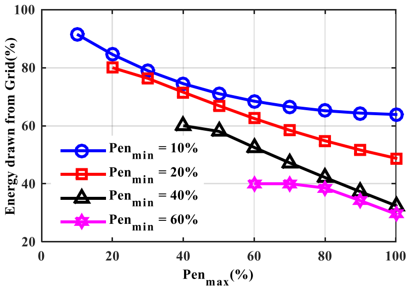

Fig. 5 Energy drawn from grid for different levels of Pen_{max}.

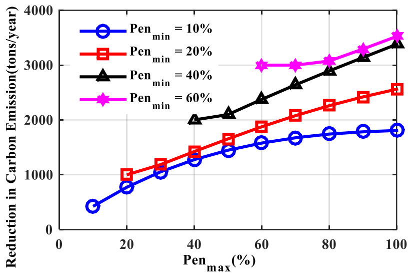

Fig. 6 Reduction in carbon emissions for different levels of Pen_{max}.

Table 8 Optimum Pen_{max} for *PS-I*.

Pen_{min} [%]	Optimum Pen_{max} [%]	Active energy losses [MWh/yr]	Reactive energy losses [MVArh/yr]
10	60	381.97	280.77
20	40	349.97	242.97
40	50	330.12	238.5
60	60	379.35	288.23

Table 9 Cost evaluation for *PS-I* (All costs are net present value over project lifespan).

Penetration level		Benefits offered by DERs			
Pen_{min} [%]	Pen_{max} [%]	Power supplied by DERs [K$]	Reduction in emission [K$]	Reduction in un-served energy [K$]	Reduction in losses [K$]
10	60	8442.5	7425.6	3.2473	411.02
20	40	7613.54	6696.44	6.083	453.47
40	50	11221	9868.88	6.081	479.82
60	60	16049.595	14116.32	6.045	414.49

As discussed in Section 2.2, the reduction in losses with DER penetration is a function of Pen_{min} as well as Pen_{max}. The impact on losses with DER penetration is critically investigated with respect to different planning scenarios in Section 4.3.

4.3 Results of Stage 3: Economic Evaluation

Having determined the optimal sizing and placement of DERs from *Stage 1* and *Stage 2* respectively, the focus of this stage is to carry out a comprehensive economic evaluation. As has been asserted in Section 2, the DER integration is planned so as to ensure a firm capacity addition to the grid. Thus, for each Pen_{min}, optimal sizing of components has been carried out considering the probabilities of wind and solar generation as well as outage probabilities of generating units. Hence, during favorable meteorological conditions, DERs can provide a much higher amount of power than committed by Pen_{min}. A high value of Pen_{max} can provide increased economic viability and reduction in carbon emissions. However, at the same time, it can have a negative effect on system losses and voltage profile. Thus, from an economic standpoint, the following four parameters are investigated in this work:
(i) Power supplied from DERs,
(ii) carbon emissions,
(iii) utility outage cost,
(iv) losses.

Fig. 4 presents the effect of variation of Pen_{max} for each level of Pen_{min} on energy supplied from DERs.

It is evident from Fig. 4 that a system designed for a Pen_{min} =10% can provide annual energy output up to 36% of annual energy demand. Similarly, systems designed for minimum 20%, 40%, and 60% penetration can also serve higher percentage of annual energy demand. Thus, it is evident that there is enough redundancy in the system at each designated Pen_{min}.

Fig. 5 shows variation of energy drawn from the grid with respect to the variation of Pen_{max} for different values of Pen_{min}. With the increase in Pen_{max}, the energy drawn from the grid reduces. This imparts increased economic viability to DER integration.

Fig. 6 demonstrates the effect of variation of Pen_{min} and Pen_{max} on reduction in carbon emissions.

It is evident from Fig. 6, that allowing higher penetration level than the defined minimum one facilitates increased reduction in carbon emissions. The economic evaluation is further extended by considering two planning scenarios as proposed in Section 3.3. The analysis is discussed in the following sub-sections.

4.3.1 Analysis of PS-I

In *PS-I*, Pen_{max} is chosen from objective of loss minimization. Table 8 shows the optimum value of Pen_{max} and corresponding active and reactive energy losses for each level of Pen_{min}. It can be observed from Table 8 that minimum losses are obtained with Pen_{min} = 40% and Pen_{max} = 50%. This gives a basis for selecting optimum values of $Pen_{\min}$. In order to have an understanding of how other economic evaluation parameters respond to *PS-I*, they are evaluated for each level of $Pen_{\min}$. Table 9 presents the benefits offered due to integration of DERs for *PS-I*.

From cost evaluation carried out for *PS-I*, the following conclusions can be drawn:

i. $Pen_{\min}$ = 10% offers better benefits in terms of power supplied by DERs in comparison with $Pen_{\min}$ = 20%. This is because selection of $Pen_{\max}$ has been done from perspective of loss minimization which is higher for $Pen_{\min}$ =10% in comparison with $Pen_{\min}$ = 20%.

ii. Benefits offered due to reduction in utility outage costs become more or less constant with increasing level of $Pen_{\min}$. This suggests that improvement in reliability with addition of generating capacity is attainable only up to a certain extent.

iii. If the objective is to obtain benefits of loss reduction, even lower levels of $Pen_{\min}$ can serve the purpose. Consideration of higher levels of Pen_{min} is justifiable only from the perspective of increasing the share of renewables.

4.3.2 Analysis of PS-II

Table 10 shows optimum $Pen_{\max}$ corresponding to each value of $Pen_{\min}$ for *PS-II*. The $Pen_{\max}$ is chosen from perspective of maximizing DER penetration. Although losses are not the criteria for selection of $Pen_{\max}$, its value is constrained so as not to exceed base case losses. It can be observed from Table 10 that if loss minimization is not the criteria, for all considered values of $Pen_{\min}$, almost 100% $Pen_{\max}$ is attainable.

Table 11 presents the benefits offered due to the integration of DERs for *PS-II*.

From cost evaluation carried out for *PS-II*, the following conclusions can be drawn:

i. *PS-II* offers substantial benefits in comparison with *PS-I* with respect to power supplied by DERs and reduction in emissions.

ii. It can be observed from Table 11 that $Pen_{\min}$ = 40% fetches higher benefits in comparison with $Pen_{\min}$ = 60% in terms of power supplied by DERs and reduction in emission. This is attributed to higher Pen_{max} attainable with $Pen_{\min}$ = 40%.

iii. Though loss minimization is not the criteria, for *PS-II*, the lowest $Pen_{\min}$ fetches the best benefits offered due to loss reduction.

Table 12 presents a comparison of economic parameters for *PS-I* and *PS-II*.

The important inferences which can be drawn based on Table 12 are as follows:

i. Due to capital intensive structure of RES technologies, the *LCOE* increases with increase in RES penetration.

ii. As can be observed from Table 12, there is a vast difference of *LCOE* between $Pen_{\min}$ = 10% and $Pen_{\min}$ = 20% with respect to both planning scenarios. However, $Pen_{\min}$ =20%, 40%, and 60% configurations do not show a significant difference in *LCOE*. This can be attributed to the introduction of storage. The storage is not required to ensure $Pen_{\min}$ = 10% penetration level. However, as penetration levels increase, the requisite amount of storage capacity has to be introduced in order to ensure firm penetration from DERs. This results in an increase in *LCOE* for higher penetration configurations.

Table 10 Optimum $Pen_{\max}$ for *PS-II*.

$Pen_{\min}$ [%]	Optimum $Pen_{\max}$ [%]	Active energy losses [MWh/yr]	Reactive energy losses [MVArh/yr]
10	100	397.02	294.81
20	90	597.2504	435.94
40	100	671.19539	496.38
60	90	580.52	436.10

Table 11 Cost evaluation for *PS-II* (All costs are net present value over project lifespan).

Penetration level		Benefits offered by DERs			
$Pen_{\min}$ [%]	$Pen_{\max}$ [%]	Power supplied by DERs [K$]	Reduction in emission [K$]	Reduction in un-served energy [K$]	Reduction in losses [K$]
10	100	9669.6	8504.85	3.2473	391.05
20	90	12947.802	11388.2	6.083	125.41
40	100	18076	15898.2	6.081	27.309
60	90	17616	15494.5	6.045	147.61

Table 12 Comparison of economic parameters for *PS-I* and *PS-II*.

$Pen_{\min}$ [%]	TLCC [K$]	Total benefits [K$]		Cost/Benefit		LCOE [$/kWh]	
		PS-I	*PS-II*	*PS-I*	*PS-II*	*PS-I*	*PS-II*
10	5874.4	16282.36	18568.75	0.361	0.316	0.0461	0.0403
20	24605	14769.533	24467.5	1.67	1.005	0.2143	0.126
40	40907.7	21575.78	34007.59	2.015	1.2	0.2418	0.1501
60	53613	30586.45	33264.155	1.752	1.61	0.2512	0.2018

iii. The cost/benefit ratio corresponding to *PS-I* is higher for $Pen_{\min}$ = 40% configuration as compared to that of $Pen_{\min}$ = 60% configuration. This is due to the reason that for *PS-I*, the criterion is the minimization of losses. This criterion restricts $Pen_{\max}$ = 50% for $Pen_{\min}$ = 40%. However, for $Pen_{\min}$ = 60% configuration, $Pen_{\max}$ is inherently higher. Thus, the benefits offered due to power supplied from DERs is higher. Although losses are higher for $Pen_{\min}$ = 60%., the benefits offered due to power supplied from DERs override benefits offered due to reduction in losses.

iv. The situation changes when *PS-II* is considered. With loss minimization constraint relaxed, the $Pen_{\max}$ for $Pen_{\min}$ = 40% configuration is now 100% resulting in increased utilization of redundancy in the system. On the other hand, $Pen_{\max}$ for $Pen_{\min}$ =60% configuration could not be increased beyond 90% due to constraint on system losses and voltage profile to be maintained at the base case level.

   Thus for *PS-II*, $Pen_{\min}$ = 40% configuration shows better utilization of DERs in comparison with $Pen_{\min}$ = 60% configuration resulting in lower Cost/Benefit ratio.

v. It can be concluded from the comprehensive cost evaluation presented in Table 12, that *PS-II* presents a more economically feasible option in comparison with *PS-I*.

   Thus in order to come up with a cost-effective planning, different planning scenarios need to be carefully investigated.

5 Conclusion and Future Work

The power system planning in presence of increasing DER penetration is a complex problem. This is accredited to the capital intensive structure of RES and their highly intermittent nature. DER planning is largely based on meteorological parameters of the site under consideration. Thus, a planning formulation and penetration level which is suitable for one site may not turn out to be optimum for the other. The proposed economic evaluation framework has been investigated for four different penetration levels. For each penetration level, an economic evaluation is carried out considering different planning scenarios. The important conclusions based on this work are as follows:

i. The economic evaluation parameters with RES-based DERs exhibit non-linear characteristics. This is apparent from the evaluation of *LCOE* for both the planning scenarios. When Pen_{min} is increased from 10% to 20%, *LCOE* shows an increase of 4.648 and 3.126 times for *PS-I* and *PS-II* respectively. However, when Pen_{min} is further increased from 20% to 40%, this factor is reduced to 1.128 and 1.1912 respectively for *PS-I* and *PS-II*.

ii. Increase in DER penetration beyond a certain limit can hamper the benefits offered by loss reduction. For *PS-I*, the reduction in active energy losses is 52.2% for $Pen_{\min}$ = 40% whereas it is 45.16% with $Pen_{\min}$ = 60%. Thus, higher DER penetration is leading to a lower benefit from perspective of loss minimization. The loss reduction with different penetration levels is also a function of planning strategy. This is evident from loss reduction analysis with *PS-II*. Here, Pen_{min} =40% offers a reduction of merely 2.98%. Thus, if loss minimization is the objective, a thorough analysis is required.

iii. Maximization of DER penetration renders higher economic benefits in comparison with minimization of system losses. It has been observed that irrespective of penetration level, lower *LCOE* is achieved with *PS-II* as compared to *PS-I*.

iv. With increase in penetration level, storage capacity becomes substantial to handle increasing effect of intermittency. Thus, benefits offered from increased DER penetration are overshadowed by increase in cost of storage integration. This fact is being captured with the evaluation of the cost/benefit ratio which escalates with increasing $Pen_{\min}$. This leads to increase in *LCOE*.

On the basis of the economic evaluation conducted in this paper, it can be concluded that it is essential to determine not only the optimum component size and placement but also the optimum penetration level. The major contributions of work presented in this paper are summarized as follows:

i. This paper proposes a new viewpoint wherein DER penetration is analyzed with the concept of $Pen_{\min}$ and $Pen_{\max}$. This significantly broadens the planning horizon and economic parameters can be more clearly investigated.

ii. The proposed formulation takes into consideration sizing, placement, penetration level and planning scenarios simultaneously.

iii. The proposed formulation effectively addresses the impact assessment of the DER penetration level on system planning. Adequate consideration has been given to system reliability, losses, voltage profile, social cost of carbon, and maximization of renewable energy penetration.

DER planning problem is a multi-faceted problem where different objectives may be conflicting in nature and thus call for a judicious compromise. The penetration level analysis presented in this paper aims to give a newfangled aspect to the planning problem. The present work can be further extended in the following areas:

i. Demand-side management can be integrated with above planning formulation.

ii. The economic model can be modified to accommodate various promotional incentives provided by the government in order to encourage renewable energy participation. The incentives comprise capital subsidies, tax holiday, subsidised interest rate on loans and depreciation benefits.

The use of storage can be extended to a wide range of applications such as energy arbitrage and ancillary services.

Intellectual Property

The authors confirm that they have given due consideration to the protection of intellectual property associated with this work and that there are no impediments to publication, including the timing of publication, with respect to intellectual property.

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Declaration of Competing Interest

The authors hereby confirm that the submitted manuscript is an original work and has not been published so far, is not under consideration for publication by any other journal and will not be submitted to any other journal until the decision will be made by this journal. All authors have approved the manuscript and agree with its submission to "Iranian Journal of Electrical and Electronic Engineering".

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