

Article

Comparison of Economical and Technical Photovoltaic Hosting Capacity Limits in Distribution Networks

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Abstract: Power distribution networks are transitioning from passive towards active networks considering the incorporation of distributed generation. Traditional energy networks require possible system upgrades due to the exponential growth of non-conventional energy resources. Thus, the cost concerns of the electric utilities regarding financial models of renewable energy sources (RES) call for the cost and benefit analysis of the networks prone to unprecedented RES integration. This paper provides an evaluation of photovoltaic (PV) hosting capacity (HC) subject to economical constraint by a probabilistic analysis based on Monte Carlo (MC) simulations to consider the stochastic nature of loads. The losses carry significance in terms of cost parameters, and this article focuses on HC investigation in terms of losses and their associated cost. The network losses followed a U-shaped trajectory with increasing PV penetration in the distribution network. In the investigated case networks, increased PV penetration reduced network costs up to around 40%, defined as a ratio to the feeding secondary transformer rating. Above 40%, the losses started to increase again and at 76–87% level, the network costs were the same as in the base cases of no PVs. This point was defined as the economical PV HC of the network. In the case of networks, this level of PV penetration did not yet lead to violations of network technical limits.

Keywords: distributed photovoltaics; economical analysis; grid losses; PV hosting capacity



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1. Introduction

The economical and reliable provision of power to the customers is the prime motivation of distribution network operators. The optimal design of the distribution network must be dealt with care considering the extensive network layouts, system losses, and frequent characteristic interruptions [1]. Energy markets around the world are based on two pricing models; zonal and nodal, to deal with congestion due to limited transmission capacity [2,3]. However, the nodal model takes into account the actual state of the power system in a transparent manner to allocate the future distributed generation [4]. A transition from passive to active networks has introduced the prosumers in energy networks. The prosumers are the energy network entities that can either generate sufficient energy for meeting their own energy demand or produce more energy to trade the surplus energy with other energy users [5,6]. In this way, prosumers enable bidirectional power flow by selling and buying electricity. Network modernization is leading towards the innovative solution in terms of digitalization and blockchain to facilitate the active participation of prosumers for energy exchange directly with nominal interference from energy companies [7,8]. Therefore, distributed generation in the network is not only beneficial in terms of reduction in carbon footprint but enhances the network efficiency by a reduction in energy price [9].

Voltage regulation and system losses play an important role in the planning of a distribution network. HC research in [10] proved that the integration of PVs can postpone

certain network upgrades of key equipment such as cables and transformers (TF) while improving the voltage profile is a positive byproduct. The authors in this study employed the simulation results of a pilot PV application to assess the grid losses, the loading level of individual grid components (cables and transformers), and voltage profiles to reach an optimal network. The load-leveling can be achieved by the optimal installation of storage systems as performed in [11] by investigating an IEEE 33-bus system to address the system losses of a distribution network under high PV penetration. Load-leveling can be achieved by storing the surplus PV power during off-peak hours and supplying the stored power in peak hours as per the findings of this study.

Network loading is an additional important criterion for the planning process apart from the consideration of losses and voltage regulation, as discussed in [12,13]. The authors in [12] proved that a better understanding of residential loads is beneficial both in terms of planning and operational perspective of the network. Similarly, changing network loading and feeder configuration was discussed in [13] to investigate a distribution feeder by adopting particle swarm optimization. This study concluded that feeders must have adequate HC to enable the customers to install the PV panels and HC should be recalculated after the possible changes in feeder configuration and loading levels. Loading profiles also influence the choice regarding the selection of optimal sizing of PV panels, as discussed in [14] for HC determination. An IEEE 123-bus system was used as a benchmark in [14] where the results were validated by analyzing a real distribution feeder in North Carolina by modeling loads of houses on each feeder at 1-min resolution.

The optimal network planning is possible by the proper selection of transformers and cables. The authors in [15] discussed the trade-off between the no-load losses and load losses for the optimal selection of transformer. They concluded that transformer loading as 40% of rated capacity is beneficial in terms of total energy dissipated. The network planning considering the appropriate transformer and cable selection was also carried out in [16] as probabilistic planning of active distribution networks under the penetration of distributed energy resources. The variability of the cost of energy losses over the entire lifetime of a transformer was discussed in [17] while discounting these losses into the present cost of the transformer for the economical evaluation of the transformer. The study was comprised of the comparison between two distribution transformers of the same size as 1000 kVA with different load and no-load losses. Research conducted in [18] shows the optimal average load to be around 50% to 75% of the rating of distribution transformer for common losses and kVA expenses of the distribution networks in Latin America. The conductor selection in a radial distribution network was performed as an optimization problem by considering the capacity of feeders and voltage drop as the primary constraints in [19]. The authors in this study investigated a distribution system with eight nodes and seven radial feeders with the length between nodes fixed as 1000 m. Similarly, the study conducted in [20] investigated the loss characteristics of DC cables for determining an optimal cable size for a system integrated with photovoltaics using actual PV generation data in Malaysia with a resolution of 5 min for thirty days. The authors discussed a trade-off between the investment cost of the cables and the cost of energy losses in the lifespan of cables in this study. Similarly, the authors in [21] proposed a study based on the capital investment and the operational costs for optimal conductor selection by fixing four to five conductor sizes between the smallest and maximum size and estimating the total costs.

The network losses can be significantly reduced with an adequate amount of distributed generation. The losses in the network without any PV integration are mainly due to feeder losses. These network losses experience a reduction due to localized energy production and consumption initially and begin to rise when generation at nodes is higher than the consumption. A cost comparison between the potential of on-load tap changer and network reinforcement for HC improvement in a real UK low voltage network is discussed in [22]. This study focused on finding the HC considering the voltage and thermal limits as performance constraints without considering network losses as the limiting factor. Similarly, an optimal model is presented in [23] where the authors discussed the potential

of battery energy storage system (BESS) for the secure functioning of networks under higher PV penetration and the optimal sizing of integrated PVs and BESS in terms of cost. However, losses contribute significantly to network costs as the losses keep on increasing during the load growth period and so does the loss cost of the network. Therefore, loss evaluation can strengthen the economical analysis of the networks.

The increasing PV integration improves the voltage profiles of the network with an added advantage of decreased active power losses, as investigated in [24]. The relative behavior of PVs and network losses was also investigated in [25,26]. In [25], the authors analyzed a Brazilian distribution feeder for the minimization of voltage rise with the use of local inverter control and observed a reduction in network losses until a certain PV penetration. Similarly, in [26], PV potential aiming at minimization of the network losses is investigated for a medium voltage distribution network in Amazon with a loss reduction recorded as 8.7%. Appropriate PV sizing and operating power factor also result in the reduction of active power losses as per the research in [27]. A study performed in [28] evaluated the impact of increasing PV penetration on power quality standards, including network losses in an urban low voltage distribution network in Sri Lanka. The authors noticed a reduction of network losses until 50% PV penetration level. However, a penetration level of 75% resulted in an increase in network losses that reinforce the fact that excessive PV penetration increases system losses.

PV hosting capacity of the network has been evaluated previously, complying with the technical constraints without considering the network losses as the performance constraint. Although, some studies conducted in [26,27] investigated the relationship between PV penetration and losses. However, optimal network formation and associated cost that is closely related to the network component's specifications was not explicitly taken into account. The network losses can impact the planning decisions and change HC if the networks are correctly dimensioned from the loss point of view. The primary contributions of this work are listed as follows.

- The estimation of the PV HC of an optimal distribution network by taking network losses as the performance constraint.
- Investigating the precedence among two types of limiting factors; technical and economical.
- The impact of concentrated and distributed PVs on HC is presented in the context of PV distribution along the length of the feeder.

The remainder of this paper is organized as follows. Section 2 introduces the scope of the work, proposed methodology, and input data for optimal dimensioning of the network's components. Section 3 describes the final selection of cables and transformers in terms of investment and loss cost for three Finnish regions. Section 4 describes the proposed assessment methodology for economical hosting capacity and presents the results. Section 5 highlights the important conclusions and discusses the importance of economical hosting capacity.

2. Problem Description

The increasing trend of rooftop photovoltaics has embarked on a discussion on the development of an optimal network that can sustain the future penetration of RES in terms of both technical and cost constraints. This requires careful investigation of capital investment, loss costs, and reliability of the network for selecting the appropriate transformers and cable sizes. The studies on network planning reveal that the HC of the network can be determined in terms of cost parameters in addition to the previously used technical limiting factors of HC. In the previous works, the HC of the network has been estimated based on the violations of technical constraints such as voltage variations, ampacity, voltage unbalance, harmonics, and flicker.

This work focuses on finding the HC of the network considering the constraint of network losses as depicted in the process model of Figure 1. The design problem of a distribution network entails the economical feasibility along with technical reliability to address the problem of network losses. Therefore, this work is based on the careful

formation of an optimal network followed by investigating the maximum amount of PVs that can be integrated into the network subject to the constraint of losses. The loss cost comparison between the original network without PV penetration and the network after PV penetration leads towards finding the point of economical hosting capacity. The integration of PVs in the network has a significant impact on system losses and this work investigates the changes in network losses with increasing PV penetration. The financial decisions regarding the network component selection are critical, and efforts should be made to take into account the uncertainties in the decisive cost parameters such as cost of energy losses and load growth. Therefore, in this work, a sensitivity analysis is carried out for a better understanding of the investment situation.

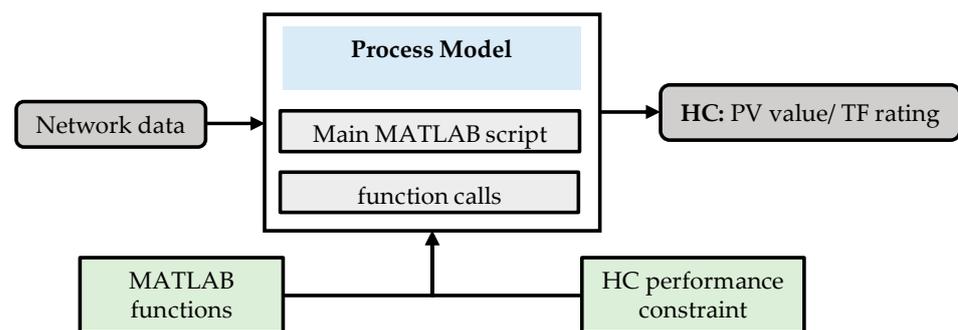


Figure 1. The process model for economical hosting capacity assessment.

2.1. Proposed Methodology

The energy markets are prone to major changes due to a rapid rise in RES integration in power systems. The residential PVs have enabled the bidirectional power flow by generating the power locally and exporting the extra power from customers towards the grid, as shown in Figure 2. The development of small generation modules is enabling the end-users of electricity to actively participate in the future electricity markets by transitioning from passive to active energy users—prosumers. The prosumers can either function as off-grid or on-grid by receiving enough generation to meet their needs or sending the extra power through the transmission to other energy users, respectively [6]. However, the excessive PV installation might cause network instability and utilities set the limits to PV penetration in the network subject to compliance with some technical constraints [29].

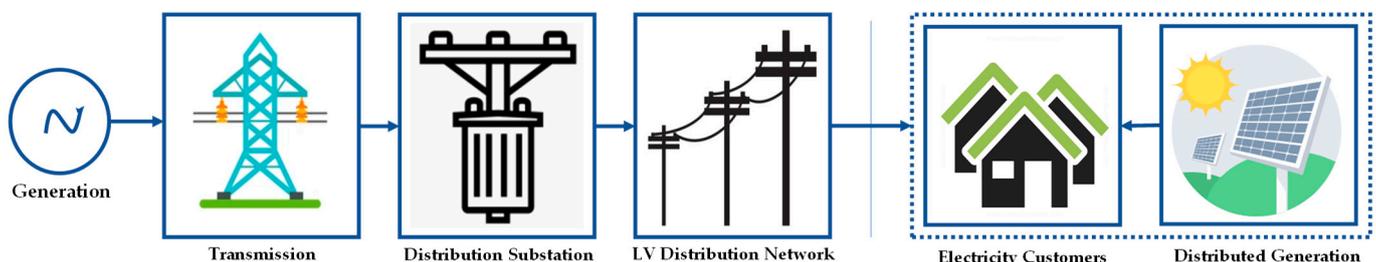


Figure 2. An illustration of distributed generation at consumer (prosumer) premises in future power system.

The optimal network selection is vital concerning the possible network reinforcements due to load growth over the review period. The calculation of PV hosting capacity, in this work, is based on the constraint of losses, and the proposed method analyses the violation of constraint while the stepwise addition of PVs among the network nodes. This constraint is based on the value of the reference losses in the optimal network before the addition of PVs. The assessment methodology employed here follows a Monte Carlo simulation approach for the accuracy of HC results.

2.2. Methods and Materials

Proper engineering verdict and historical features regarding network loading conditions play an important role in the planning process. The network planning must ensure to satisfy the demand requirements of the load, voltage drop within the statutory limits, and thermal stability by summing the branch currents upstream. Moreover, it should ensure to avoid the prolonged overloading of the transformer. The network formation in this work is based on optimal dimensioning of network components such as transformer and cables for distribution networks formulated in [30]. The network layout, used in this article, including the number of feeders, nodes per feeder, and the number of customers per node, is provided in Table 1.

Table 1. Network layout for three distinct Finnish regions.

Region	No. of Feeders	Nodes/Feeder	Customers/Node	Total Customers	Cable Length (m)
Rural	1	8	1	8	150
Suburban	3	4,3,3	4	40	100
Urban	3	2,2,1	60	300	100

It is worth mentioning that the network layout follows the radial configuration with one feeding transformer without any backup option in contrast to meshed network configuration as shown in Figure 3. This aspect of radial network configuration has a significant effect on network planning to consider the worst contingencies in case of customer outages.

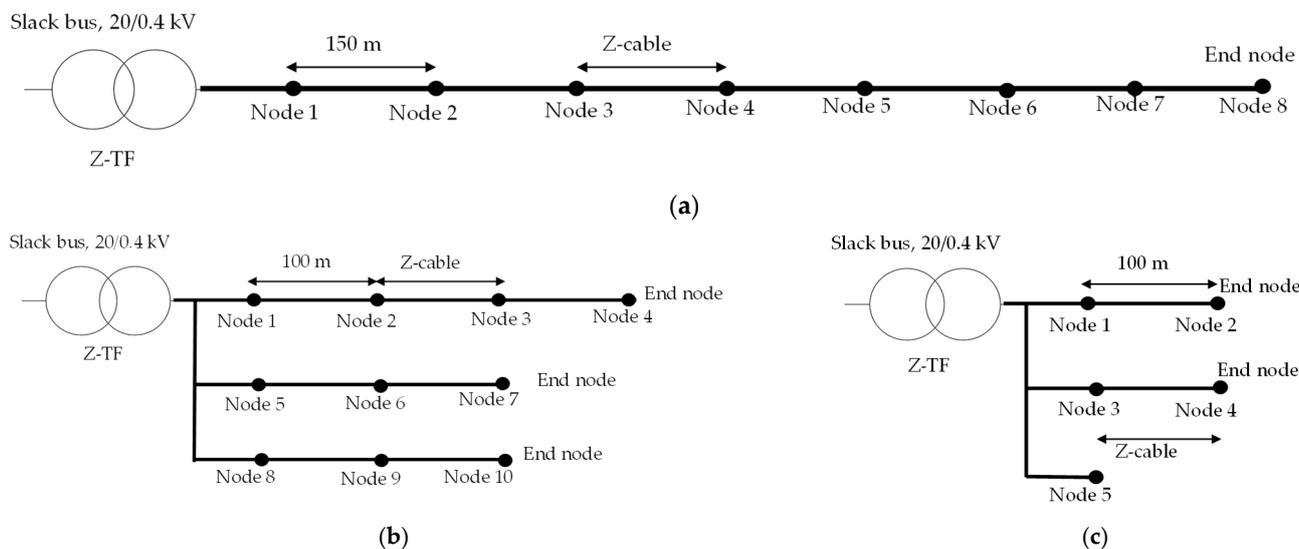


Figure 3. Network topology of three Finnish low voltage distribution networks: (a) Rural; (b) suburban; (c) urban.

The annuity of the investment and discount factor are two important parameters to consider the annualized investment and loss costs, respectively, for cost analysis. The loss costs grow quadratically with the load growth, and thus, the cost of energy losses is discounted to the present cost of the components by using a discount factor. The discount factor as given in (1) takes into account increasing losses during the entire life of the transformer and cables. The annuity of the investment is another important parameter that links the annual payment “ S_a ” for an initial investment “ S_o ” of a commodity as given in (2). The parameter values of t , T , p , and g used in (1) and (2) are described and given in Table 2.

$$k = \alpha_1 \times \frac{\alpha_1^t - 1}{\alpha_1^t - 1} + \alpha_2 \times \frac{(1+r)^{2t}}{(1+p)^t} \times \frac{(\alpha_2^{T-t} - 1)}{(\alpha_2 - 1)} \tag{1}$$

$$\text{Where } \alpha_1 = \frac{(1+r)^2}{(1+p)} \text{ and } \alpha_2 = \frac{1}{1+p}$$

$$S_a = S_o \times p \times \frac{1}{1 - 1/(1+p)^T} \quad (2)$$

$$\text{Annuity} = e = p \times \frac{1}{1 - 1/(1+p)^T} \quad (3)$$

Table 2. Parameters for the cost evaluation of transformer and cables.

Parameter	Value
Planning horizon (T)	40 years
Load growth period (t)	20 years
Interest rate (p)	5%
Load growth rate (r)	3%

The terms “*k*” and “*e*” are the discount factor and annuity of investment, respectively.

The load losses contribute significantly to the cost analysis of the network and thus, the actual load profiles are used for estimating the maximum load of the network by utilizing the heating mode contributions of three regions. This is because the customers in an area have different loading profiles based on different percentage contributions of heating modes as shown in Table 3. The heating modes and their significance in the context of Finnish low voltage networks have been discussed in [31].

Table 3. The loading contribution of heating modes in three Finnish regions.

Region	Storage Heating (%)	District Heating (%)	Direct Electric Heating (%)
Rural	5.9	52.9	41.2
Suburban	7.6	52.5	39.9
Urban	0.5	95.3	4.2

The information regarding the cost parameters of transformers and cables is based on data by Finnish Energy Authority [32]. Also, the technical specifications such as resistance, reactance, voltage, rating, load, and no-load losses follow the data values from transformer and cable manufacturers in Finland. Please refer to Appendix A for technical and cost parameters of network components. The PV generation data employed in this study is based on an annual (8760 h) PV power curve model based on the global irradiance time-series data from the solar array positioned in Helsinki, Finland [29]. The power curve modeling is based on the analysis of various PV generation scenarios depending on geographical areas of different sizes and the amount of installed photovoltaics [33].

3. Optimal Network Formation

The sizing of network components plays an important role in the network’s cost evaluation and it depends on the loading value and hence on the region and the customers to be served. This section explains the optimal dimensioning of transformer and cables due to the substantial investment and loss costs of these network components. The installation cost of the transformer is 4 to 10 times the actual cost of transformers, so the utilities are inclined towards installing oversized transformers to avoid the replacement of transformers in case of network reconfiguration and load growth during planning horizon time [15]. However, research conducted in [18] shows that most of the distribution transformers in Latin America are only loaded up to 20% of their rated capacity, and oversizing transformers can increase expenses for the distribution company. Sizing of transformer based on peak load control is a widespread practice and thus, Section 3.1 of the work investigates the peak

load values for optimal transformer selection. The maximum load dictates the size of the transformer as the transformer should not be overloaded to reach the hottest point limit to damage the insulation and the windings. On the other hand, underloading the transformer depicts its over dimensioning and thus excessive investment cost. Therefore, an accurate assessment of network loading is crucial for the optimal selection of the transformer.

The optimal selection of conductors in the distribution network requires a lot of attention concerning the cost and technical features of the entire set of cables in the network. Thus, the cable selection is carefully made initially to meet the two main technical requirements, i.e., the ampacity of the cables and the voltage drop of the network. Various cables differ in their resistance, reactance, maximum current carrying capacity known as ampacity, cross-section, and the investment cost per unit length. The cable selection has been performed by carrying out a probabilistic analysis considering the stochasticity of expected loads of the network. The reach of the conductor is defined by thermal and economical reach and [21] shows that the conductor selection is made optimally after fixing the reach of the conductor. Therefore, as per the research conducted in [21], cable section length is defined (Table 1) for each region before the selection of the optimal cable size. Moreover, the lifespan of the network components is assumed as same in this analysis.

3.1. Optimal Transformer Selection

The transformer selection is based on the peak network load for three Finnish low voltage distribution networks that have different load consumption profiles based on heating modes given in Table 3. Network load growth is typically strong for a certain period “*t*” after which it becomes stable until the planning horizon time “*T*”. Therefore, the transformer rating is selected to accommodate the first-year loading as well as increased load growth after the load growth period.

The most widely employed approach for transformer cost evaluation is based on the total owning cost (TOC) of the transformer to minimize the investment and the loss cost of the transformer [17]. The TOC approach is based on the calculation of the loss costs of the transformer. The loss costs for each region depend on the peak load of the network that is based on the distinct load profiles of the network, as shown in (4). Therefore, the main idea is to minimize the cost of the transformer, as given in (6).

$$\text{Load losses at any time instant} = P_{cu} \times \left(\frac{\text{maximum load}}{\text{transformer rating}} \right)^2 \quad (4)$$

$$\text{Annualized loss costs} = (e \times \text{losses} \times ut \times ce) \times k \quad (5)$$

$$\text{Transformer total cost} = \text{Investment cost} + \text{Annualized loss costs}. \quad (6)$$

The terms “*ut*” and “*ce*” in (5) are the loss utilization time and the cost of energy losses employed in the cost and benefit analysis as discussed in [34]. This study utilized the cost perspective for network generation and investigated the balance between loss cost and capital investment. Annualized loss costs in (5) further depict that the loss costs are discounted to present by multiplying the cost of losses with the discount factor *k*. Load losses of the transformer at any instant are variable depending on the loading of the network and can be calculated by (4) using the full load copper losses P_{cu} multiplied by the transformer utilization factor.

A MATLAB script was created for the optimal selection of transformer and peak load values were selected from the annual load distribution data values for three types of customers based on heating modes, i.e., dielectric heating, storage heating, and district heating. These maximum load values for each type of customer were later multiplied by the heating mode contributions of customers. Finally, the maximum load values were multiplied by the nodes and number of customers specified for a region. The maximum initial loading values of rural, suburban, and urban networks are calculated as 24.06 kW, 123.26 kW, and 402.90 kW, respectively. The algorithm for finding the optimal transformer started by finding the maximum network load for each of the three regions and finding the

final maximum load after the load growth period with a growth rate of 3%. The optimal transformer selection was made by comparing two different transformers to accommodate the peak load values of three Finnish regions in terms of their investment and loss costs, as shown in Table 4. Table 4d shows the economically feasible transformer ratings in terms of investment and loss costs for rural, suburban, and urban regions. Moreover, these transformer ratings were found to be sufficient to accommodate the peak load values even after the load growth period of 20 years. The over/under dimensioned transformers than these values for the given networks resulted in an increased TOC. It is apparent that the loss cost and thus the total cost keeps on increasing during the entire load growth period, as shown in Figure 4. A similar trend of load and cost changes is observed for the suburban and urban regions.

Table 4. Optimal transformer selection and comparison for three Finnish regions. (a) Transformer comparison for the rural region. (b) Transformer comparison for the suburban region. (c) Transformer comparison for the urban region. (d) Final transformer selection based on savings in costs by using optimal transformers.

(a)								
Rural (TF = 30 kVA)					Rural (TF = 50 kVA)			
Year	Load (kW)	Load/TF Rating (%)	Loss Cost (€)	Total Cost (€)	Load (kW)	Load/TF Rating (%)	Loss Cost (€)	Total Cost (€)
1	24.06	80.0	129.84	402.58	24.06	48	75.64	355.96
20	42.19	140.6	358.27	631.01	42.19	84	191.62	471.93
(b)								
Suburban (TF = 200 kVA)					Suburban (TF = 250 kVA)			
Year	Load (kW)	Load/TF Rating (%)	Loss Cost (€)	Total Cost (€)	Load (kW)	Load/TF Rating (%)	Loss Cost (€)	Total Cost (€)
1	123.26	61	291.70	750.1	123.26	49	239.00	743.9
20	216.13	108	781.74	1240.1	216.13	86	598.84	1103.6
(c)								
Urban (TF = 800 kVA)					Urban (TF = 1000 kVA)			
Year	Load (kW)	Load/TF Rating (%)	Loss Cost (€)	Total Cost (€)	Load (kW)	Load/TF Rating (%)	Loss Cost (€)	Total Cost (€)
1	402.90	50	610	1617.8	402.90	40	543.0	1755
20	706.49	88	1580	2587.7	706.49	70	1318.9	2531
(d)								
Region	Transformer (kVA)	Load/TF Rating (%)		Savings in Cost (€)				
		1st Year		1st Year	20th Year			
Rural	50	48		46.62	159.08			
Suburban	250	49		6.20	136.50			
Urban	1000	40		−137.20	56.70			

3.2. Optimal Cable Selection

The maximum current flowing in the cable sections satisfying the loads along the length of the feeder must be below the ampacity value of the cables used in the network routing. Thus, the conductor is chosen depending on the branch current as calculated by the load flow analysis in this work. The voltage drop as the second criterion of technical feasibility of the cables is satisfied by maintaining the acceptable voltage drop below 5% of the nominal voltage. In some networks, the increased investment cost, by using one size larger conductors than technically required, can be compensated by the savings in the cost of energy losses that keep on decreasing over the review period with the use of larger conductor than technically required [35]. So, this analysis investigates the technical and economical feasibility of cables through this approach by analyzing the annualized cost of losses after the cable upgrade of the technically suitable cables. The cable costs are

divided into investment and loss costs, and this analysis takes into account the annualized investment and loss costs by using the discount factor and annuity parameters for the determination of total life cycle costs of lines.

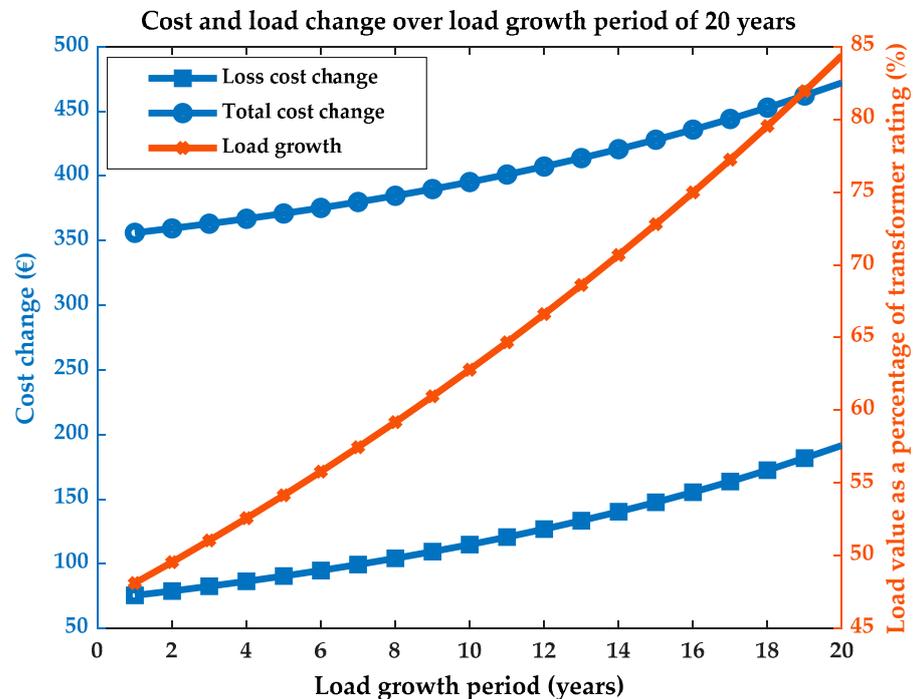


Figure 4. Cost and load changes of transformer over load growth period for the rural region with a load growth rate of 3%.

The energy losses of the cables are given by (7).

$$Energy\ losses = 3 \times I^2 \times R \times L \quad (7)$$

The parameters I , L , and R in (7) represent the branch current (A), length (m), and the resistance of the cable section (ohms/m), respectively. Similarly, the annualized investment and loss costs are given in (8) and (9), respectively.

$$Annualized\ investment\ cost = e \times investment\ cost \quad (8)$$

$$Annualized\ loss\ costs = e \times k \times energy\ losses \times ut \times ce \quad (9)$$

where “ ut ” and “ ce ” are the loss utilization time and the cost of energy losses and “ e ” represents the annuity of investment.

The resistance and reactance of conductors in the network have an important influence on voltage variations. The proper cable selection for a radial distribution network requires the information about the current in each section and the voltage at each node that is calculated by using the Backward/Forward Sweep (BFS) load flow algorithm. This load flow algorithm for network simulations takes into account the network topology, number of customers, cable parameters (resistance and reactance), and real and reactive power at the nodes.

The cable selection is based on the following two main considerations.

1. The cables are selected to supply the peak load, and
2. the network is radially configured.

The cables are selected to handle the branch currents (unique for each network branch) and the node voltages calculated using the BFS load flow algorithm as shown in Figure 5. This is an iterative approach generally employed for distribution network’s power flow

calculations by branch current update in the backward sweep from the last branch towards the slack bus and updating the node voltages in the forward sweep from the slack bus towards the end node.

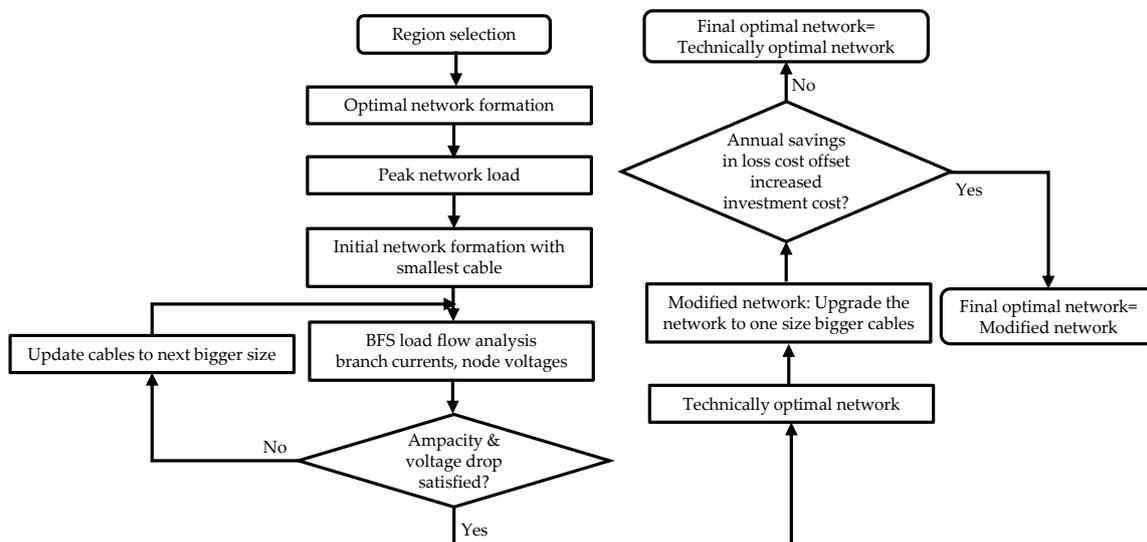


Figure 5. The optimal cable selection in terms of annualized investment and loss costs.

A MATLAB function is created for updating the network cables satisfying ampacity and voltage drop requirements that are employed in the main script for economical hosting capacity assessment. Initially, the networks in rural, suburban and urban regions are designed with the smallest cable with a current-carrying capacity of 125 A in all the sections. A load flow analysis is carried out at this stage to determine the initial branch currents and voltages at each node. The network cables are compared with the branch currents in terms of their current carrying capacity, and the network cables are updated to a one bigger size cable if branch currents exceeded the ampacity limits of the cables. Later, a second load flow analysis is carried out on the newly formed network with the updated cables to check if the new network can withstand the voltage drop requirement. The network cables are updated again until the voltage at each node satisfied the minimum voltage drop requirement. The algorithm for voltage drop check works by checking the voltage at each node and comparing this value with the voltage drop limit (nominal voltage—5% of nominal voltage).

Network topology contributed significantly to the network update for satisfying the voltage drop criteria as the networks in suburban and urban regions are comprised of three feeders instead of one feeder for the rural region, as shown in Figure 3. The transformer impedance is added with the impedance of the cable for updating the first branch section of the network starting from the slack bus. Therefore, the concept of end nodes has been utilized while updating the cables in terms of voltage drop criterion as there is a single end node in the rural region and three end nodes in suburban and urban regions. Therefore, individual feeders are inspected for voltage drop compliance in the case of the suburban and urban regions with more than one feeder considering more than one end node. The cables are upgraded starting from the first node until the cable size when the cables satisfy the voltage drop threshold.

The optimal cable sizing satisfying the technical requirements must fulfill both criteria of ampacity and voltage drop. Therefore, if the cable section satisfying the ampacity limits is smaller in size than the cable size satisfying the voltage drop criterion, then the bigger cable among the two is chosen as the most optimal cable. Simulation results for optimal cable selection show that voltage drop limits are the deciding criteria for the cable selection in the rural region with long strings and suburban regions comprising three feeders of varying lengths. However, the urban region experienced both the cable ampacity violation

as well as significant voltage drop occurrences, as shown in Table 5 by using the smallest cable size for the network.

Table 5. Voltage and current profiles of three regions with initial cable selection of smallest size before upgrading the cables for optimal network formation.

Rural		Suburban		Urban	
Voltage profile (p.u.)	Branch current (A)	Voltage profile (p.u.)	Branch current (A)	Voltage profile (p.u.)	Branch current (A)
Feeder 1	Feeder 1	Feeder 1	Feeder 1	Feeder 1	Feeder 1
0.963	34.43	0.966	67.64	0.883	261.60
0.943	30.34	0.945	51.18	0.826	135.19
0.927	26.18	0.930	34.34	Feeder 2	Feeder 2
0.913	21.94	0.923	17.24	0.883	261.60
0.902	17.63	Feeder 2	Feeder 2	0.826	135.19
0.893	13.27	0.975	49.54	Feeder 3	Feeder 3
0.888	8.87	0.961	33.22	0.947	117.89
0.885	4.44	0.954	16.67		
		Feeder 3	Feeder 3		
		0.975	49.54		
		0.961	33.22		
		0.954	16.67		

It has been observed that even the minimum cable size in the rural area did not pose any problem regarding ampacity limits. However, significant voltage drop events have been observed at all nodes except the first node by using the minimum cable size for the rural area. Therefore, network cables are upgraded for optimal network formation. The optimal utilization of cables resulted in improved voltage profiles for each region, as shown in Figure 6.

The final cable selection based on the simulation results of the voltage and current profiles in Table 5 resulted in the optimal cable selection as given in Table 6. The use of larger cable sizes for optimal network selection in the case of the rural region as compared to the suburban region is justified as apparent from the significant voltage drop occurrences (Table 5) in the case of the rural region by using the smaller cable size. However, the voltage drop in the case of the suburban region did not show any occurrence of voltage value to be lower than 210 V due to three different feeders of shorter length compared to the rural region with only one feeder of a longer span. The simulation results of this work for using the larger cables as the optimal cables to maintain the voltage profile of the rural area coincide with a study performed in [36] where the rural networks experienced more tap changing operations for voltage control. This study [36] investigated the variability of solar photovoltaics in three reference networks in rural, suburban, and urban regions and discussed the potential of on-load tap changer for the voltage management of medium voltage networks in Malaysia. It was concluded that the rural networks experienced the tap changer operation for voltage control more frequently than suburban and urban networks due to varying diversity factors of these regions.

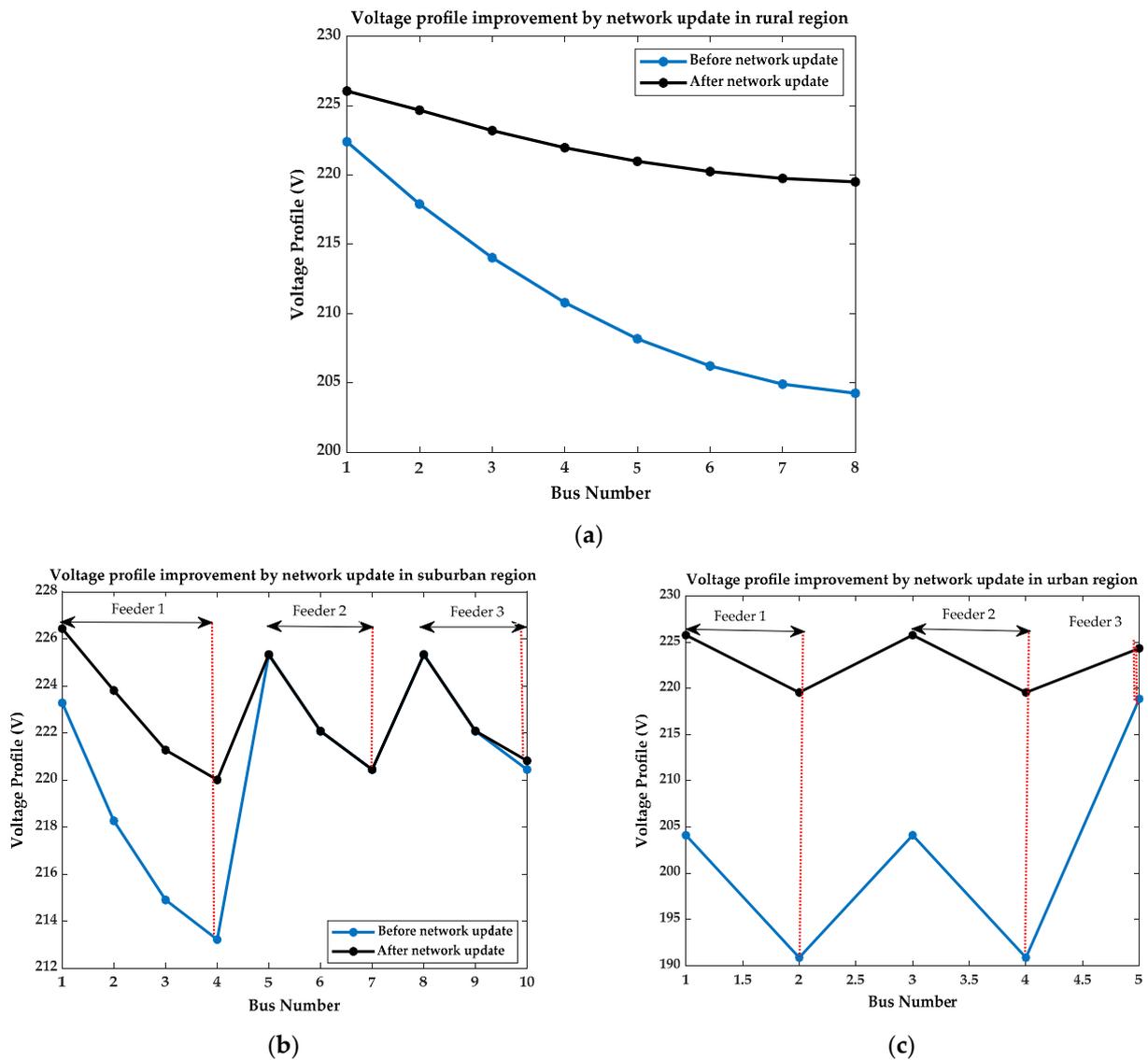


Figure 6. The voltage profile improvement by optimal network formation for three regions: (a) Rural; (b) suburban; (c) urban.

Table 6. Final cables selection for the three regions satisfying the technical and cost constraints.

Rural (50 kVA)	Suburban (250 kVA)		Urban (1000 kVA)
Cables (A)	Cables (A)		Cables (A)
Feeder 1	Feeder 1	Feeder 3	Feeder 1
255	220	150	430
255	220	150	220
220	185	150	Feeder 2
220	185		430
220	Feeder 2		220
220	150		Feeder 3
220	150		185
220	150		

4. Assessment Methodology for Hosting Capacity

The integration of renewable energy in the low voltage distribution networks has raised concerns concerning technical and cost perspectives. Distribution network planning demands the optimum selection of cables and transformers to supply the designated loads

in particular regions to minimize the investment and loss costs. This section introduces a simulation model for the calculation of economical hosting capacity and presents hosting capacity results. This work investigates HC concerning two types of limiting factors; technical and economical. Limiting factors used in this work are listed as:

- Upper voltage bound as +5% of nominal voltage (U_n);
- cable ampacity as static loading;
- transformer static overloading limit;
- negative sequence voltage unbalance as +2% of U_n ;
- neutral wire ampacity; and
- in addition, the limit for the cost constraint as performance index is defined as references loss point (base losses) in the optimal network before any PV addition.

4.1. Simulation Model

The optimal network planning and the determination of HC for cost constraints is formulated as a stochastic problem in this work by a Monte-Carlo simulation approach with an iteration count of 1000 to sample the stochastic loads. Load profiling is an important aspect of consideration regarding network asset management and energy markets. The introduction of smart metering in the low voltage distribution networks provides information on the time-series electrical load values of the customers. Many studies are focused on generating the representative load profiles by using statistical modeling or summing distinct loads with different resolutions; for example, 1 min, half-hourly, hourly, and daily load profiles. The electric utilities commonly possess the data based on the hourly resolution loading profiles of residential customers. The load demand is stochastic in nature and therefore the load profiles are examined using a probabilistic approach in this study. It is done by sampling the hourly loads for each customer separately instead of sampling the lumped customers on each node to diversify the hourly loading profiles. PV HC is calculated considering theoretical maximum PV generation data without considering any weather conditions that hinder the irradiance profiles. The aim of using the highest PV generation is to consider the worst possible case. The PVs are randomly distributed among the nodes and phases of the investigated networks and PV power is scaled with respect to the theoretical maximum PV generation data.

Hosting capacity relative to cost parameters is useful when assessing the energy networks in terms of energy losses and their associated costs. The main steps of the economical HC determination algorithm are shown in Figure 7 and described as follows.

1. The region (rural, suburban, or urban) selection is made as the first step, and the optimal network is created for satisfying the peak load demand.
2. Afterward, a BFS load flow analysis is conducted to find the branch currents and the losses of the optimal network without adding any PVs.
3. The optimal network formation and loss calculation is followed by the penetration of PVs in the system by taking the losses as the performance constraint. The PVs are added homogeneously among the network nodes in steps of 100 W.
4. The cost of the network losses is calculated by carrying out load flow analysis again for the optimal network after PV addition that is compared to the cost of the losses of the network before PV addition as calculated in step 2.
5. Further PV addition is stopped when the losses of the network after PV addition coincide with the losses of the network before the PVs were added in the network. The PV penetration is reduced by a step of 100 W at this point and the hosting capacity is calculated accordingly after subtraction.

4.2. HC Results

The economical hosting capacity is investigated here using secondary transformer rating as the reference value for HC. The determination of hosting capacity for three regions revealed that the network hosting capacity for a network case considered is subject to changing the specifications of network components. The HC determining factor is the

network loss point at which the network losses after PV penetration become greater than or equal to the network losses before PV addition.

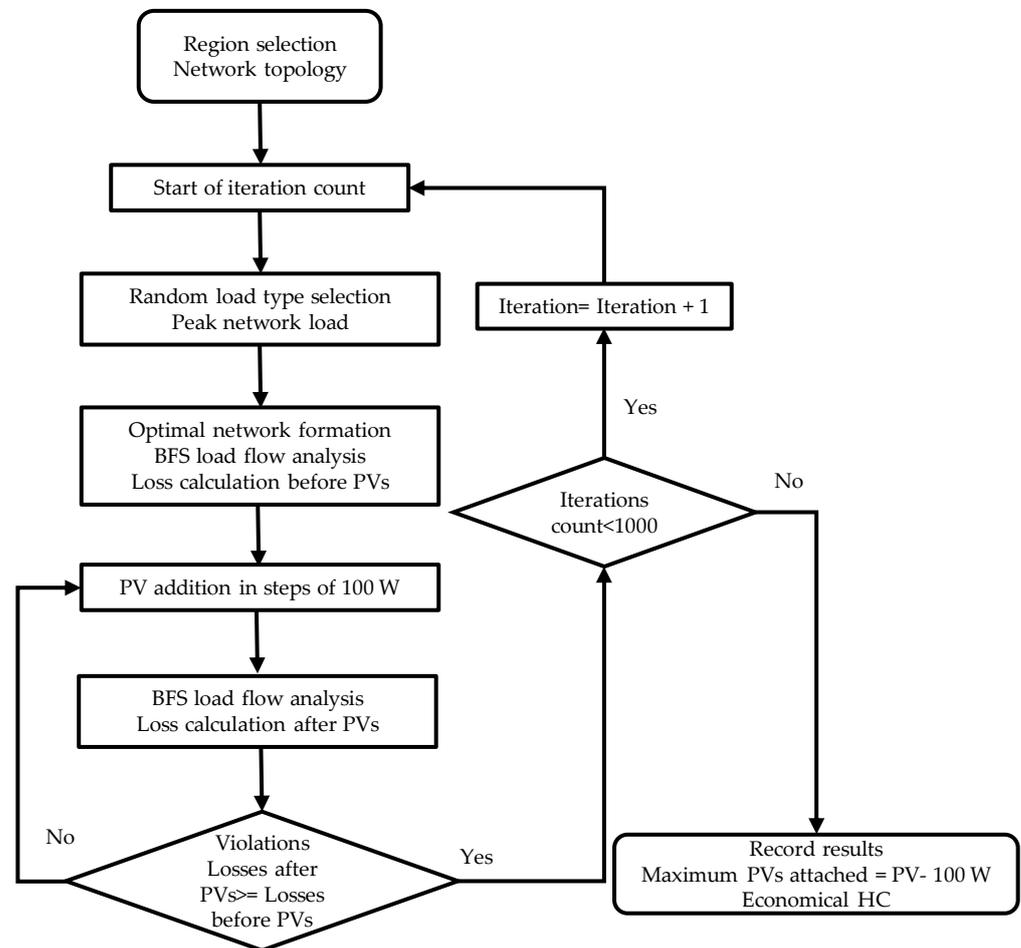


Figure 7. The assessment methodology for economical hosting capacity.

The authors in [29] proposed the utilization of cables with the current carrying capacity of 185 A, 330 A, and 660 A for rural, suburban, and urban regions, respectively, of the same networks as used in this article. Moreover, they fixed the cable sizes for the entire network sections. However, the cable selection in Table 6 shows that cable sizes, in this article, are not fixed for each section of the network. Thus, different cable sizes are proposed for different network sections based on compliance with the technical and cost parameters. Therefore, the optimal cable selection resulted in a larger cable size for the rural region than the suburban region to meet the voltage drop criterion that is more prominent in the rural region. Moreover, the optimal transformer selection of this article accords with the transformer sizes in rural and urban regions of [29]. However, the optimal transformer rating for the suburban region turned out to be 250 kVA as opposed to the transformer selection in [29] as 200 kVA. Therefore, the cable and transformer selection of this article results in different hosting capacity values.

The hosting capacity values in Table 7 show the reduction of hosting capacity in all regions compared to the hosting capacity values computed in [29]. These HC values are compared with the results obtained in [29] where the HC was estimated considering only the technical constraints as shown in Table 8. This comparison reveals that if the networks are correctly dimensioned from the loss point of view, they also have adequate PV HC from a technical perspective.

Table 7. Economical hosting capacity for three regions.

Region	Balanced PVs			Unbalanced PVs		
	PVs Attached (kW)	Limiting Factor	Economical HC (%)	PVs Attached (kW)	Limiting Factor	Economical HC (%)
Rural	5.4	Network losses	87.0	4.5	Network losses	71.0
Suburban	21.2	Network losses	84.8	13.8	Network losses	55.2
Urban	152.6	Network losses	76.3	64.5	Network losses	32.0

Table 8. The comparison between technical and economical HC values by using secondary transformer rating as the reference value for HC.

Region	Economical HC (%)	Technical HC (%)
Rural	87.0	105.3
Suburban	84.8	110.3
Urban	76.3	107.8

This comparison shows that the cost constraint of losses is violated before technical constraint violations if the network is optimally rated. It is worthwhile to find the margin between the technical and economical HC and it is noticed that the technical violation is observed soon after recording the point of economical HC as shown in Figure 8.

4.3. Impact of the Amount of PVs on Network Losses

The calculation of hosting capacity in this work is accompanied by investigating the impact of the amount of PV addition on network losses. The loss evaluation starts from calculating the optimal network losses without any PV penetration as the base case that is referred to as the reference losses in this work. Load flow analysis is an important step in the loss calculation to find the branch currents. The network losses initially start to drop from their original value (reference losses before PV addition) with the addition of PVs among nodes until the PV penetration level results in minimum network losses.

After the minimum point, the network losses exhibit a rising trend when PV power is further exceeded, and losses follow a U-shaped parabola trajectory, as shown in Figure 8, which is similar to the results in [27]. The network apparent power before PV addition is comprised of an active and reactive load component that takes the form of (10) after the addition of distributed photovoltaics. The PVs are added as the negative active power among the nodes with a unity power factor as shown in (10).

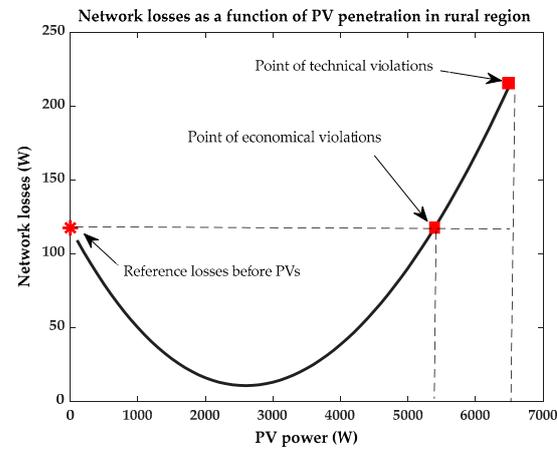
$$S_{node} = (P_{load} - P_{pv}) + j(Q_{load} - Q_{pv}). \quad (10)$$

P_{load} and P_{pv} are the load active power values at each node and the PV power added among the nodes in steps of 100 W. Similarly, Q corresponds to the reactive power of the loads and the added PVs where the term Q_{pv} in (10) is zero in this analysis due to unity power factor of PVs. The S_{node} is the node apparent power that is further used in the BFS load flow analysis for the calculation of nodal currents as (11) and V_{node} is the voltage at each network node.

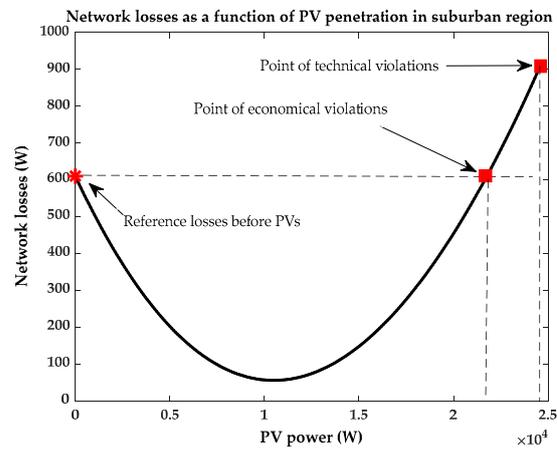
$$Nodal\ current = (S_{node}) / (V_{node}). \quad (11)$$

The change in network losses by comparing the load power and PV penetration has been illustrated in Figure 9. The loss value as reference losses corresponds to the point of the original network losses before any PV penetration. The network losses are primarily the result of cable resistance and can be reduced by a fair amount of PV penetration by supplying the loads locally. However, the higher integration levels might interrupt the system balance due to reverse power flow and thus increase the system losses. The impact of PV penetration on network losses can be further extended towards finding the optimal

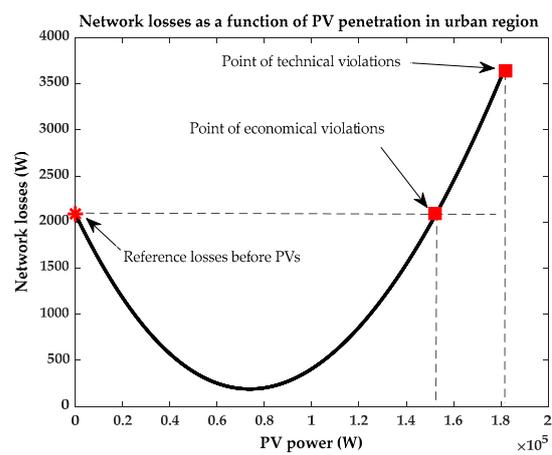
point of network losses and finding the PV hosting capacity at the point of minimum network losses as shown in Figure 10.



(a)



(b)



(c)

Figure 8. Variation of network losses and an illustration of a margin between economical and technical violations: (a) Rural; (b) suburban; (c) urban.

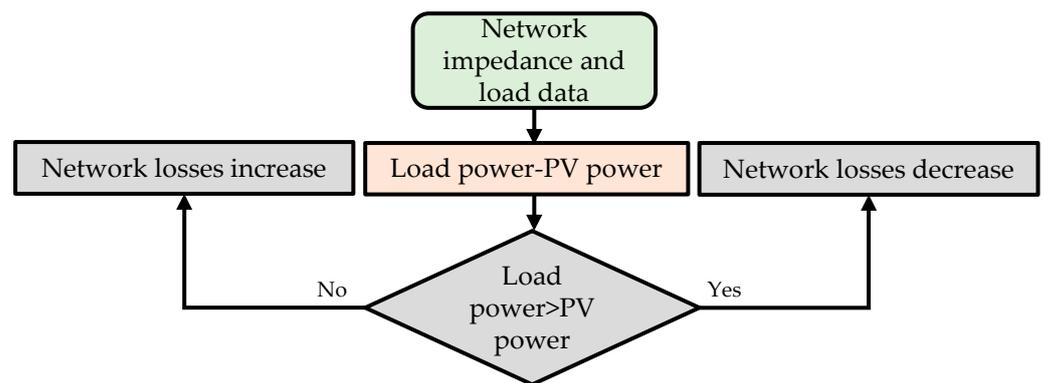


Figure 9. Network loss variation with respect to load and PV power.

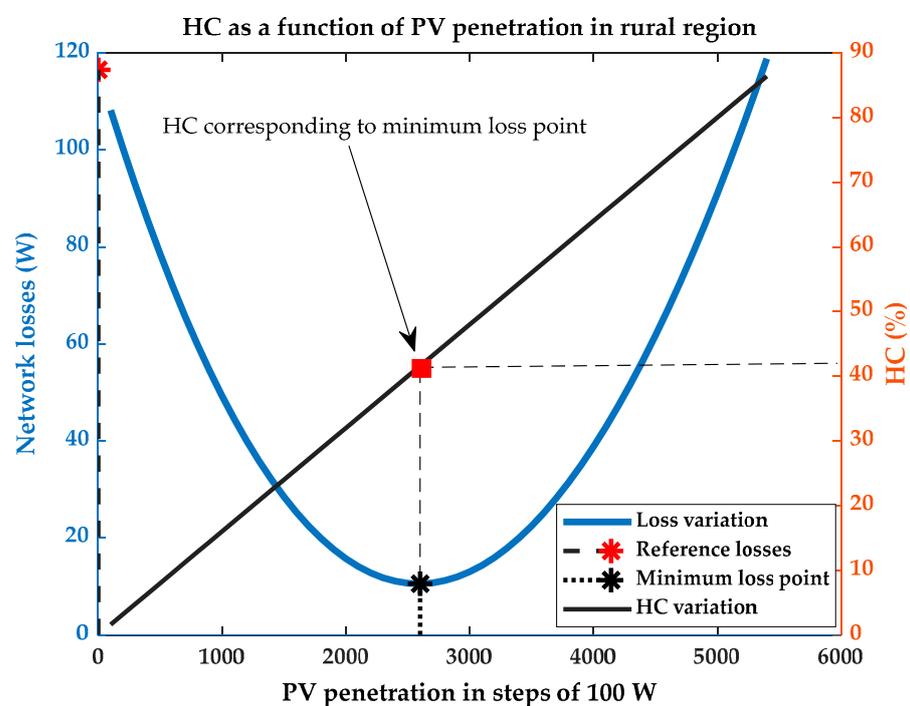


Figure 10. HC variation with network losses and HC corresponding to optimal loss point of network.

This calculation aims to find the point of PV value when the network losses reach the minimum value while the gradual decrease in losses with increasing PV penetration. The minimum loss value refers to the point when the loads and PV power commensurate in value such that the power delivered by PVs is absorbed by the loads. The value of minimum network losses and the associated PV penetration is given in Table 9. This table shows the value of PV penetration beyond which the network losses ascend gradually to form a U-shaped curve and reach the point of reference losses again. The economical hosting capacity corresponds to the PV penetration level when the network losses again coincide with the reference losses of the network.

Finally, the impact of PV deployment is evaluated by concentrating and spreading the PVs at various locations along the length of the low voltage feeder. The authors of research conducted in [37] considered the impact of locational criteria of PV positioning and noticed a higher PV penetration with distributed PV deployment. Similarly, a higher PV capacity can be installed with an increase in PV HC by dispersing the PV generation along the feeder instead of concentrating the PV panels at a few locations, as illustrated in Figure 11 for networks in different regions. The three regions are investigated in terms of

concentrating the PV power at 2, 3, and 5 locations along the length of low voltage feeder, and a higher PV HC is observed with more dispersed PV distribution.

Table 9. PV penetration level at the minimum point of network losses for three regions for the balanced PV deployment scenario.

Region	Reference Losses (W)	Minimum Network Losses (W)	PV Penetration (W)	Hosting Capacity (%)
Rural	118.88	10.76	2600	41.6
Suburban	612.44	55.54	10,500	42.0
Urban	2090.70	190.34	73,800	36.9

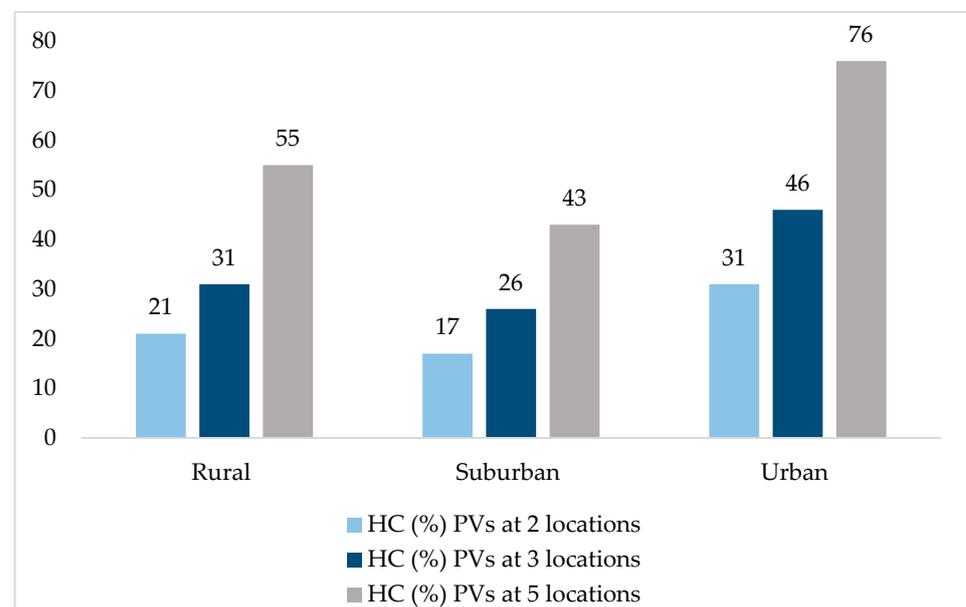


Figure 11. HC variation with PV distribution as concentrated and dispersed.

4.4. Sensitivity Analysis

The investment decisions regarding the grid assets can be strengthened by a sensitivity analysis that takes into account the variation of the factors influencing the cost assessment. The sensitivity analysis holds extra importance in the cost analysis of the networks prone to intermittent integration of RES due to the changes in certain cost parameters over the project lifetime. The factors affecting the investments include but are not limited to the load growth and cost of energy losses. The changing values of load growth directly impact the optimal network formation due to the dependence of cable and transformer selection on peak load values. Similarly, the cost of energy losses influences the annualized assessment of losses and their associated cost. Therefore, the results of hosting capacity are validated by changing these parameters to investigate the possible impacts on the hosting capacity of the network. The simulation results reveal that the hosting capacity values remain consistent by changing these parameters with a tolerance level of $\pm 5\text{--}\pm 15\%$ as given in Table 10.

This analysis leads towards the fact that changing values of load growth and cost of energy losses by this factor results in a similar network formation and thus, similar hosting capacity. Moreover, the variation of cost of energy losses is investigated up to the extent of 2 times, and the hosting capacity of rural, suburban and urban regions turned out as 85%, 86%, and 76%, respectively.

Table 10. Sensitivity analysis of economical hosting capacity in the cost analysis of three Finnish distribution networks by changing the cost of energy losses (ce) and load growth (r) by a factor of $\pm 5\%$, $\pm 10\%$, and $\pm 15\%$. (a). HC change with respect to the cost of energy losses deviation. (b). HC change with respect to load growth deviation.

(a)						
Region	Cost of Energy Losses (ce)					
	+15%	+10%	+5%	−5%	−10%	−15%
Rural	84.7	85.7	85.0	87.3	87.8	88.6
Suburban	83.6	84.0	84.3	88.0	87.0	88.5
Urban	76.4	76.3	76.0	76.0	76.0	76.8
(b)						
Region	Load Growth (r)					
	+15%	+10%	+5%	−5%	−10%	−15%
Rural	87.9	87.2	87.9	87.4	87.5	87.4
Suburban	86.2	86.0	86.2	84.0	85.0	86.3
Urban	76.2	76.2	76.2	76.0	76.2	76.4

5. Discussion and Conclusions

The management of grid assets can significantly impact the hosting capacity assessment in addition to the technical parameters such as voltage variation, thermal limits, harmonics, and flicker. The critical constraints for power distribution planning are voltage drop limits, the capacity of the substation, ampacity of network feeders, proper cable and transformer sizes, and suitable connectivity to feed all the buses. Peak load capacity, loss costs arising from resistive losses, transformer loading, and future network reconfiguration for accommodating increased PVs is quite closely related to the network cost. Some network expenditures such as investment costs are one-off, whereas the others are changing and recurring such as loss costs. Accordingly, network operators are now interested in the minimization of the cost in terms of investment, maintenance, losses, and interruptions that are subject to voltage drops, loading, and protection protocols. Therefore, transformer and cable sizing for the networks with potential PV installations needs to fulfill the regulatory requirements, including the technical and economic benefits.

Therefore, this article introduced the term economical hosting capacity based on finding the maximum amount of photovoltaics penetration for an optimal network in rural, suburban, and urban regions subject to the constraint of losses. Firstly, an optimal network was created for three Finnish regions in terms of optimal transformers and cables. The optimal use of cables resulted in the voltage profile improvement of the network and this is followed by integrating the PVs in the network until the losses reach the reference losses in the original network. The transformer selection followed a cost and benefit analysis approach and the optimal transformer for the urban region is selected to be 1000 kVA instead of 800 kVA even with a slight difference in cost among the two options. The bigger transformer selection for the urban region is attributed to the substantial replacement cost of transformers. Thus, a bigger transformer is more suitable to accommodate the load growth over the review period instead of installing a smaller transformer prone to replacement over the planning horizon time of the network.

The hosting capacity has been determined in this work by a stochastic approach due to the inability of deterministic methods to take into account the stochasticity of the consumer loads and PVs. The simulation results revealed that the network losses are the deciding limiting factor for the assessment of hosting capacity. The violation of cost constraint of network losses preceded the technical limiting factors and thus, defined the hosting capacity of the network. Optimal network selection resulted in the HC of the network being lower in value subject to cost constraints than the HC of the same networks calculated in [29] subjected to technical factors. This is attributed to different cable and transformer

selection in this article based on optimal network formation compared to [29] as per the author's informed guess. It has been observed that an optimal network formation can either increase or decrease the network hosting capacity. Therefore, economical hosting capacity estimates the maximum amount of photovoltaic penetration in the distribution network depending on the losses of the original network.

The losses of the grid can be reduced by the incorporation of distributed generation, network reconfiguration, or the placement of capacitors. This article investigated the changing network losses with increased PV penetration in the distribution network, and the losses experienced a U-shaped parabola trend with increasing integration levels. PV penetration level corresponding to the minimum loss point of the network gives an idea about the maximum PV level beyond which the network losses start increasing. Thus, an estimation of this penetration level can provide useful information to the network planners to design the network complying with the loss values. Finally, the HC is evaluated in terms of PV positioning and a higher HC is observed in case of distributed PVs instead of concentrating PVs at only a few locations along the length of feeder. The HC investigation in terms of losses is further beneficial for the future economic analysis of the distribution networks to accommodate the increasing amount of distributed generation. The idea of network loss reduction by PV penetration can be investigated further along network reconfiguration to improve the hosting capacity of the distribution networks.

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Abbreviations

BESS	Battery energy storage system
BFS	Backward/forward sweep
HC	Hosting capacity
MC	Monte Carlo
PV	Photovoltaic
P_{cu}	Copper losses
p.u.	Per unit
RES	Renewable energy sources
TF	Transformer
TOC	Total owning cost
T	Planning horizon
Z	Impedance
ut	Loss utilization time
ce	Cost of energy losses

t	Load growth
p	Interest rate
r	Load growth rate
k	Discount factor
e	Annuity

Appendix A

Table 1. Electrical parameters of transformers for three regions [32].

Region	Nominal Rating (kVA)	Nominal Voltage (kV)	No-Load Losses P_o (W)	Full Load Losses P_{cu} (W)	Investment Cost (€)
Rural	50	20/0.4	90	1100	4810
Suburban	250	20/0.4	300	3250	8661
Urban	1000	20/0.4	770	10,500	20,800

Table 2. Cable sizes and distinctive parameters.

Cable Size (m ²)	Resistance (Ω/km)	Reactance (Ω/km)	Investment Cost (€/meter)	Ampacity (A)
35	1.0	0.09	27.3	125
50	0.77	0.09	30.0	150
70	0.53	0.08	32.7	185
95	0.39	0.08	36.3	220
120	0.31	0.08	42.9	255
150	0.25	0.08	49.5	280
185	0.20	0.08	54.3	330
240	0.16	0.08	60.9	375
300	0.13	0.08	76.5	430

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