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Original Research Article

Impact of Photovoltaic Penetration on the Distribution System Operation. Case Study Albania

Andi Hida*¹, Olsi Karapici¹, Rajmonda Bualoti¹, Diamant Gashi²
¹Department of Electrical Power Systems, Polytechnic University of Tirana, Tirana, Albania
e-mail: andihida@fie-upt.edu.al, okarapici@gmail.com, r_bualoti@yahoo.com
²Electricity Power Distribution System Operator, OSHEE GROUP, Tirana, Albania
e-mail: diamant.gashi@fie.edu.al

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ABSTRACT

The increase in photovoltaic penetration, especially in the low voltage distribution system, requires the necessity to identify the problems it causes, as well as the benefits it provides. In this context, this paper presents the impact of small-scale photovoltaic penetration in a radial feeder of the Albanian distribution system, in different connection points (in each feeder's transformer, in the first half-length, or the second half). Furthermore, the study is based on the investigation of the maximum photovoltaic capacity that can be connected to a feeder, limited by current hosting capacity through evaluation of Active and Reactive Power, Voltage Profile, as well as Line and Transformer Losses. The simulation results show that while an improvement is observed in the feeder voltage profile, problems appear regarding the loading of some transformers and the increase in losses. Meanwhile, the results show that the photovoltaics installation along the entire feeder is the best option. On the other hand, while the most favourable case would be the installation in the first half of the feeder minimum load scenario, the installation in its second half-length would be useful for the maximum feeder's load scenario. In addition to these results achieved from the technical analysis, almost the same results came from the economic analysis carried out in this paper (considering the total investment cost of the photovoltaic systems, cost savings from reduced losses after photovoltaic integration, and the revenue from selling photovoltaic energy to consumers). When photovoltaic systems are connected suitably (in the first or second half length of the feeder), considering the load level, the total revenue can be increased by 1.7 times or the cost savings from fewer losses can be increased by 2.2 times. The result obtained for different operating scenarios gives important information for the RESs industry, distribution system operators, and prosumers.

KEYWORDS

Solar PV, Radial feeder, Distribution system, Hosting capacity, Voltage profile, Power losses.

INTRODUCTION

Electricity production using renewable energy sources (RESs) has increased due to numerous advantages, considering the economic, social, and environmental benefits. Among RESs, solar photovoltaic (PV) is one of the most promising technologies, especially in conditions of actual energy crisis [1]. For example, the European Union sets a target of 400

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[*] Corresponding author

GW installed solar PVs by 2025, as well as 730 GW by 2030 [2]. This will increase PV ambition in Europe by 43%.

In the same vein, the energy policies in Albania promote the development of RESs through different mechanisms [3]. In this context, the energy produced from the new solar PVs is growing at a rapid rate. Except for several massive PVs installation, most of them are small-scale PVs for self-consumption [4]. Furthermore, the possibility of using unusable land surfaces for other purposes is being considered (for example floating PV [5], rooftop PV [6], or solar car parks). Last year, a total of 130 MW capacity for self-consumption was installed in different feeders [7], close to consumers, increasing energy production by 26%. Most of this capacity is installed in the distribution network (as roof PV sources). In addition to the advantages, the problems that these new PVs cause in the distribution system feeders should also be studied [8]. In this context, this paper deals with the impact of PV generation in a radial distribution feeder considering different generation/load scenarios, as well as different connection points.

The researcher's focus on solar PVs has been increased. There is considerable literature on their techno-economic feasibility analysis. For example, reference [9] recommends methods to maximize the PV energy output in Urban Areas, considering tilt angle and total area occupied. In the same vein, reference [10] evaluates the capacity of PV integration in a Dense Urban Context. On the other hand, a cost-benefit analysis would also be preferable, to have a clearer view of the PV benefits. Considering various scenarios, through this economic analysis the most favourable scenario could be chosen. In this way, Jean *et al.* [11] have performed an economic analysis on a solar photovoltaic system model connected in the rural settlements to the Brazilian semi-arid region. Furthermore, this study calculates the revenue from selling energy on the grid concerning the minimum and maximum electrical load. Different values of the region's energy tariff are used to carry out the scenarios for surplus sales. The results show an annual gain that varies between US$ 1,244.64 to US$ 2,489.28.

In particular, except techno-economic feasibility assessment, the impact of PV Penetration in the Distribution system should be considered [12]. For example, in the Croatian distribution system, the influence of PV systems on the grid's voltage quality characteristics must be measured by the user in order to fulfil all Grid code standards [13]. In particular, this study shows that this penetration will result in significant problems with voltage quality, if not implemented properly. In addition to voltage quality, other parameter indices must be analysed. Thus, the authors in [14] have studied this impact on voltage stability, power loss, and short circuits for peak/no load scenarios using the DlgSILENT Power Factory software. Initially, PV penetration of 500 kW per node is added, to further evaluate the maximum potential PV penetration. It points out that the highest power loss occurs during peak load conditions (191 kW), at 0% PV penetration level. This corresponds to the maximum load and no PV integration case in the distribution feeder. Therefore, in addition to knowing the total load, it is important to determine the maximum generation. Meanwhile, even in the opposite scenario, no-load condition, and 100% PV penetration, also cause problems on the grid. Due to these extreme conditions, the reverse power flow phenomenon will occur. Likewise, this phenomenon occurs whenever the PV power generation in a grid-connected network exceeds the local load demand. In this case, due to the high current that will pass through the line, an increase in outages will occur. This unfavourable situation, not only can cause temperature increases in the line sections, but also will overload the distribution transformers. The latter, beyond a limit, would directly affect the transformer's technical life. To clearly understand the fluctuation in transformer overload, the authors in [15], have analysed a low-voltage distribution system in Ghana, against various PV penetration levels. For 0% of PV penetration, a 100% transformer operating load corresponds to 315.1 kVA. Meanwhile, in the optimal case (83% PV penetration), the transformer operating load decreases to 24.8%. In general, for a long-life span of transformers, their loading should be below 100%. In addition, losses are reduced from 7kW to 0.55 kW, respectively. On the other hand, the authors in reference [16] showed that the lifespan of a 15 MVA transformer is significantly extended when the penetration level is below 100%.

In particular, the proper positioning of PV in the distribution system affects its performance. For this purpose, Pan *et al.* [17] tested the IEEE 33-bus systems using DIgSILENT. The results show that the optimized power losses can be reduced from 179.46 kW to around 5 kW (for the optimal connecting point). This paper also emphasizes the load variations impact on power losses. Specifically, increasing the load in each system bus by 50% resulted in a change in losses of up to 36.8 kW. Moreover, an improvement in the voltage profile has resulted (all the voltage values are above 0.95 p.u.). The performance of the technical parameters of the network is also studied in reference [18]. In this work, the voltage profile across the feeder, in per unit (p.u.), is studied separately. The results show that specific sizes and locations of PVs could minimize negative impacts. Furthermore, authors in [19] argue about the transformer hosting capacity for residential consumption, using dynamic transformer rating. This study points out that the transformer can be loaded up to 35% to host PV capacity and up to 100% for the peak load, beyond the normal operational limits.

On the other hand, Ebe *et al.* [20] have studied the PV hosting capacity connected at the medium-voltage feeders, by increasing the utilization factor up to 100%. The different scenarios in this paper consider several setpoint values of the maximum loading of the transformers. Meanwhile, three 'Upscaling Methods' have been used in the study: Even PV increase (All together), Forward PV increase, and Backward PV increase. The results showed that an even distribution of PV systems along the feeders leads to higher PV hosting capacity. In addition, the 'Forward' method results in the lowest hosting capacity for Transformer overload of 1 p.u.

However, in addition to the latest study, there is an absence of literature on comparisons of cases where PVs are installed along the entire feeder or along its first/second half. Moreover, there are few studies on the impact of PV integration on the Albanian Distribution System [21]. Meanwhile, in the case of low-voltage feeders, they are almost non-existent. This paper aims to fill this gap. In addition, this study could be useful for the RES industry, as well as for the Albanian Distribution System Operator (DSO), considering the future work of the network operation.

The objective of this study is to investigate the impact of the PVs connection point in a distribution radial feeder, considering different generation/load scenarios. While maximum PV installed capacity (in kWp) is selected equal to the transformer's active power rating, it is important to determine their most appropriate positioning in the feeder: installing in each feeder transformer, in its first half or its second half-length. Moreover, the contribution of this study is extended through an economic analysis for each scenario, considering the total investment cost of the PV systems, cost savings from reduced losses after PV integration, as well as the revenue from selling PV energy to consumers.

Meanwhile, it is worth noting that the climatic conditions taken into consideration in the study are those of Mediterranean countries, such as Albania [22]. (with very favourable climatic conditions for solar energy considering: solar radiation, duration, temperature, and humidity of the air). More specifically, Albania is exposed to radiation ranging from 1185 kWh/m^2 per year to 1700 kWh/m^2 per year [4]. Regardless of this, the analysis is not limited by the specific case analysed, which served as an example to verify the methodology addressed.

MATERIALS AND METHODS

This section explains the method employed in this work, using DIgSILENT Power Factory Software. Furthermore, various data used to model the distribution system elements and calculate and interpret the results are presented.

Methods

Figure 1 clarifies the study method employed in this work. Thus, three different cases for the solar PV connection points are selected. Moreover, four different scenarios with max/min PV generation and max/min load are taken into account.

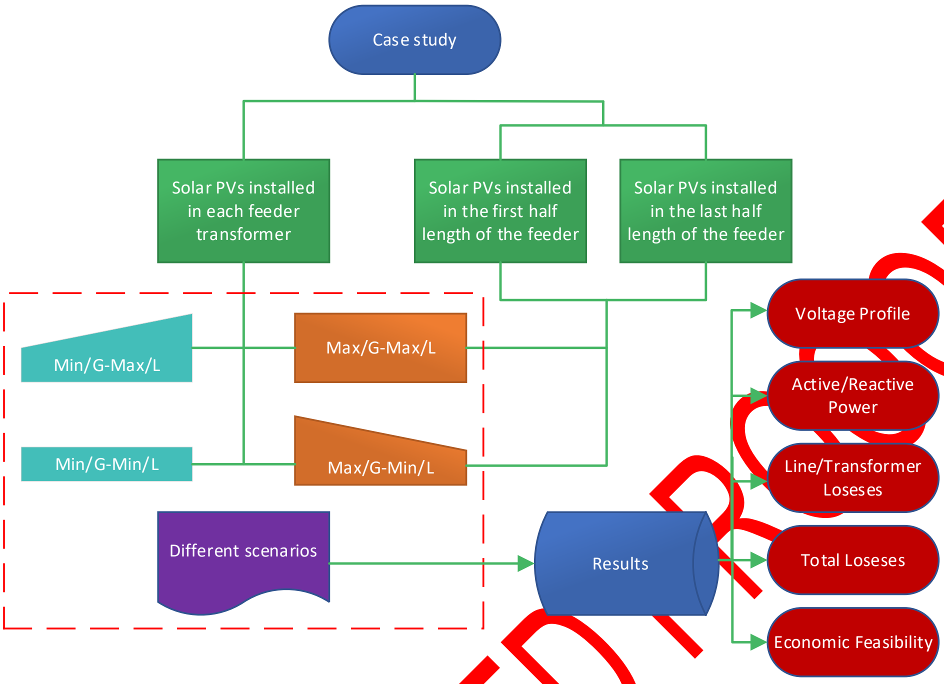


Figure 1. Flowchart of the study method

The maximum PV capacity that can be connected to a feeder is limited by transformers hosting capacity. Thus, in each cabin, maximum PV installed capacity (in kWp) is chosen equal to the transformers active power rating. However, in each case, a safety margin of 10% of the transformer's rated capacity is chosen as set point to ensure their reliability and longevity. All transformers that exceed this limit will appear in with orange colour in the scheme.

Transformer loading also depends on the load. The increase in loading would further increase the losses. In this study, the real-world load data are used for the distribution feeder, in order to find the peak load (Max/L), as well as minimum load (Min/L).

On the other hand, determining the energy produced by photovoltaics is very important. Moreover, PV systems depend heavily on atmospheric conditions (such as radiation, temperature, etc.) and perform differently from one country to another. In addition, it depends on technology and manufacturers. A quick way to find the energy produced by a photovoltaic system is by multiplying its installed power by the annual yield (kWh/kWp). Meanwhile, the minimum generation in this study is taken as 10% of the maximum one, also taking into account the transformer limits.

The goal is determinate the PVs impact on technical parameters such as, voltage profile, power flow and line/transformers losses. For this purpose, DlgSILENT Power Factory 2021 SP2 is used as the primary software to obtain all simulation results in this paper. It is an advanced software to analyse the impact of power flows injected from the integration of RESs in the distribution system, used in many scientific studies. Through its optimizations, the hosting capacity for different generation and load scenarios can be evaluated [23]. Furthermore, this software is used by the Albanian DSO to study the possibility of increasing the new generation capacities in the system.

On the other hand, to address the cost implications, an economic feasibility is done for each configuration. In this analysis, the total cost of the PV systems, cost savings from reduced losses after PV integration, as well as the profit from selling PV energy to consumers are taken into account. A more detailed explanation for them is given in the following paragraph.

Modelling of elements and Performance of technical parameters

All the grid system, are modelled in Power Factory software. Lines, transformers, HPP synchronous machines, feeders, as well as the loads are selected according to the data received from Albanian DSO. Meanwhile, it is worth mentioning that the Simplified PV Penetration model, which considers the ambient temperature and solar irradiance [24], can be expressed through Equation (1):

$$P_{PV} = \frac{G}{G_{ref}} \times P_r \times [1 + K\left(\left(T_{amb} + G\left[\frac{T_{NOCT} - 20}{800}\right]\right) - T_{ref}\right)] \tag{1}$$

where:

- P_{PV} is the output power of solar PV, in watts (W);
- G is the solar radiation, in W/m^2;
- G_{ref} is the solar radiation at standard test conditions (STC) = 1000 W/m^2;
- P_r is the rated power at the STC, in watts (W);
- K is the temperature coefficient = $-3{,}7 \times 10^{-3}$ (1/^{0}C);
- T_{amb} is the ambient temperature = 25 ^{0}C;
- T_{NOCT} is the nominal operating temperature of the cell;
- T_{ref} is the cell temperature at STC, in ^{0}C.

While PVs are limited by the transformer's hosting capacity, the below performance parameters should be considered.

Voltage in feeder nodes. The installation of solar PVs affects the fluctuation of the voltage profile along the radial distribution feeder. For this reason, it is important to calculate the voltage deviation of all nodes on the feeder, to fulfil the minimum technical requirements [13]. It can be expressed as a decimal or percentage value. The voltage values in 'per-unit' (p.u.) are used in this study, which are often expressed as below:

$$V(p.u.) = \frac{V}{V_b} \tag{2}$$

where: V and V_b, are respectively the actual voltage and the base voltage (in kV). Often the base voltage is taken equal to the nominal voltage (V_n).

Meanwhile, according to ADFC [25], the Operating Low Voltage Range should be from -5% to +5% of base (or nominal) voltage. For the 'per-unit' system, the range of voltage fluctuations should be in the interval [0.95-1.05] p.u.

Line losses in a distribution feeder. Due to the through of current flows in the power lines that supply the loads, electrical losses appear in them. According to the paper [26], these line losses (in MW) can be calculated using Equation (3):

$$\begin{aligned} P_L(loss) &= I_L^2 \times R \times (Loss\ factor) \\ &= I_L^2 \times R \times [(0.3 \times Load\ factor) + 0.7 \times (Load\ factor)^2] \end{aligned} \tag{3}$$

where:

- I_L represents the maximum current, in Amperes (A), drawn from the feeder. Furthermore, this current given as Equation (4), depends on: P (Maximum monthly loading on the feeders in MW), V (line voltage in kV), as well as cosφ (power factor).

$$I_L = \frac{P}{\sqrt{3} \times V \times cos\varphi} \tag{4}$$

- R represents distribution feeder resistance, in Ohms (Ω). In addition, this resistance depends on the parameters: ρ (resistivity in Ω*m), l (length of the feeders in km) and A (cross sectional area of line conductor in mm^2). It can be calculated using Equation (5):

$$R = \rho \times \frac{l}{A} \tag{5}$$

- Load factor, takes into account the electrical load change (demand for electricity) and is given by Equation (6):

$$Load\ factor = \frac{Average\ load}{Peak\ load} \tag{6}$$

Transformer losses in a distribution feeder. The total power transformer losses (P_{PT} (loss) in kW), are expressed by Equation (7):

$$P_{PT}(loss) = P_{cl} \cdot \left(\frac{S_{max}}{S_r}\right)^2 \cdot (Load\ Loss\ factor) + P_{PTnL} \tag{7}$$

$$Load\ Loss\ factor = \frac{Actual\ loss\ during\ a\ period\ (in\ kVA)}{Loss\ at\ maximum\ current\ (in\ kVA)} \tag{8}$$

where:

- P_{cl} is full load copper loss;
- S_{max} is maximum demand in a period (in kVA);
- S_r is transformer rating (in kVA);
- P_{PTnL} are No-load losses;
- Load Loss factor describes the average energy losses (Eq. (8)).

Total losses. The total power losses in each feeder are given in Equation (9):

$$Total\ Power\ Losses = P_L(loss) + P_{PT}(loss) \tag{9}$$

Cost saving from reduced losses. The total cost saving due to power loss in a distribution feeder [27] are expressed by Equation (10):

$$Cost\ saving\ due\ to\ Losses = Total\ Losses \times \text{Time} \times \text{Tariff for electricity} \tag{10}$$

The income from PV generation. The income from PV generation depends on the size of the PV system, the mereological condition, as well as the electricity tariff. Furthermore, it is given in Equation (11):

$$The\ income\ from\ PV = P_{PV} \times \text{production kWh/kWp} \times \text{ Tariff for electricity} \tag{11}$$

<u>Total investment cost of PV</u>. The total investment cost for a PV system is expressed by Equation (12):

$$Investment\ cost\ of\ PV = P_{PV} \times \text{cost per watt} \tag{12}$$

The installation cost of the PV system depends on the technology and manufacturers. It also varies from state to state.

<u>Payback period</u>. The payback period is the ratio of the total investment cost to the benefit (saving cost + income) in a year. Moreover, it is given by Equation (13):

$$Investment\ cost\ of\ PV = \frac{Invesment\ cost}{Saving\ cost + Income} \tag{13}$$

Thus, the interval of time needed to recover the investment's costs is known as the payback period. In addition, it is a very essential value to assess the economic feasibility of a PV system.

Distribution System Area

This paragraph discusses the application of the discussed method in the case of a specific DSO feeder. The Kukes distribution system [28] has been selected as a case study. It is one of the 11 areas of the Albanian DSO, located in the north-east of the country. Based on the technical data received from the Electricity DSO [29], the full scheme of the Kukes area has been built, in the DlgSILENT Power Factory Software (this program is used by DSO for all the distribution schemes of Albania).

This scheme, as shown in Figure 2, includes 3 electrical substations and their respective feeders. As shown, 5 Hydro Power Plants (HPPs) at different voltage levels have been connected in this area. For example, HPP Pobreg is installed at the Busbar of 10 kV Kukes (Rexhepaj) substation, near its feeders.

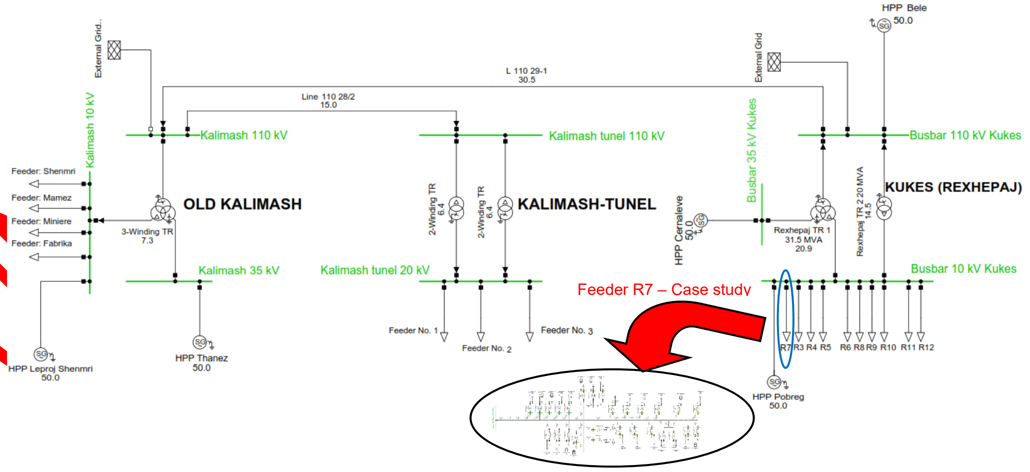


Figure 2. Main scheme of Kukes Distribution System

On the other hand, there are no solar PVs installed at Busbar or inside the feeders. For this reason, the possibility of installing solar PVs in the nodes of one of the feeders has been studied. Considering all the feeders, the "R7" one is chosen. The technical parameters of this feeder, as well as the others, are shown in Table 1.

In particular, R7 Feeder includes 27 power transformers, as well as 27 electrical cabins, with a total installed power of 4235 kVA, and a peak load of around 2200 kW. Furthermore, it is built by overhead and underground lines, with a total length of 12.77 km. The installation of solar PVs, considering transformer hosting capacity, is planned in these electrical cabins. The total PV capacity is not expected to exceed the total installed transformer capacity.

However, the solar PV output power highly depends on meteorological conditions such as solar irradiation, air temperature, etc. [30]. In this context, these meteorological variables should be measured [31].

Table 1. Technical data of Kukes Distribution System

Substation	Voltage (kV)	Feeder	Underground line (km)	Overhead line (km)	Type of cabin				Power Transformer (kVA)
					Brick wall	Box	Pole mounted	Metallic	
REXHEPAJ (110/10 KV)	10	R9	0.55	71.95	23	0	42	2	7,360
		R4	0.440	25.85	4		20		3,663
		R5	2.934	4.600	18	0	9	0	7,116
		R6	0.58	19.26	12	0	12	0	3,620
		R7	0.21	12.51	7	0	20	0	4,235
		R8	0.21	60.10	19	0	28	2	6,650
		R3	0.28	4.90	1	0	0	0	500
		R10	2.90	11.06	14	0	13	1	7,130
		R11	1.585	4.51	9	0	10	0	4,416
		R12	0.59	14.700	12		9	2	5,800
TOTAL 1		10	10.281	229.44	119	0	163	7	50,490
KALIMASH (110/35/10kV)	10	Miniere	0.05	4.00	3	0	2	0	950
		Fabrike	0.05	8.10	2	0	1	0	2,830
		Mamez	0.05	42.15	12	1	12	10	3,770
		Shemri	0.05	35.30	5	0	16	2	2,140
TOTAL 2		4	0.20	89.55	22	1	31	12	9,690
KALIMASH TUNEL (110/20 kV)	20	Feeder Nr.1	5.70		1	0	0	0	2,400
		Feeder Nr.2	0.10	5.40	1	0	0	0	400
		Feeder Nr.3	0.20	0.10			1		50
TOTAL 3		3	6.00	5.50	2		1		2850

According to the Albanian National Agency of Natural Resources [32], Figure 3 shows the Daily & Monthly averages irradiation of the Kukes area. For example, December's solar irradiation is roughly 10% of July's (the numbers at the bottom of the graph correspond to the 'time of day'). Meanwhile, this area has the lowest solar irradiation in the country.

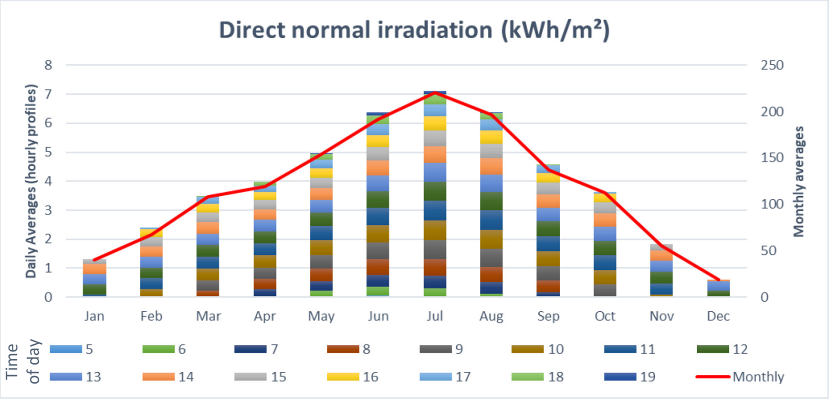


Figure 3. Daily & Monthly Averages of Direct normal irradiation of Kukes area

In addition, **Table 2** represents other meteorological data about temperature and precipitation days, for each month. The yearly average temperature in this area is around 10.2^{0}C (lower than PV cell temperature at standard test conditions (STC)=25^{0}C [11]).

Table 2. Monthly average temperature and precipitation days in Kukes area

Mon.	**Ja**	**Fe**	**Ma**	**Ap**	**Ma**	**Ju**	**Ju**	**Au**	**Se**	**Oc**	**No**	**De**	**Yearl.**
Temp. (°C)	-0.9	1.3	4.6	9.4	13.3	17.8	20.6	21	16.2	11.3	6.6	1	10.2
Prec. days	11.5	13.3	13.8	12.8	14.7	12.9	11.3	8	9.8	7.9	9.6	9.9	11.3

The standard test conditions are performed for a spectral radiation AM 1.5, with a solar radiation flux of 1000 W/m^2, at a temperature of 25^{0}C. Deviating from these conditions would result in a change in the energy produced by a PV system. Thus, it is important to consider solar irradiation (given in **Figure 3**), as well as the ambient temperature (given in **Table 2**) for each geographic location. For these reasons, PV generation will be different for different areas.

Case study: Feeder "R7"

To study the impact of the solar PV installation in low-voltage buses, within the main scheme of the Kukes area, the "R7" radial feeder scheme has been expanded (see **Figure 2**). The impact of the PV connection point in the feeder is investigated, considering different generation/load scenarios. More specifically, the possibility of installing solar PVs in each feeder transformer, as well as in its first/second half-length, has been studied. Moreover, small-scale solar PVs, connected to the "R7" radial feeder, are modelled to operate as active power generators.

Solar PVs are installed in each feeder transformer. Considering hosting capacity, 27 solar PVs are installed in each transformer, as shown in **Figure 4**.

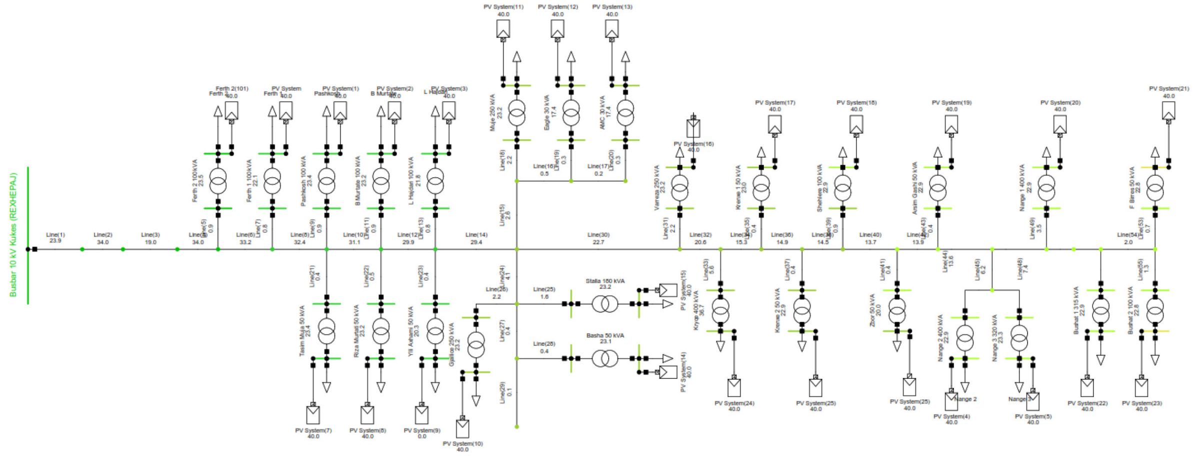


Figure 4. Feeder "R7" with Solar PVs installed in each power transformer

The length of the main line of this feeder is about 6.83 km, while there are several other nodes in it. In addition, a total of 3975 kW of solar PVs is connected in this case.

Solar PVs are installed in the first/second half length of the feeder. First of all, the case of solar PV installation in the first half length of the feeder is studied (see Figure 5).

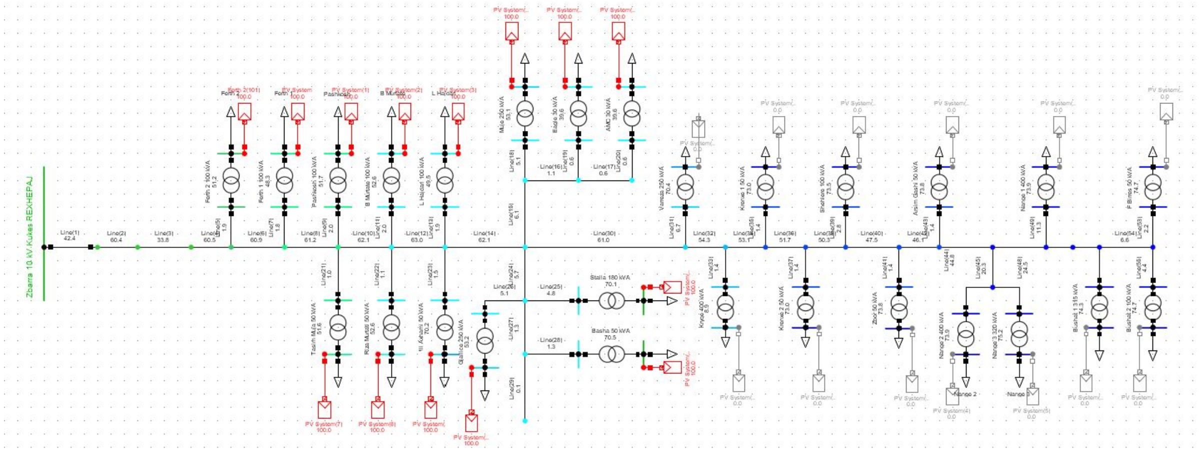


Figure 5. Solar PVs installed in the first half length of the Feeder "R7"

On the other hand, the case of connecting solar PVs in the second half length of the feeder, as shown in Figure 6, has also been considered.

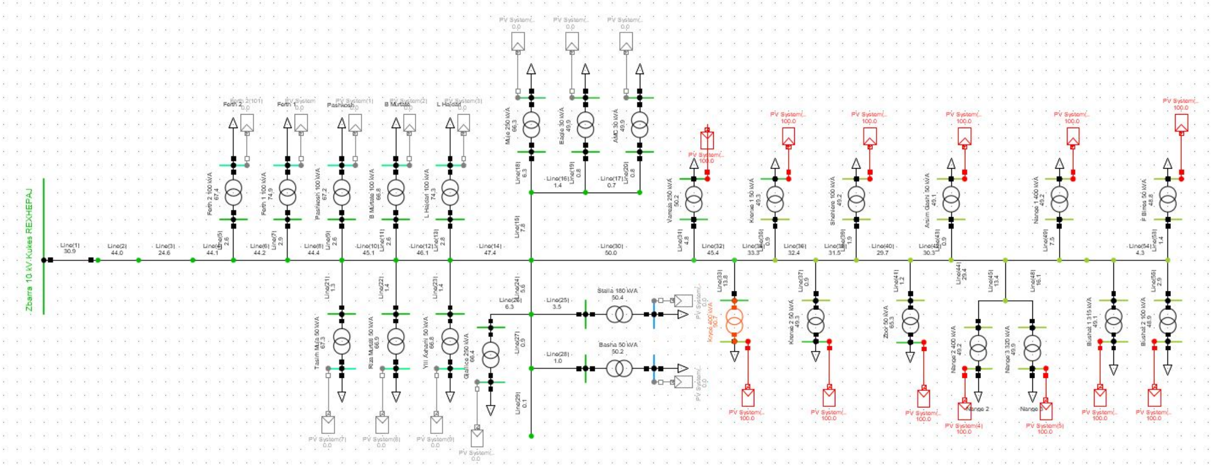


Figure 6. Solar PVs installed in the second half length of the Feeder "R7"

Comparisons between these 2 cases, present the impact of the PVs connection point in a radial feeder. In addition, different scenarios for max/min load have been taken into consideration.

RESULTS AND DISCUSSION

The main results obtained according to the method used in the previous section, are shown and discussed below. While solar PVs are limited by the transformer's hosting capacity, different generation/load scenarios are considered and compared. It is worth mentioning that the minimum generation of PVs has been chosen as 10% of the maximum generation (see meteorological area conditions in **Figure 3**). In the same vein, the minimum load is also selected (10% of the peak load).

Solar Photovoltaics are installed in each feeder transformer

The first case study is the connection of solar PVs in each feeder transformer. A total of 3975 kW of solar PVs is connected for the maximum generation case. Considering different generation/load scenarios, voltage profiles, power flows, as well as technical losses have been compared.

<u>Voltage profile</u>. Firstly, the voltage profile curves for 4 different scenarios are presented in **Figure 7**. These graphs are obtained through the results of the voltage level (in p.u.) fluctuation as a function of the length of the main line (6.83 km) or feeder nodes. The red lines indicate overloads of the feeder elements.

In the scenarios when generation and load follow each other (Max/G-Max/L and Min/G-Min/L), the voltage levels are very close to the 1 p.u. value. Furthermore, all the node's feeder voltage respects the fluctuation limits according to the ADFC (0.95-1.05 p.u.). Moreover, no overloaded element appears in these two scenarios. Thus, it is important to analyse the current load flow to consider the possibility of increasing the generation capacity. Similarly, the voltage profile in reference [33] indicates that voltage decreases with distance from the source. Meanwhile, the distinction in this paper is the power factor control. Furthermore, reference [34] shows that the Unity Power Factor causes an increase in voltage levels compared to the Constant Power Factor of 0.99.

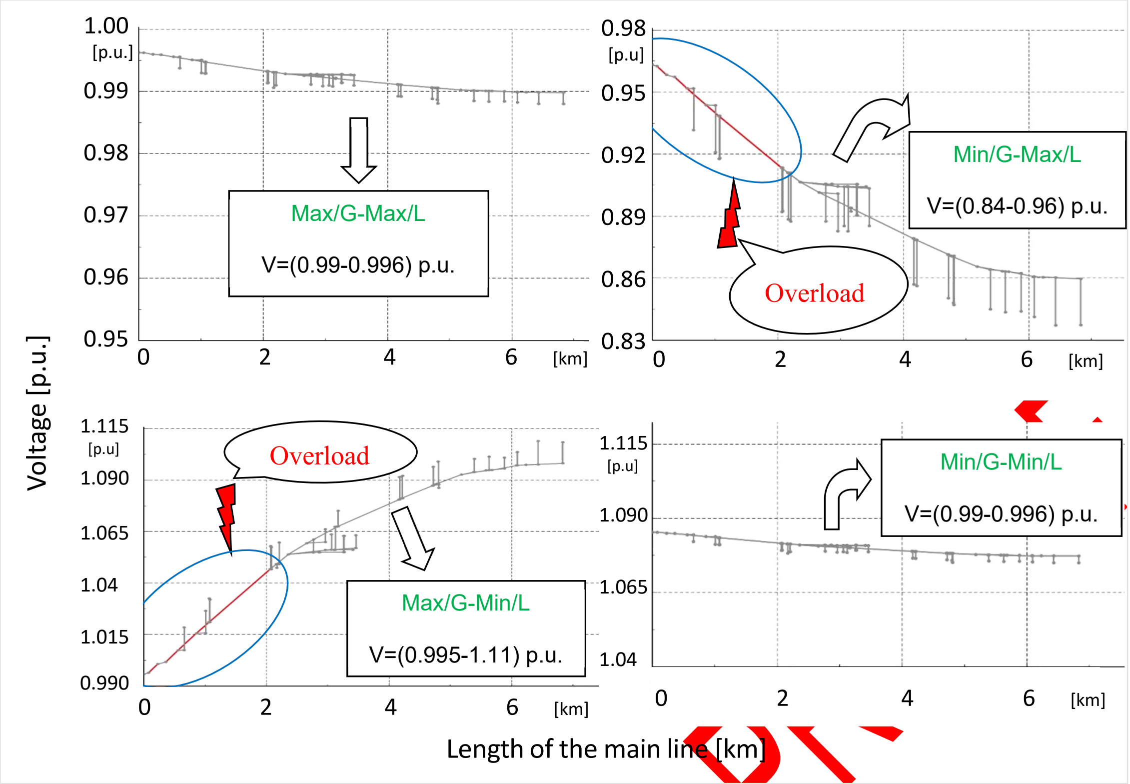
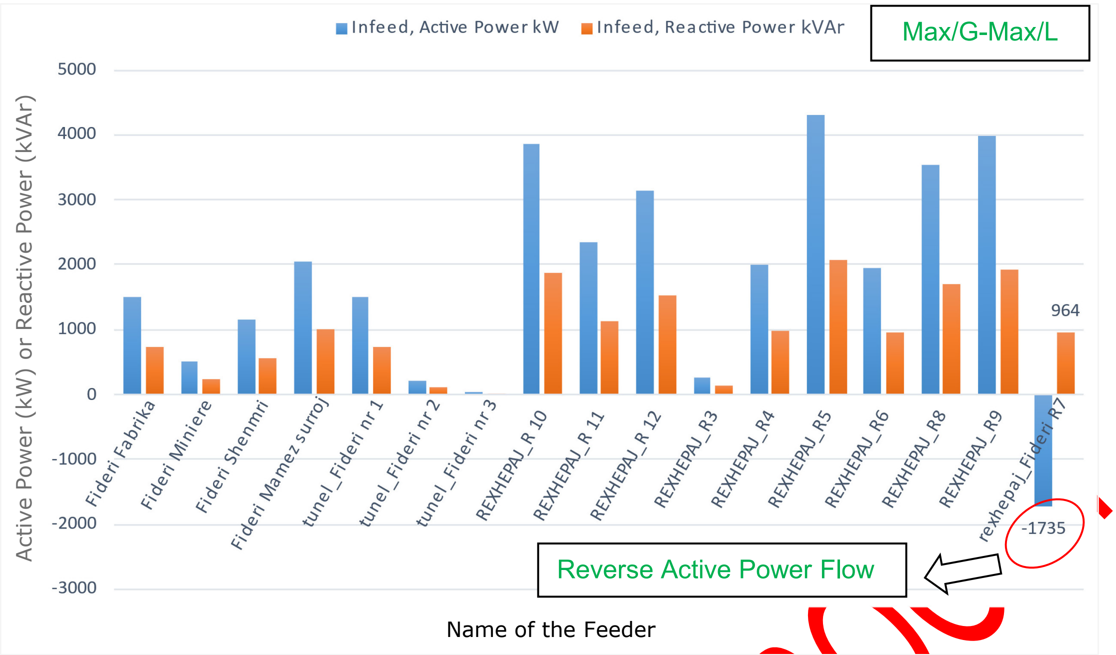


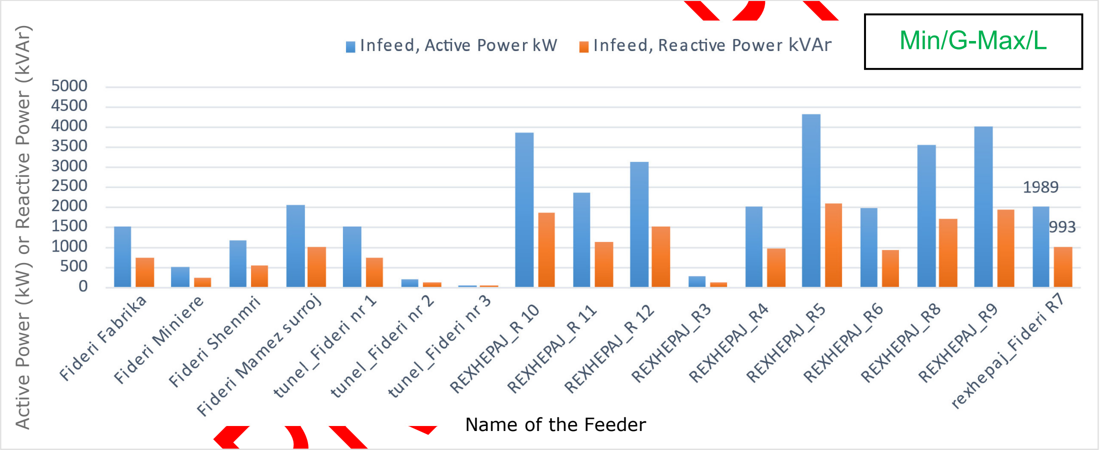
Figure 7. Voltage profile plot for 4 different scenarios

On the other hand, for the unbalanced scenarios (Min/G-Max/L and Max/G-Min/L) the voltage levels in both scenarios fluctuate outside the ADFC limits. In particular, in both scenarios, an overload on the initial part of the main feeder line has been detected (see the red lines in **Figure 7**). As a conclusion, these two scenarios are not preferable. In the same vein, for 80% PV integration, reference [11], indicates a voltage increase beyond 1.5 p.u. at the end of the line.

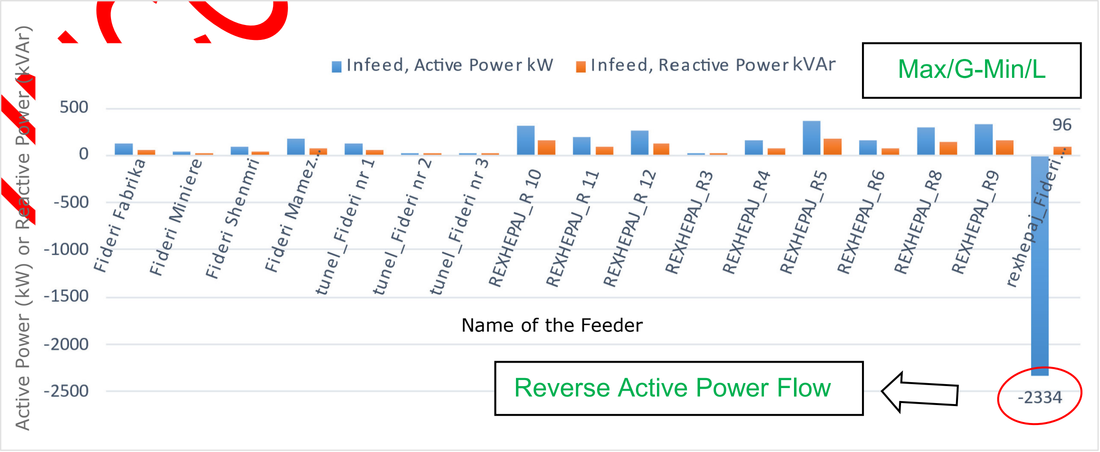
Active and Reactive Power Flows in Distribution Feeders. The installation of generation capacities turns the feeder network from passive to active. For this purpose, the influence of this generating feeder on other power flow feeders must be analysed. In this context, **Figure 8** shows Active & Reactive Power Flows in distribution feeders for different generation/load scenarios.


Infeed, Active Power kW
Infeed, Reactive Power kVAr
Max/G-Max/L
Active Power (kW) or Reactive Power (kVAr)
5000
4000
3000
2000
1000
0
-1000
-2000
-3000
964
-1735
Fideri Fabrika
Fideri Miniere
Fideri Shenmri
Fideri Mamez surroj
tunel_Fideri nr 1
tunel_Fideri nr 2
tunel_Fideri nr 3
REXHEPAJ_R 10
REXHEPAJ_R 11
REXHEPAJ_R 12
REXHEPAJ_R3
REXHEPAJ_R4
REXHEPAJ_R5
REXHEPAJ_R6
REXHEPAJ_R8
REXHEPAJ_R9
rexhepaj_Fideri R7
Reverse Active Power Flow
Name of the Feeder

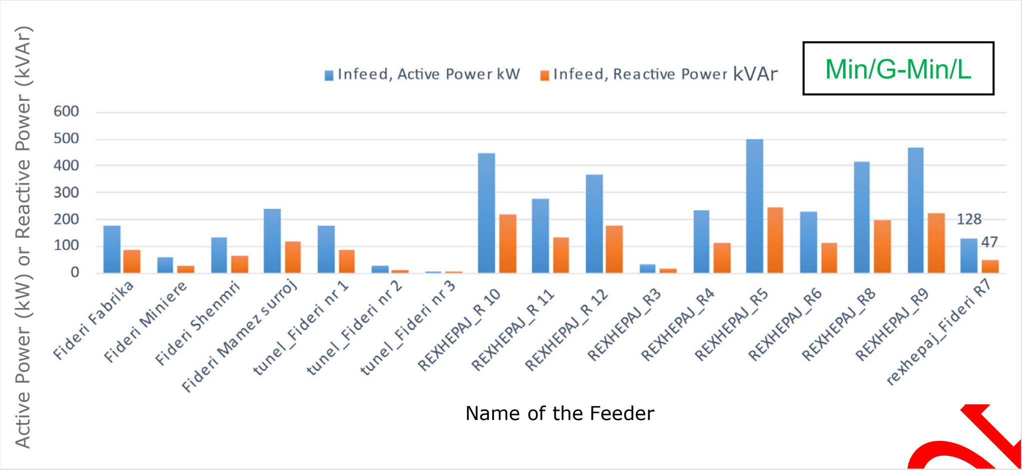
(a)


Infeed, Active Power kW
Infeed, Reactive Power kVAr
Min/G-Max/L
Active Power (kW) or Reactive Power (kVAr)
5000
4500
4000
3500
3000
2500
2000
1500
1000
500
0
1989
993
Fideri Fabrika
Fideri Miniere
Fideri Shenmri
Fideri Mamez surroj
tunel_Fideri nr 1
tunel_Fideri nr 2
tunel_Fideri nr 3
REXHEPAJ_R 10
REXHEPAJ_R 11
REXHEPAJ_R 12
REXHEPAJ_R3
REXHEPAJ_R4
REXHEPAJ_R5
REXHEPAJ_R6
REXHEPAJ_R8
REXHEPAJ_R9
rexhepaj_Fideri R7
Name of the Feeder

(b)


Infeed, Active Power kW
Infeed, Reactive Power kVAr
Max/G-Min/L
Active Power (kW) or Reactive Power (kVAr)
500
0
-500
-1000
-1500
-2000
-2500
96
-2334
Fideri Fabrika
Fideri Miniere
Fideri Shenmri
Fideri Mamez...
tunel_Fideri nr 1
tunel_Fideri nr 2
tunel_Fideri nr 3
REXHEPAJ_R 10
REXHEPAJ_R 11
REXHEPAJ_R 12
REXHEPAJ_R3
REXHEPAJ_R4
REXHEPAJ_R5
REXHEPAJ_R6
REXHEPAJ_R8
REXHEPAJ_R9
rexhepaj_Fideri...
Name of the Feeder
Reverse Active Power Flow

(c)



(d)

Figure 8. Active & Reactive Power Flows in distribution feeders for the scenario: Max/G-Max/L (a), Min/G-Max/L (b), Max/G-Min/L (c), Min/G-Min/L (d)

In both maximum generation scenarios (Max/G-Max/L), a negative value of the active power flow of the "R7" Feeder is observed. This means that PV output exceeds the feeder load, causing a reverse active power flow. As can be seen from **Figure 8(a)** and **Figure 8(c)**, the smaller the load, the greater the reverse power flow. This surplus of active power flow can be consumed by the other feeder's load. The same situation also resulted in reference [21].

On the other hand, in the minimal generation scenarios (Min/G-Max/L and Min/G-Min/L), no reverse power flow is observed. While positive values of Active Infeed Power are seen in both scenarios, this value is higher for maximum load.

Losses. **Figure 9** shows the line losses, transformer losses as well as the total losses of the R7 feeder.

Figure 9. Line, Transformer & Total losses of the "R7" feeder for different scenarios

Line losses are greater than transformer losses. This is a consequence of the power flows that pass through them. Looking at the scenarios, the losses are greater in scenarios 2 and 3 due to the higher currents. For example, the largest line losses occur in scenario 2 (Min/G-Max/L). Similarly, reference [14] indicates that 0% PV penetration (comparable to Min/G) causes the greatest power loss during peak load situations. As explained through Equation (3), line losses are directly proportional to the square of the current flow as well as the Loss Factor. Due to this latter factor, the first scenario also results in large losses on the line (peak load). However, considering that in this scenario the line currents are smaller, the losses are also smaller compared to the 2 scenarios analysed above. Meanwhile, in the fourth scenario, line losses are lower due to lower currents (generation and load follow each other), as well as due to the low Loss factor (min load).

The same analysis can be done regarding transformer losses. In this case, in addition to the Load Loss Factor, the maximum demand also has its impact (see Equation (7) and Equation (8)). Due to a high Load Loss Factor, in scenario 3 (Max/G – Min/L) transformer losses result higher. Furthermore, in the case of maximum loads (scenarios 1 and 2), considering high demand, transformer losses are similarly high. Only in the last scenario, where both factors are lower, the transformer losses are relatively low. Meanwhile in reference [27], the largest losses result for the 0% PV penetration scenario, compared to the 80% PV penetration scenario (considering the same load). This is more or less the same conclusion as the results shown in **Figure 9**.

On the other hand, while the smallest losses result in the Min/G-Min/L scenario, the increase in load or generation causes large total losses. However, the first scenario shows a lower value than the second and third.

Economic feasibility. To study the economic impact of PV penetration, the following values are considered and calculated: the total cost of PV installation, the cost savings resulting from the reduction of losses after PV integration, as well as the revenue from selling PV energy to consumers.

To calculate the required values, several unit prices must be taken into account, which vary from one country to another. Thus, According to ERA, the electricity price from Albanian DSO to customers is 9.5 ALL/kWh [7], or around 0.1 $/kWh. Meanwhile, the authors in the literature [4], recommend that the price per unit of solar PV be chosen at 883 $/kWp. In addition, the annual yield for the geographical area and the selected type of photovoltaic system is around 1200 kWh/kWp.

Thus, using Equation (12), the total investment cost for the PV installation on all feeder transformers results: 3875 kWp x 883 $/kWp = 3421625 $. But these PV systems, for maximum generation, would produce 3875 kWp * 1200 kWh/kWp = 4650000 kWh/year. This amount of energy would be sold for $0.1/kWh, generating annual revenues of: 4650000kWh/year * 0.1 $/kWh = 465000 $. In addition, in the Max/G-Max/L scenario, total feeder losses decrease by 220.41 kW, from 391 kW to 170.59 kW. This would result in a Cost saving from reduced losses of 193079.2 $ (220.41 kW * 8760 hours * 0.1 $/kWh). Finally, dividing the total cost of the PV investment by the revenue obtained (from the sale of electricity + Cost savings from reduced losses), results in a payback period of 5.2 years. In contrast, the payback period for the integration of the PV system in Bahir Dar (Ethiopia) [27], resulted in 3.85 years. In another study in Tirana, Albania, this period has resulted in approximately 3.9 years [4]. The same calculations can be done for the other 3 scenarios, while the total investment cost would remain unchanged.

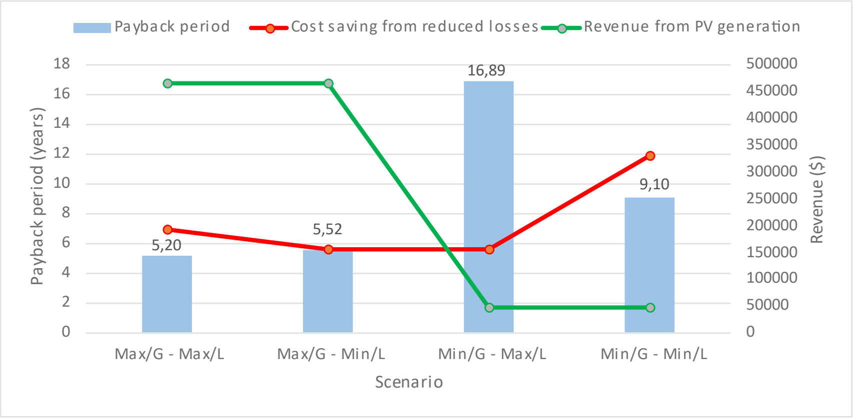


Figure 10. Payback period and revenues from PV penetration for different scenarios

Thus, **Figure 10** shows the payback period for different scenarios, considering total investment cost, cost savings from reduced losses, and revenue from the sale of electricity generated by PV. It is worth noting that other costs have not been taken into account, such as maintenance costs, costs of new investments to reinforce the network as a result of deterioration of performance indices, etc.

Based on the payback period, the PV installation along the entire feeder for minimal generation has no interest, considering high values (16.89 years for peak load and 9.1 years for minimum load) due to the high investment cost. Meanwhile, the greatest benefit appears for maximum generation and maximum load (payback period is 5.2 years). Because energy losses are further minimized at maximum load (see **Figure 9**), the return on investment is faster than in the minimum load scenario (5.52 years).

Solar Photovoltaics are installed in first/second half length of the feeder

To study the impact of the solar PV connection points, the cases of their installation in the first half of the length of the feeder, as well as in its second half, are considered. In the same vein as in the first case, the performance of the technical feeder parameters is discussed as follows. While in the first half scenario, there is no transformer overloaded above the set point (90%), in the second scenario a transformer overloaded around 91% (shown in **Figure 6** in orange) results.

Voltage profile. **Figure 11** presents the voltage profile curves for 2 cases (first half vs second half installation). Assuming maximum generation, minimum and maximum load scenarios are considered. Based on the voltage profiles, for the Max/G-Max/L scenario, the best option is to install solar PVs in the first half length of the feeder. This is due to keeping the voltage level within the code limits. The only issue is the overload of one of the feeder nodes (see the red line). Similarly, reference **[20]** shows that the 'Backward' method causes voltage violations at the main branch components. Meanwhile, in this study, the 'Forward' method causes the smallest change in voltage level.

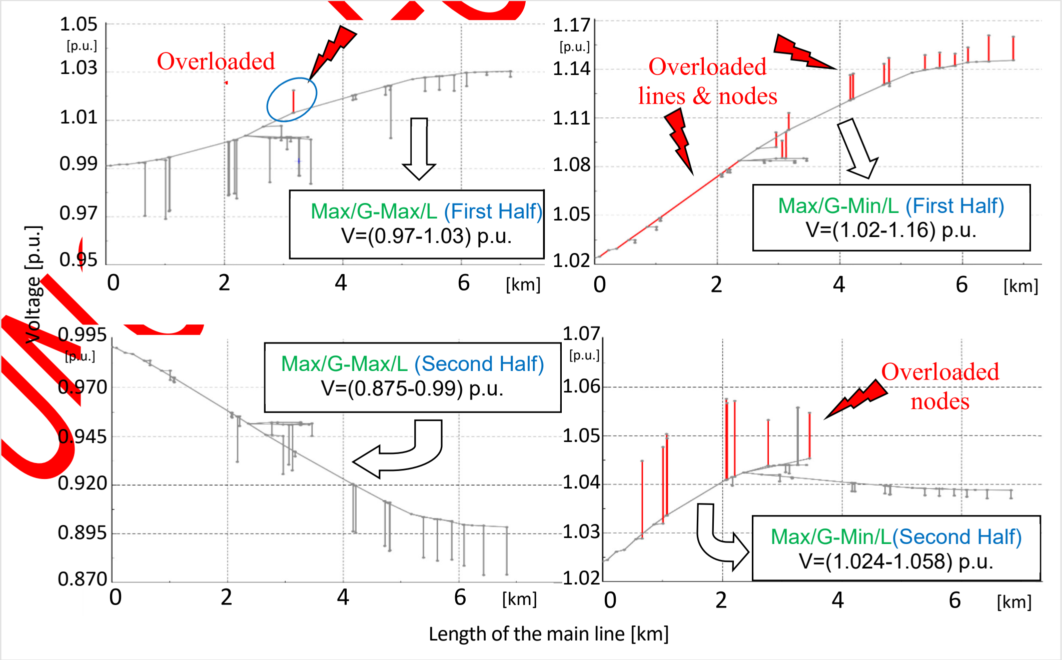


Figure 11. Voltage profile plot for different scenarios (Solar PVs installed in the first/second half length of the feeder)

On the other hand, the Max/G-Min/L scenario causes many overloads, for both cases. Furthermore, at the end of the feeder, the voltage rises outside the required limits. This case represents a risk since in the conditions of minimal load, the distribution feeder capacities are weak.

Active and Reactive Power Flow of the "R7" feeder. For both cases, in **Figure 12**, the active and reactive power flows of the feeder are presented.

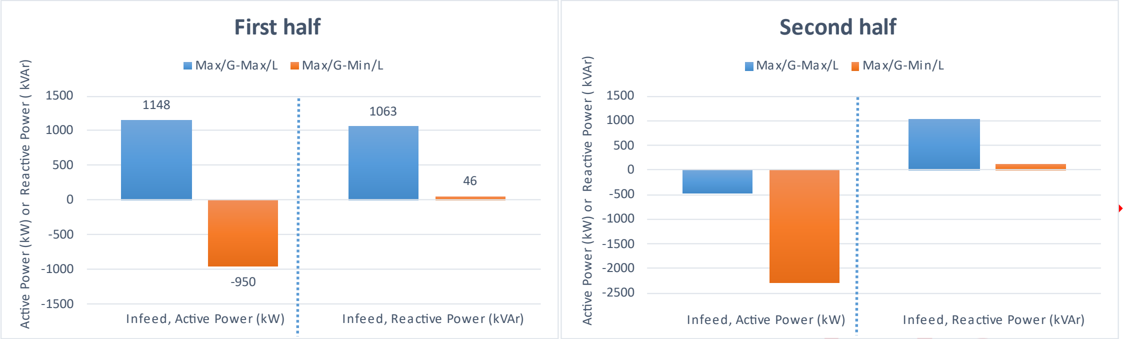


Figure 12. Feeder Power Flow for different scenarios (Solar PVs installed in the first/second half length of the feeder)

In the case of installation in the second half of the feeder, a reverse active power appears in each scenario. For the minimal load, it reaches the value of -2277 kW, which supplies the other feeders. Meanwhile, for the "first half" case, reverse power appears only in the Max/G-Min/L scenario.

Losses. Line & Transformer Losses, considering each case, are shown in **Figure 13**.

Figure 13. Line & Transformer Losses for different scenarios (Solar PVs installed in the first/second half length of the feeder)

The transformer losses appear higher when solar PVs are installed in the second half of the feeder, in every scenario. Meanwhile, the line losses depend a lot on the load. The best scenario, when solar PVs are installed in the first half of the feeder, is that of Max/G-Min/L. Even the smallest losses result there. The opposite occurs in the other scenario.

On the other hand, the total power losses in the feeder are presented in **Figure 14**. It is seen that the most favourable case would be the installation in the first half of the feeder, especially in the Max/G-Min/L scenario. While the installation in its second half-length, it would be useful for the maximum feeder's load scenario. However, due to these losses, the reinforcement of the feeder is necessary. For example, reference 5 recommends that the need for investments increases more than linearly, starting at around 40–50% PV penetration **[35]**.

Finally, an equal solar PV installation in the feeder cabins would be the best possible solution, considering voltage stability, as well as the power losses. The same conclusion was reached by the authors in reference [20]. In the same vein, the 'Forward' method results in the lowest hosting capacity than the 'Backward' method. The same result is obtained again with this paper.

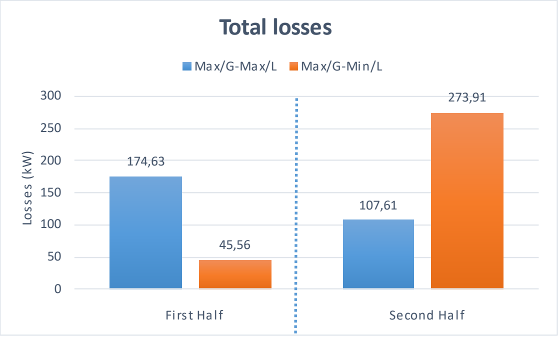


Figure 14. Total Losses for different scenarios (Solar PVs installed in the first/second half length of the feeder)

Economic feasibility. The same economic analysis performed in the case of PV installation on all feeder transformers can also be done in the case of installation on the length of the first/second half of the feeder. The electricity price from Albanian DSO to customers, the cost per unit of solar PV, and the annual yield are again taken respectively: 0.1 $/kWh, 883 $/kWp, and 1200 kWh/kWp. While the PV systems installed in the first half of the feeder have an installed power of 1160 kWp, those installed in its second half have an installed power of 2715kWp. This change is a consequence of a greater number of nodes in the second half of the feeder as well as a greater hosting capacity of their transformers. In this way, the cost of PV installation in the second half of the feeder (3258 k$) turns out to be higher than in the first case (1392 k$). However, this larger installation quantity also brings higher income from PV generation (see Figure 15). Moreover, it turns out that for the Max/G – Max/L scenario, the highest revenues are in the case of installing PV on the second feeder half-length. Meanwhile, for the minimum load (Min/L), revenues are higher for the installation in the first half of its length. This is the same conclusion that resulted from the technical analysis carried out in the section above.

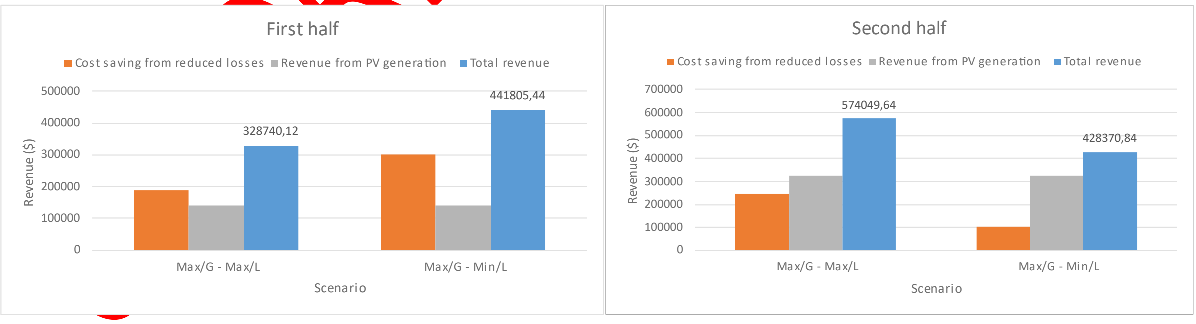


Figure 15. Revenue for different scenarios (Solar PVs installed in the first/second half length of the feeder)

On the other hand, the comparison of the Payback period between the different scenarios is given in Figure 16. Installation in the first half is significantly more profitable than installation in the second half (2.32 years vs. 6.6 years) when the feeder load is minimal. Again, it is worth noting that in this case (Min/L), the installation should be done in the first half. Meanwhile, for maximum load, the difference between the two connection typologies is only 1 year. Although the income is higher for the installation in the second half (see **Figure 15**), the payback period is slightly lower, since the PV investment cost is greater (due to the typology of the feeder).

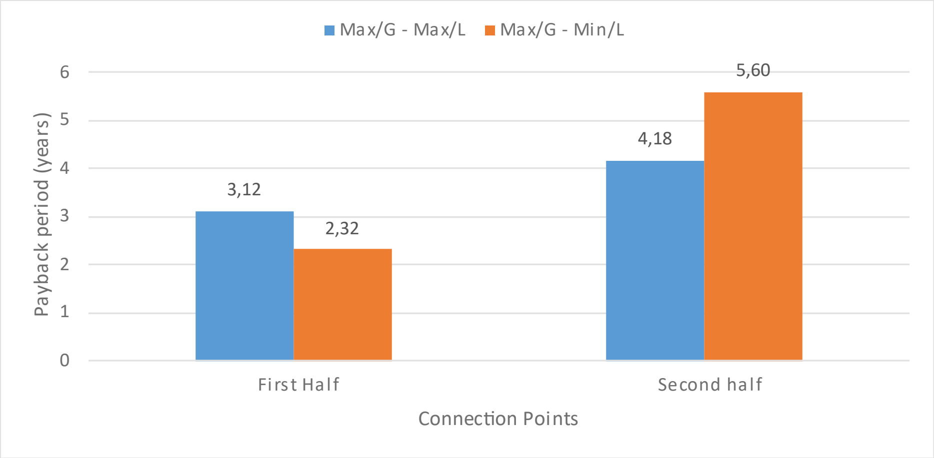


Figure 16. Payback period for different connection points (Solar PVs installed in the first/second half length of the feeder)

Finally, by comparing the Payback period values presented in **Figure 16** with those of the PV installation on all feeder transformers case (presented in **Figure 10**), the economic analysis results that the return on investment is slightly greater in the second case. However, in the case of PV installation in the first or second half, as discussed in the technical analysis, there would be a deterioration of the parameter indices. This would require the reinforcement of the feeder, increasing the investment costs (which are not considered in the calculations). For example, the transformer replacement costs should be taken into account for future scenarios **[20]**. Due to these additional costs, the Payback period values, given in **Figure 16**, would be much higher. In this way, if no investment were made in the feeder, it would be more appropriate to distribute the PV throughout the entire feeder, compared to the other 2 connection cases.

CONCLUSION

This paper performs the impact of solar PV installation in a radial distribution feeder. The methodology used is tested in an Albanian case study. The focus is on the investigation of distribution system parameter fluctuations, considering four different scenarios with maximum PV generation/min and maximum load/min for different connection points. Using DlgSILENT Power Factory Software, solar PV generation is limited by the transformer's hosting capacity. Furthermore, a comparison of the results has been carried out for each scenario, from the point of view of the fluctuations of the voltage profiles along the entire feeder, line, and transformer losses, as well as active and reactive power flows. The obtained results are useful for the RES industry, as well as for the Albanian DSO, considering the future work of the network operation.

The case study shows that the connection of solar PVs in each feeder node is the best option. Moreover, in the scenarios when generation and load follow each other (Max/G-Max/L and Min/G-Min/L), the voltage levels are very close to 1 p.u. value. All the node's feeder voltage respects the fluctuation limits according to the ADFC (0.95-1.05 p.u.). Meanwhile for the unbalanced scenarios (Min/G-Max/L and Max/G-Min/L), an overload on the initial part of the main feeder line has been detected. While the smallest losses result for scenario Min/G-Min/L, the increase in load or generation causes large losses. In addition, the economic analysis shows that the total revenues from PV penetration range from 202 k$/year (for Min/G-Max/L) to 658 k$/year (for Max/G-Max/L). Whereas the Payback period values are 16.89 years and 5.2 years, respectively. It is worth noting that in the economic analysis, the future investment costs for the reinforcement of the feeder (due to the deterioration of the parameter indices) are not considered.

On the other hand, comparing “first half” vs “second half” cases, the most favourable would be the installation in the first half of the feeder, especially in the Max/G-Min/L scenario. While the installation in its second half-length, it would be useful for the maximum feeder's load scenario. Furthermore, the economic analysis shows that to determine the suitable connection of the PV systems (in the first or second half-length of the feeder), it is crucial to know the feeder load. While for the peak load scenario, the highest revenues are in the case of PV penetration on the second feeder half length, for the minimum load case, they are higher for the installation in the first half of its length.

In a summary manner, the main points on the impact of PV penetration in a radial distribution feeder, as well as practical recommendations for policymakers and DSOs, are as follows:

- Solar Photovoltaic penetration seems to have benefits. Thus, policymakers should promote the use of PVs, especially for the prosumers. However, based on their effect on the low/medium voltage network, the best way to install them needs to be determined. It is also important to note that the total generation must be close to the feeder load.
- Voltage Fluctuations: In some cases, the solar PV integration to the feeder causes large voltage fluctuations. This can be eliminated by distributing them along all feeder nodes, as well as if generation and load follow each other. In each distribution system of different countries, the Distribution Functioning Code must be respected.
- Overloads: The PVs cause overloads of the feeder elements (lines and transformers). The results obtained from this work show a need to increase the cross-section of the first part of the main feeder line, in order to generally avoid overloads. However, if the generation and load are the same, there is no need for repairs.
- Losses: For maximum load, if the focus is on the reduction of total losses, the best way is to install PV in the second half of the feeder. This is more dedicated to the reduction of line losses than the transformer. Meanwhile, for minimum load, it is better to install PV in the first half of the feeder (for maximum generation) or along its entire length (for minimum generation). It is worth noting that there are other ways to reduce the total losses in the feeder, such as replacing some old transformers or upgrading the operating feeder voltage from 10 kV to 20 kV (voltage level used a lot in recent years in the Albanian distribution system).
- Power Flows: If PV output exceeds the feeder load, it causes a reverse power flow in it. This happens especially in the case of maximum generation. For this reason, it is important to study local meteorological conditions, which affect PV production. Meanwhile, a worse case would be if, in addition to maximum generation, the load is minimal. This large energy surplus would increase losses and cause overvoltages. It is again worth noting that for maximum load, PV should be installed in the second half of the feeder. The opposite occurs for minimal load.

The future work will evaluate the impact of wind turbines on distribution system parameters.

NOMENCLATURE

Symbols

P	active power	[kW]
P_L	line losses	[kW]
P_{PT}	total power transformer losses	[kW]
P_{PV}	output power of solar PV	[kW]
Q	reactive power	[kVAr]
V	voltage	[p.u.]

Abbreviations

ADFC	Albanian Distribution Functioning Code
DSO	Distribution System Operator
HPP	Hydro Power Plant
Max/G	Maximum Generation
Max/L	Maximum Load
Min/G	Minimum Generation
Min/L	Minimum Load
p.u.	Per unit
RESs	Renewable Energy Sources
Solar PVs	Solar Photovoltaics

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