Impacts of Photovoltaics in Low-Voltage Distribution Networks. Case Study, Malta

Yesbol Gabdullin; Brian Azzopardi

Published in: Energies

Publication date: In Press

Document Version

Peer Reviewed

Citation for published version (IEEE format):

Y. Gabdullin, B. Azzopardi, "Impacts of Photovoltaics in Low-Voltage Distribution Networks. Case Study, Malta," Energies, in press.

energies

MDPI

Type of the Paper (Article)

Impacts of Photovoltaics in Low-Voltage Distribution Networks: Case Study - Malta

Yesbol Gabdullin [1] and Brian Azzopardi [1,2] *

[1] MCAST Energy Research Group, Institute for Engineering and Transport, Malta College of Arts, Science and Technology (MCAST), Malta;
[2] Azzopardi & Associates Consulting Firm, Malta;
* Correspondence: brian.azzopardi@mcast.edu.mt;

Abstract: Photovoltaic systems (PVs) are promising low-carbon technologies playing a major role in the electricity business. In terms of voltage variation and feeder usage capacity, high PV penetration levels have significant technical implications for grid stability, particularly in Low Voltage (LV) networks. This paper presents a comprehensive PV integration analysis on real-life residential LV networks in Malta using recorded smart metering data. The methodology framework and tools developed are highlighted through step by step results on their usefulness. First, at the substation level, an LV network with seven LV feeders is analyzed using Monte Carlo simulations and OpenDSS. Then, Cumulative Distribution Functions (CDFs) are extracted to establish the likelihood of LV network challenges. Afterwards, 95 multi-feeder analysis assesses impact assessment on the first occurrence of LV network challenges and predominant issues. Finally, a Regression Analysis Tool, considering the regression's standard error, is built for seven feeder characteristics to predict impacts. The stochastic processes reveal strong relationships with feeder characteristics that are helpful for network planning and operations. However, the Maltese grid currently has less than 20% PV penetration at any LV feeder. Hence significant technological hurdles are absent.

Keywords: Photovoltaic systems (PVs), Low Voltage (LV) networks, Stochastic processes, Monte Carlo methods, Optimal Power Flow

Citation: Lastname, F.; Lastname, F.; Lastname, F. Title. *Energies* **2022**, *15*, x. https://doi.org/10.3390/xxxxx

Academic Editor: Firstname Lastname

Received: date
Accepted: date
Published: date

1. Introduction

FUTURE-PROOF electrical energy and power networks become more sustainable with well-integrated Distributed Generation (DG) units [1]. Decarbonization, digitalization, decentralization and disintermediation are key drivers of disruption for energy utilities. Voltage variation and feeder utilization level in Low Voltage (LV) electric networks (<1kV) are the first major challenges addressed by the utilities. These challenges are especially exhibited during peak DG generation, and low consumption causes reverse power flows which may degrade the network stability [2], raise voltages [3]–[13] and cause overloading [7], [9], [10].

Photovoltaic systems (PVs) are extremely promising low-carbon technologies playing a major role in the electricity industry. The PV market has the fastest annual growth rate of around +30% [14]. The EU's PV capacity increased to 166GW in 2021 around 17% of global installed PVs [15]. Therefore, unique impact studies based on large electric networks considering real-case scenarios and smart meter data enrich our insights on PV integration in LV distribution networks. These studies are especially important in Malta, a solar country that has set its PV support programme as the most proven to expand the PV market. The Maltese PV support programme guarantees tariffs to all potential developers and attractive financial security that cover developers' costs with long-term certainty [16].

Located centrally in the Mediterranean Sea, Malta is the southmost EU country and receives the highest EU solar irradiance. As an island state, Malta presents a unique scenario over its just above 316 km2 surface area, dense population of 1,300pp/km^2 and over 300,000 utility customers that enjoyed the first nation roll out of smart meters worldwide. PV installations have reached 184.6MWp of the total PV capacity, mostly from residential units that are usually less than 3.1kWp systems connected to LV networks [17].

While a variety of definitions of high penetration are suggested, throughout this work, the term 'high penetration' will be used to refer to the level at which an electric distribution network has a high probability of experiencing thermal and voltage violations. The penetration level in this paper is defined as the number of consumers with PV connected to the total number of consumers. No PV case means 0% penetration, whereas if all houses were to integrate PV, the penetration level would be 100%.

Many studies have investigated the potential impacts of PV integration on distribution networks. A summary of some of the studies is in Table 1. For instance, the impacts

Table 1. Summary of PV impact studies

Ref	Network	Simulation/ analysis technique	Conclusions
[3]	Test LV Network	Unbalanced three-phase load flow	A penetration level of 50% does not increase the voltage significantly on a typical UK Network; peak loadings are unaffected
[4]	Real LV networks in Sweden	Power flow, stochastic approach	No violations in voltage limits for any network; larger variation in a rural network
[6]	Representative LV feeder	Time series power flow (MATLAB/Simulink)	Voltage violation occurs in the time between 11 a.m. and 2 p.m.
[7]	128 real UK LV feeders	Time-series unbalanced power flow (OpenDSS)	PV integration produced problems in 47% of the feeders.
[8]	One representative LV network	Unbalanced Probabilistic load flow (time-series)	The reactive power consumed by the PV inverter can decrease the overvoltage probabilities during critical situations and increase the power losses.
[18]	Representative LV network	Balanced three-phase load flow	Distribution networks can host large amounts of embedded generation with some changes in the setting of the no-load voltage
[9]	Real UK LV network	Unbalanced three-phase power flow (OpenDSS)	Longer feeders present more problems. No impacts up to 20% PV penetration
[10]	2 real UK LV networks	Unbalanced three-phase power flow (OpenDSS)	Voltage problems occur at 40% penetration. No issues for short feeders
[12]	Modified IEEE 130-bus test system	Balanced three-phase load flow (MATLAB/Simulink)	Voltage problems and reverse power flows were investigated for distributed generators – mitigations using STATCOM
[13]	LV CIGRE Residential Network	PSCAD	compares six techniques to increase the PV penetration limit in the LV residential network

of PV integration on voltage profile and feeder utilization were assessed, respectively.

However, most studies were carried out on representative networks [3], [6], [8], [11-12], [18]. Representative network studies provide a basic understanding of the problems that may occur but cannot be applied to other networks. In addition, it does not provide information on the proportion of LV networks experiencing technical problems.

Furthermore, studies [3], [4], [6]–[10] were based on solar irradiance measurements, which are not always available for utilities and do not consider the efficiency of cells.

Based on this review, the following considerations are outlined to investigate the impacts of PV integration on LV networks adequately:

i. realistic and adequate LV networks based on the geographical region of interest
ii. time-series analysis to cater for the time-varying nature of residential loads and PVs, and
iii. multiple LV feeders' analysis to cater for their diversity; this will allow analyzing of the parameters of the feeders that can explain the occurrence of technical problem

Using Monte Carlo methods, this work embeds the uncertainties of residential loads and PVs related to size and behaviour. The real Maltese LV networks analysis considers smart meter residential load and PV profiles in 15-minute resolution.

The aim is to deliver the first thorough case study based on smart metered home loads and PV generating profiles in Malta. The methodology uses a stochastic scenario-based Monte Carlo framework. Each scenario is evaluated for EN50160 voltage difficulties (or voltage boundaries) and feeder capacity.

The paper is structured as follows. Section II describes the methodology base framework of the study. Then Section III presents the application of the methodology base framework through an impact analysis on one real-life Maltese LV network from one 11/0.4kV substation with seven LV feeders. The likelihood of LV Network challenges is discussed through the extracted Cumulative Distribution Function (CDF) within the Monte Carlo methods in Section IV. Afterwards, the comprehensive real-life Maltese 95 LV multi-feeder impact analysis results are presented and discussed in Section V. Then, in Section VI, a regression analysis tool and its results are highlighted. Finally, Section VII presents the main conclusions and a key finding distinctive from previous studies on the inadequate metric for non-linear regression.

2. The Methodology-Based Framework

OpenDSS performs three-phase unbalanced time-series power flow [19]. Figure 1 depicts the framework for studying PV penetration on LV networks based on size and behaviour uncertainties. First, LV feeder computer models are created, and then smart meter load and PV profiles are loaded. A Monte Carlo simulation is run for a specified feeder. Multiple power flows for each PV penetration (from 0% to 100% in 10% steps) are evaluated. Each power flow study uses a random load and PV profile from the pool of profiles. Each simulation's effect analysis measure (utilization factor, proportion of users with voltage issues) is saved. On finalizes by correlating many feeders to find feeder attributes that may explain technical concerns.

2.1. Smart meter profiles

The widespread use of PV systems necessitates a clear need for long-term knowledge of LV networks. In the world's first deployment of a nationwide smart-meter infrastructure, Malta's energy company Enemalta plc reached 90% of its customers by 2014. Enemalta plc is the owner and manager of the LV networks.

Based on data provided by smart meters, a probabilistic methodology is used in this study. [11], [20] and no more on solar irradiance measurements as in [3], [4], [6]–[10]. The

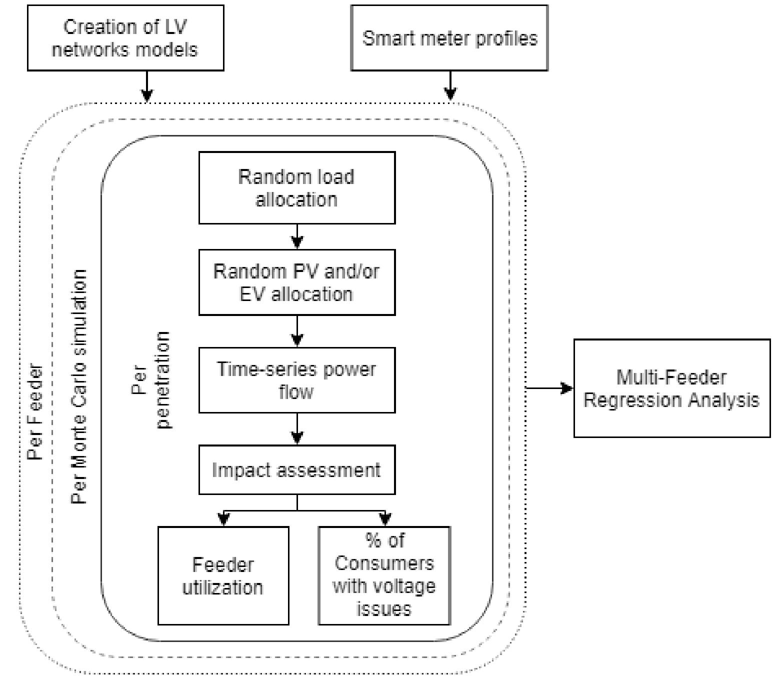


Figure. 1. Methodology Base Framework

profiles comprise 2000 PV profiles and 5000 residential, domestic, and commercial loads. Figure 2 presents the average profile for residential consumers and PV generation.

Weekdays often have low noon demand, which falls during the peak time for PV generation. These circumstances present the grid with its most significant challenge regarding voltage stability since they could result in reverse power flows that go up toward the transformer. After reviewing the data profiles, a day in April was selected since April is a month with high PV generation due to favourable weather. It is sufficient to depict the worst-case scenario of PV generation. Hence only one day was used in the simulation.

2.2. Impact Assessment

The methodology outlined in this work employs Monte Carlo simulations to account for PVs' size and behaviour uncertainties. For the following two PV allocation scenarios, 100 simulations are conducted with 11 penetration levels ranging from 0% to 100% in 10% increments:

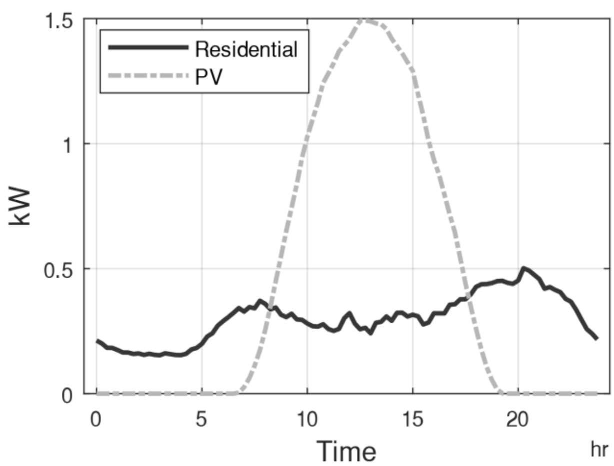


Figure. 2. Average profile for residential consumers and PV generation

i. Downstream: PVs are allocated from the substation down to the furthest consumer
ii. Upstream: PVs are assigned from the last consumer to the transformer

These allocation scenarios are employed to cater for worst-case scenarios to identify the boundaries of LV networks.

It is crucial to realize that because PV generation and electricity consumption vary over time, technical consequences change during the day. Therefore, when quantifying, technological concerns, this needs to be taken into account. Two in-dice are shown in the impact evaluation for this reason.

i. *Voltage issues*: This index uses the voltage calculated for each customer to determine whether it complies with European Standard EN50160 (the voltage magnitude should be within 230V +/- 10%). [21], that is, the violation is flagged when the voltage is below 207V or above 253V. Throughout this work, the term 'voltage issues/problems' or 'voltage challenges' refers to voltage violation in terms of voltage magnitude, typically overvoltage due to reverse power flows caused by high penetration of PV integration. A consumer is said to have a problem if they are not compliant. The percentage that corresponds to the total number of consumers experiencing voltage problems is determined. Since the profiles have a resolution of fifteen minutes, violating the restriction by even one value would be against the EN50160 standard.
ii. *Feeder utilization*: calculated by dividing the maximum current by the head of the feeder's ampacity. This index illustrates how the LV feeder is used at various levels of penetration.

3. Application of the Methodology Framework

3.1. Real-life Maltese LV Network

The impact analysis is highlighted with the application of the methodology framework for one real-life Maltese LV network from one 11/0.4kV substation with seven three-phase LV feeders, as illustrated in Figure 3. The LV network's main characteristics are listed in Table 2 based on Geographic Information System (GIS) modelling considering conductor characteristics, location of consumers, phase connectivity and network topology. LV Feeder 4 was chosen to highlight the per feeder results as it is regarded as the most loaded feeder in this case.

Figure. 3. The real-life Maltese LV network with seven feeders

3.2. Summary of Results for Real-life Maltese LV Network

Table 3 summarises the results for all seven (7) feeders. The results depict the first occurrences of technical challenges due to PV penetration. For utilization capacity, 70% threshold was selected to indicate potential limitations in headroom capacity for operational tasks.

3.3. Voltage Issues

The number and corresponding percentage of consumers with voltage issues are analyzed, and the mean value and its standard deviation are depicted using Monte Carlo simulations. Figure 4 (a) presents the consumers with voltage problems with different PV penetrations. The range of impacts can be clearly observed between downstream and upstream allocation scenarios. For instance, the percentage of consumers with voltage problems is below 10% and around 40% at 50% PV penetration for downstream and upstream scenarios, respectively. As can be seen, the voltage issues start on average at 20% and 50% PV penetration for upstream and downstream allocation scenarios, respectively.

3.4. Utilization

Figure 4 (b) presents the average utilization factor and its corresponding standard deviation at the head of the feeder for both allocation scenarios. As expected, there is a slight variation between downstream and upstream scenarios. The initial loading level is at 70% on average. It decreases as more PV units are connected. This decrease means that the household demand is partly supplied by the local generation, and reverse power flows are lower than the base case, 0% PV penetration. However, this decrease is negligible because the peaks of consumption and generation do not coincide, as presented in Figure 2.

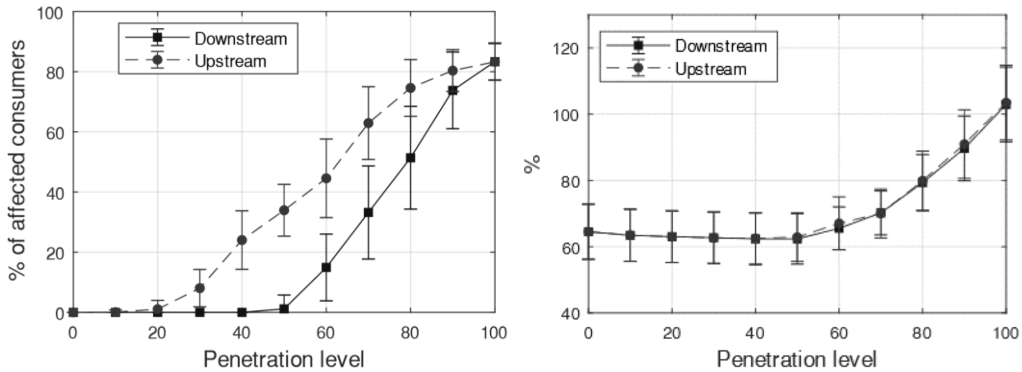
The utilization factor starts to increase after 50% PV penetration. At 60% of penetration, the utilization exceeded the base case meaning that reverse power flows are more significant than with no PV case. The feeder capacity is surpassed on average at 90% of penetration.

Table 2. Main characteristics of LV Networks

Feeder	Total Length (m)	No of loads	Phase connectivity		
			Phase 'blue'	Phase' red	Phase 'yellow'
1	1706.3	121	0.31	0.39	0.3
2	461.9	30	0.33	0.33	0.33
3	1558.1	128	0.294	0.319	0.387
4	1391.4	146	0.28	0.372	0.348
5	1015.6	83	0.351	0.378	0.271
6	778.1	71	0.354	0.384	0.262
7	565.2	50	0.25	0.375	0.375

Table 3. Summary of penetration levels, technical challenges thresholds

Feeder	Technical challenges due to PV penetration			
	Voltage issues Downstream	Voltage issues Upstream	Utilization factor >70% Downstream	Utilization factor >70% Upstream
1	30%	20%	80%	80%
2	-	-	-	-
3	50%	30%	70%	70%
4	50%	30%	70%	70%
5	60%	40%	100%	100%
6	80%	40%	-	-
7	-	-	-	-



(a) (b)

Figure. 4. Feeder 4 results: (a) consumers with voltage issues and (b) feeder utilization capacity

3.5. Conclusion on Single LV network Analysis

Although the findings are limited to only one LV network, it can be observed that relatively short feeders with few loads do not present any technical problems. On the other hand, more loaded and longer feeders are more likely to present technical challenges at some penetration level. Finally, it is important to note that until 10% of penetration, no voltage and utilization problems were observed. However, to truly investigate these technical problems on different LV feeders, a multi-feeder assessment is performed in Section 4.

4. Likelihood of LV Network Challenges

The impact analysis presented in previous sections can be extended given its stochastic nature by extracting the Cumulative Distribution Function (CDF) to demonstrate the probability of experiencing voltage or utilization capacity issues. This tool is used to conclude whether a given PV penetration level causing technical problems is acceptable. Quantifying this probability can help utility companies to determine whether it is feasible to accept penetration levels representing low probabilities of technical challenges instead of investing in infrastructure.

Given empirical data, i.e. results for 100 simulations, an empirical CDF is chosen. It is similar to CDF. That is, they are both probability models for data. However, empirical CDF models observed data, whereas CDF is a hypothetical distribution model.

Empirical CDF assigns a probability of 1/n and calculates the sum of these probabilities up to and including each datum. The result is a step function increased by 1/n with at each step.

Let X be the percentage of consumers with voltage violations. Figure 5 illustrates the CDFs representing the probability of having at least x% of consumers with voltage issues for downstream and upstream allocation scenarios. For downstream allocation, it suggests that the likelihood of having more than 20% (0.2) of consumers with voltage issues is about 0.2, 0.85 and 0.95 at 50%, 60% and 70% of penetration levels. In contrast, the likelihood of no consumers with voltage issues is 0.4 and 0.75 probability for 50% and 20% penetration levels for downstream and upstream PV allocation scenarios.

Figure 6 presents the mean percentage of consumers with voltage violations +/- one standard deviation on Feeder 4 and the probability of having more than 1% of consumers with voltage problems for each penetration level. For a downstream scenario, the likelihood of having more than 1% of consumers with voltage problems is around 0.1 at 50% of the penetration level. In comparison, at least 1% of consumers with voltage issues above 70% PV penetration. For upstream PV allocation scenario, it is a more conservative case where above 40% of penetration level there are always at least 1% of consumers with voltage issues.

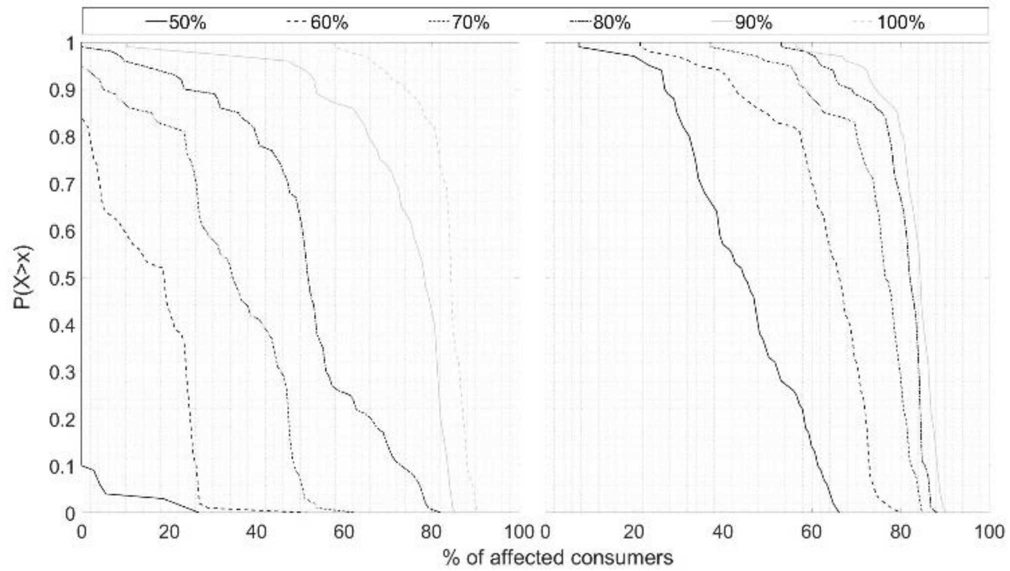


Figure. 5. Feeder 4 CDFs results: voltage issues

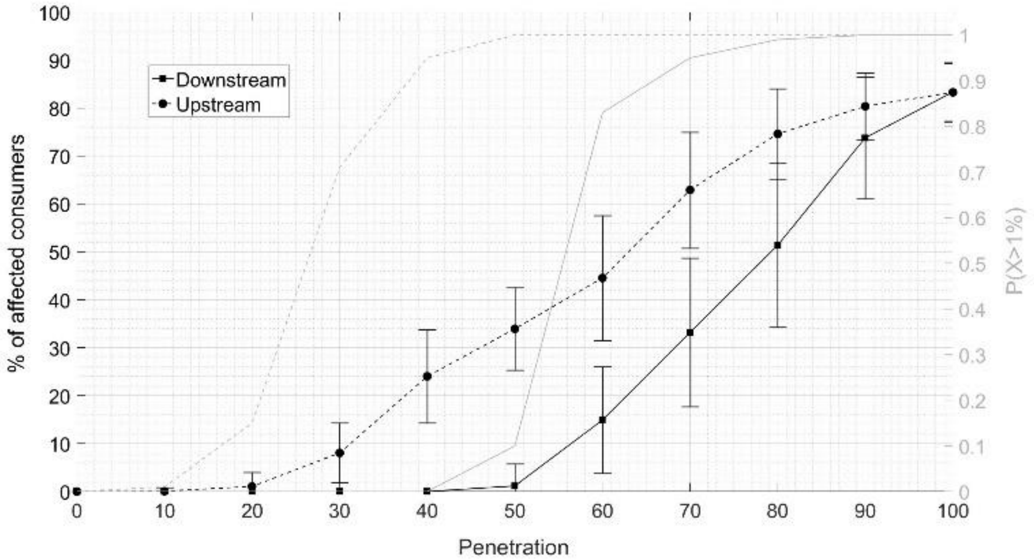


Figure. 6. Feeder 4 Probability of voltage issues

Let Y be the utilization factor at the head of the feeder. For example, Figure 7 suggests that the probability of surpassing loading capacity (utilization factor > 1.0) is 0.55 at 90% PV penetration and 0.95 at 100% of penetration level. Meanwhile, the likelihood of surpassing loading capacity is close to zero for 80% and 70% penetration levels for downstream and upstream PV allocation scenarios.

Figure 8 presents the probability of a utilization factor higher than 1.0 (>100%) and the average percentage +/- one standard deviation. For 95% PV penetration, the probability of exceeding cable ratings is about 0.5 and negligible probability of occurrence before 80% penetration.

5. Multi-feeder Impact Analysis

The first-ever comprehensive real-life Maltese LV multi-feeder stochastic impact analysis results are summarised and discussed in this section.

A voltage violation is flagged if the feeder's probability of having more than 1% of consumers with voltage issues (+X) is higher than a certain threshold α, that is $P(X \geq 1) \geq \alpha$.

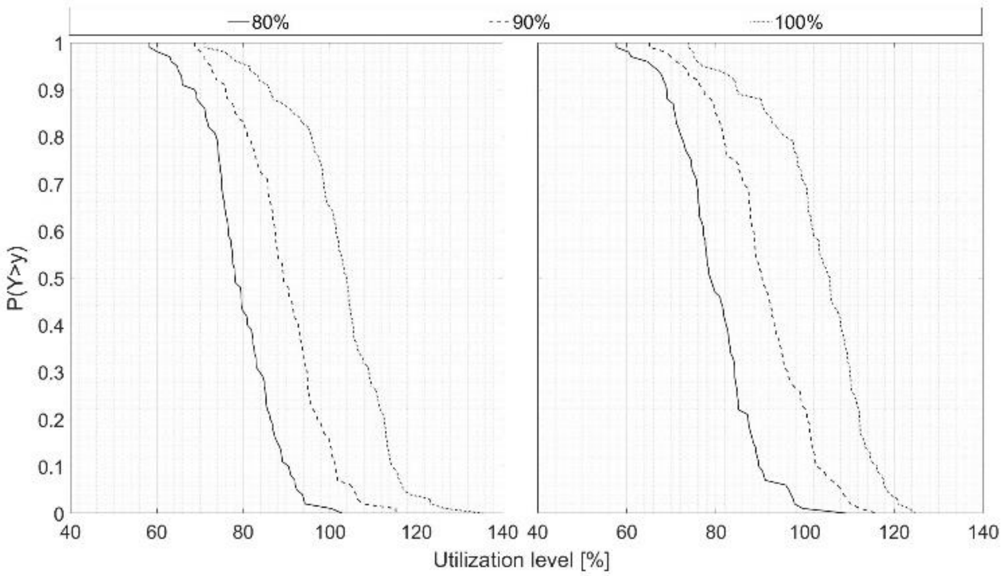


Figure. 7. Feeder 4 CDFs results: utilization capacity level

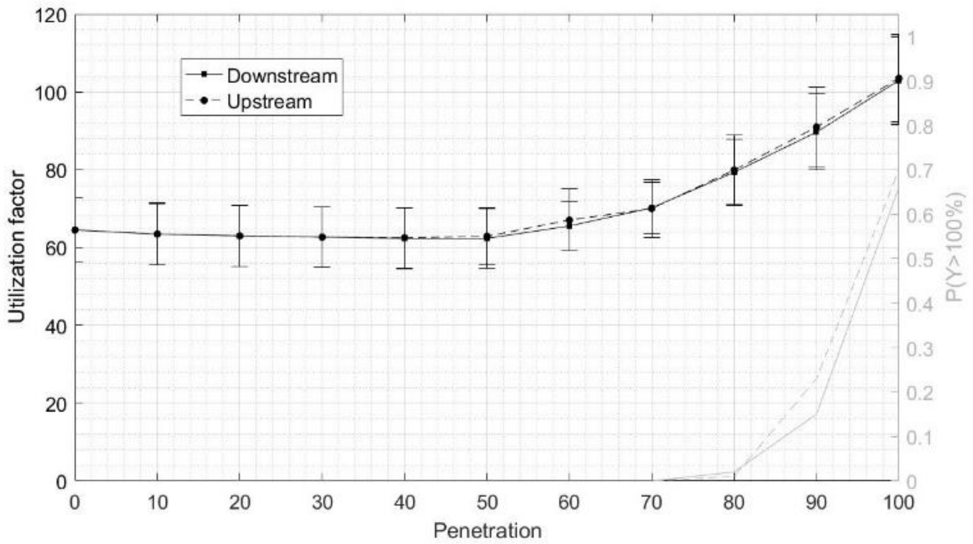


Figure. 8. Feeder 4: the probability of utilization factor higher than 1.0 (>100%)

The utility company sets this threshold according to its acceptance of potential technical problems. Meanwhile, a feeder is considered overloaded if the probability of having a utilization factor above 100% of the rated feeder capacity is higher than α, that is, $P(Y>100)\geq\alpha$.

Hence, if the utility set α to zero, technical issues are recorded immediately after one of the simulations presents a flagged case. On the other hand, if α is set to 0.05, the technical issues are recorded if at least 5% of the simulations present flagged issues.

Table 4 summarises this multi-feeder analysis for the percentage of feeders with voltage and utilization capacity issues for two thresholds: conservative $\alpha = 0$ and $\alpha = 0.05$. The latter threshold is commonly acceptable by utilities. For the conservative scenario, about 80% and 36% of the feeders recorded at any simulation and penetration level voltage and utilization capacity technical issues, respectively. The predominant technical issues emerged as voltage issues rather than utilization capacity issues. The latter technical issue is seen at close to very high penetration levels.

Table 4. Percentage of feeders with technical problems

Allocation scenario	α = 0		α = 0.05	
	Voltage problems	Overloading	Voltage problems	Overloading
Downstream	78.3	37.4	75.7	31.3
Upstream	80.9	34.8	78.3	29.6

5.1. *First Occurrence of LV network challenges*

The first occurrence of LV network challenges provides a deeper investigation of PV penetration impact assessment. This section demonstrates the histograms of the penetration level at which feeders start experiencing technical problems. The penetration level is calculated in (1) and (2).

$$p_1 \equiv \{\min(p_i) \in Q \mid P(X(p_i) \geq 1) \geq \alpha\} \quad (1)$$

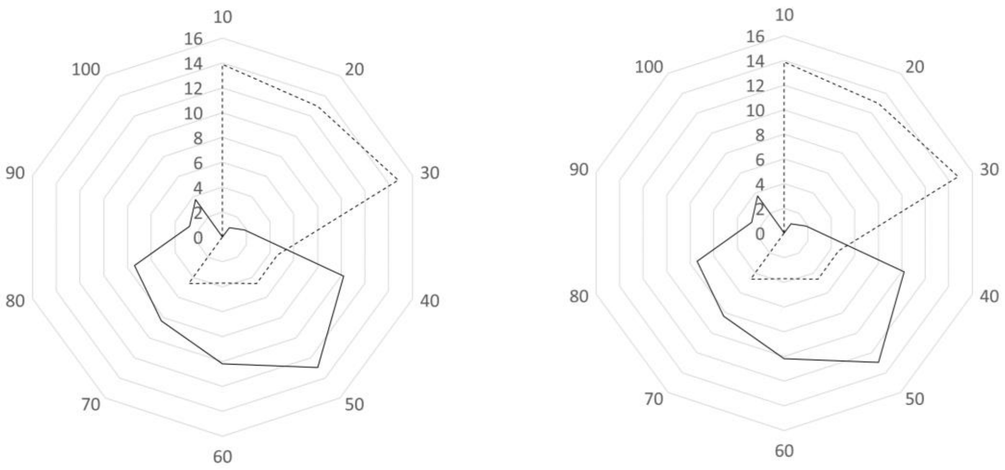
$$p_2 = \{\min(p_i) \in Q \mid P(Y(p_i) > 100) \geq \alpha\} \quad (2)$$

where Q is the set of penetration levels (0% to 100%), and pi is the penetration level i. Therefore, p1 and p2 represent the first penetration level where voltage or overloading issues are experienced.

Figure 9 illustrates the result of the first occurrence of LV network challenges considering the most conservation threshold recorded, α = 0.05, that is, recording at any simulation and penetration level voltage and utilization capacity technical issues.

6. Regression Tool for Impact Predictions

Regression analysis is an extremely powerful tool in network planning and operation. The regression results can benefit utilities about the hosting capacity insights of Maltese LV networks. As a result, the utility may assess and even predict the technical challenges of future high PV penetration levels and identify the boundaries of PV hosting capacity on specific LV network characteristics without running power flow analysis. The parameters with the best fit are plotted. The standard error of the regression, also known as the standard error of the estimate, is a preferred measure of the goodness-of-fit in this study over the coefficient of determination, R^2, as S can be used both for linear and non-linear models, unlike R^2, which is not valid for non-linear models [15].



(a) (b)

Figure. 9. First occurrence of voltage (a) and utilization (b) capacity issues in downstream (fixed) and upstream (dashed) scenarios (α = 0.05)

5.1. Defining Characteristics of LV Feeders

The seven investigated feeder characteristics are defined as follows:

i. Feeder Length: Total length of the feeder, including both underground and overhead cables,
ii. Number of consumers: Total number of consumers supplied per feeder,
iii. Total path resistance (TPR): Sum of all resistances between the busbar and each consumer. TPR is calculated as shown in (3)

$$TPR = \sum_{i=1}^{N} path\ resistance_i \quad (3)$$

where TPR is the Total Path Resistance, N is the total number of consumers and path resistance is the resistance between the busbar and consumer i,
iv. Initial utilization factor: The mean value of the utilization factor is the maximum current divided by its corresponding ampacity at the head of the feeder from 100 simulations without any PVs integrated,
v. Main path: Distance between busbar and furthest consumer,
vi. Main path resistance (MPR): Sum of all resistance in the main path, that is, between the substation and the last consumer, and
vii. Total resistance: Sum of all feeder resistances, including underground and overhead cables.

It is important to note that complex impedance is not calculated, and only resistance is considered as calculating resistance is a more straightforward and less expensive approach for the utility to implement.

5.2. Regression Analysis Tool Methodology

The regression analysis is performed for PV integration by considering seven investigated feeder characteristics and plotting them against the penetration at which problems occur, considering thresholds for potential technical issues α=0 and α=0.05. Hence, (4) calculates the minimum penetration at which feeders experience technical challenges.

$$p_{min} = \min\{p_1, p_2\} \quad (4)$$

where p_1 and p_2 refer to voltage and utilization capacity issues, respectively. Afterwards, a regression analysis is carried out to identify the best fit using the standard error of the regression (S) as a metric.

Since more than 20% of the feeders did not present any issues for any of the simulations for any of the penetration levels up to 100%, additional penetration levels are investigated. Therefore, 31 penetration levels are studied from 0% to 300% in steps of 10%. This means that a house can integrate multiple PV units at the same time.

The Assessment of penetration levels beyond 100% will give valuable information that can be included in regression analysis because it allows identifying penetration level that triggers a technical challenge in the feeder. Hence, this will result in more accurate estimates.

5.3. Regression Tool Analysis

The regression analysis is scattered data points representing the results of each studied LV feeder plotted. The scattered data points are plotted on the PV penetration levels at which the impact assessment records the first occurrence of LV network challenge against the characteristics of LV Feeders.

For example, in Figures 10 and 11, feeders with more consumers present earlier technical challenges at lower PV penetration levels than those having fewer customers. The S is used to test the strength of this conclusion. In this case, S is 39.1 and 45.1 for downstream and upstream allocation scenarios, respectively. This means that the average distance of the data points from the fitted line is about 39% and 45% of the penetration level for downstream and upstream allocation scenarios, respectively.

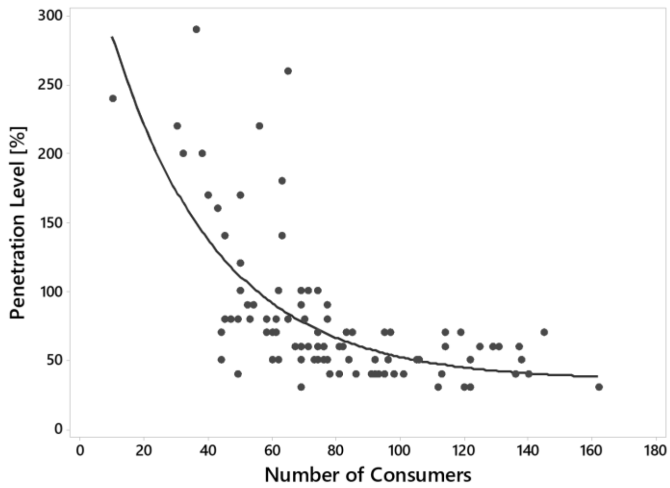


Figure. 10. Regression analysis – Penetration vs Number of consumers (Downstream allocation scenario)

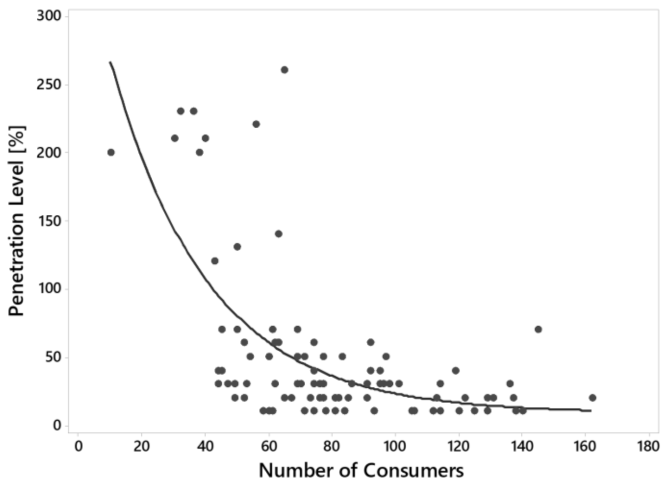


Figure. 11. Regression analysis – Penetration vs Number of consumers (Upstream allocation scenario)

This means there is an error of a maximum of 3 steps in 31 steps PV simulated penetration levels. The smaller S, the stronger the relationship.

Table 5 summarises the regression analysis results standard error of regression for each parameter for both downstream and upstream allocation scenarios. Since the results for both thresholds are similar, only the corresponding S is shown for α=0, the most conservative threshold. This table suggests that the parameters with the strongest relationships are the Feeder Length, Total Path Resistance and Total Resistance. The former embeds the overall resistance of the feeders. Hence there is a good relationship with the possible voltage rises in the case of PV integration.

7. Conclusion

This article introduces the first of its type in Malta, a real-world LV network multi-feeder effect analysis and regression analysis tool for PV integration. In the upcoming ten years, photovoltaics (PVs), a very promising developing technology, are anticipated to have a big impact on the electrical sector. Malta will most definitely not be left out as a solar priority nation.

Table 5. Standard error of regression for each parameter

Parameter	Downstream	Upstream
Feeder Length	25.5	31.9
No of Consumers	39.1	45.1
Total Path Resistance	25.0	33.1
Initial loading	38.1	44.8
Main Path	43.5	45.7
Main Path Resistance	44.0	45.7
Total Resistance	29.4	35.6

Limited studies on PV integration on LV distribution networks exist, and only a few studies carried out regression analysis. Furthermore, previous studies implemented inadequate metrics (coefficient of determination, R^2) to assess the goodness-of-fit for non-linear model. It was shown that the coefficient of determination is an inadequate metric for non-linear regression. However, it is widely used in scientific literature. This work presented the first study with an adequate metric, the standard error of the regression, *S*, implemented to examine the goodness of fit of the non-linear model.

The methodology was thoroughly shown by utilizing the OpenDSS for power flow analysis and the Monte Carlo Technique on a real three-phase LV distribution network with seven feeders. After that, the Cumulative Distribution Function (CDF) is retrieved to show the likelihood of experiencing voltage and utilization issues. The findings show that voltage problems are the 'bottleneck' for PV integration. Following that, a multi-feeder impact evaluation revealed tendencies in the early detection of network issues. This prompted the development of a regression analysis tool for utilities to establish relationships between various parameters, including feeder length, consumer count, total path resistance, main path resistance, initial utilization level, total resistance, and the occurrence of technical issues for the first time, to investigate why some feeders exhibit technical issues more frequently than others.

Significant technical hurdles are not yet evident because PV penetration levels are currently lower than 20% at any LV feeder in the Maltese network. The results demonstrate that voltage concerns are more restricting while limited utilization capacity issues are encountered, typically at high penetration levels. The results have evaluated worst-case scenarios to define the network boundaries. Due to pre-existing infrastructure, this article illustrates profiles similar to earlier studies in the literature but with significantly fewer PV integration problems.

Author Contributions: Conceptualization, methodology, formal analysis, writing, Yesbol Gabdullin and Brian Azzopardi; software, validation, writing—original draft preparation, Yesbol Gabdullin.; visualization, supervision, project administration, funding acquisition, Brian Azzopardi. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported in part by the European Commission H2020 TWINNING JUMP2Excel (Joint Universal activities for Mediterranean PV integration Excellence) project under grant 810809, and the Malta Council for Science and Technology (MCST) 3DMgrid (Design, Development and Demonstration of a Smart Micro-Grid) project under grant ENM-2016-002a and EDGE-WISE (Energy and Water Systems Integration and Management) project under grant ENM-2016-001 through the ERANETMED initiative of Member States, Associated Countries and Mediterranean Partner Countries.

Acknowledgments: The authors gratefully acknowledge Enemalta PLC for the availability of real-life Maltese LV Networks and smart meter data profiles. In addition, the authors would like to thank Inġ. Carmel Xerri, Inġ. George Portelli and Mr Karl Cilia for their work in reviewing the final version of this paper.

Conflicts of Interest: The authors declare no conflict of interest.

References

[1] B. Azzopardi and A. Gabriel-Buenaventura, "Feasibility assessment for high penetration of distributed photovoltaics based on net demand planning," Energy, vol. 76, pp. 233–240, Nov. 2014.

[2] S. Conti, S. Raiti, G. Tina, and U. Vagliasindi, "Integration of multiple PV units in urban power distribution systems," Solar Energy, vol. 75, no. 2, pp. 87–94, Aug. 2003.

[3] M. Thomson and D. G. Infield, "Impact of widespread photovoltaics generation on distribution systems," IET Renewable Power Generation, vol. 1, no. 1, p. 33, 2007.

[4] J. Widén, E. Wäckelgård, J. Paatero, and P. Lund, "Impacts of distributed photovoltaics on network voltages: Stochastic simulations of three Swedish low-voltage distribution grids," Electric Power Systems Research, vol. 80, no. 12, pp. 1562–1571, Dec. 2010.

[5] R. Tonkoski, D. Turcotte, and T. H. M. El-Fouly, "Impact of High PV Penetration on Voltage Profiles in Residential Neighborhoods," IEEE Transactions on Sustainable Energy, vol. 3, no. 3, pp. 518–527, Jul. 2012.

[6] S. Ali, N. Pearsall, and G. Putrus, "Impact of High Penetration Level of Grid-Connected Photovoltaic Systems on the UK Low Voltage Distribution Network," Renewable Energy and Power Quality Journal, pp. 519–522, Apr. 2012.

[7] A. Navarro-Espinosa and L. F. Ochoa, "Probabilistic Impact Assessment of Low Carbon Technologies in LV Distribution Systems," IEEE Transactions on Power Systems, vol. 31, no. 3, pp. 2192–2203, May 2016.

[8] F. Demailly, O. Ninet, and A. Even, "Numerical Tools and Models for Monte Carlo Studies of the Influence on Embedded Generation on Voltage Limits in LV Grids," IEEE Transactions on Power Delivery, vol. 20, no. 3, pp. 2343–2350, Jul. 2005.

[9] P. Mancarella, D. Randles, A. Navarro, and L. F. Ochoa, "Impacts of photovoltaics on low voltage networks: a case study for the north west of England," 2013, pp. 1419–1419.

[10] A. Navarro, L. F. Ochoa, and D. Randles, "Monte Carlo-based assessment of PV impacts on real UK low voltage networks," 2013, pp. 1–5.

[11] Y. Gabdullin, B. Azzopardi, C. Xerri, K. Cilia, and G. Portelli, "Solar Photovoltaics Penetration Impact on a Low Voltage Network: A Case Study for the Island of Gozo, Malta."

[12] A.S. Akinyemi, K. Musasa, and I.E. Davidson, Analysis of voltage rise phenomena in electrical power network with high concentration of renewable distributed generations. Sci Rep 12, 7815 (2022).

[13] M. Wajahat, H.A. Khalid, G.M Bhutto, C. Leth Bak, A Comparative Study into Enhancing the PV Penetration Limit of a LV CIGRE Residential Network with Distributed Grid-Tied Single-Phase PV Systems. Energies 2019, 12, 2964.

[14] G. Masson, and I Kaizuka, “Trends in Photovoltaic Applications 2021” International Energy Agency: Photovoltaic Power Systems Programme, Report IEA PVPS T1-41:2021.

[15] A. Jaeger-Waldau “Snapshot of photovoltaics – February 2022, EPJ Photovolt. Vol. 13 2022.

[16] V. Matulaitis, G. Straukaitė, B. Azzopardi, and E. A. Martinez-Cesena, "Multi-criteria decision making for PV deployment on multinational level," Solar Energy Materials and Solar Cells, vol. 156, no. Supplement C, pp. 122–127, Nov. 2016.

[17] NSO Malta, "Renewable Energy from Photovoltaic Panels (PVs): 2020" News Release June 2021.

[18] F. Vallée, V. Klonari, T. Lisiecki, O. Durieux, F. Moiny, and J. Lobry, "Development of a probabilistic tool using Monte Carlo simulation and smart meters measurements for the long term analysis of low voltage distribution grids with photovoltaic generation," International Journal of Electrical Power & Energy Systems, vol. 53, pp. 468–477, Dec. 2013.

[19] R. C. Dugan and T. E. McDermott, "An open source platform for collaborating on smart grid research," 2011, pp. 1–7.

[20] Y. Gabdullin and B. Azzopardi, "Impacts of High Penetration of Photovoltaic Integration in Malta," in 2018 IEEE 7th World Conference on Photovoltaic Energy Conversion (WCPEC) (A Joint Conference of 45th IEEE PVSC, 28th PVSEC & 34th EU PVSEC), Waikoloa Village, HI, 2018, pp. 1398–1401.

[21] British Standards Institution, "EN 50160: Voltage Characteristics of Electricity Supplied by Public Distribution Systems," 2000.