Impact of Grid-Connected Photovoltaic Distributed Generation on a 66 kV Sub-Transmission Network in Southern Libya: A Case Study

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***Abstract*—This paper investigates the integration of a 5 MW photovoltaic (PV) distributed generation (DG) system into the 66 kV Tragan sub-transmission network in southern Libya, a weak grid with poor voltage performance and high reactive power demand. The PV system is sized using PV*SOL, while load flow and contingency analyses are carried out using NEPLAN.**

The results show that PV-DG significantly improves network performance. Real power losses are reduced by 30.6% (from 3.501 MW to 2.429 MW), while the minimum bus voltage increases from 90.4% to 97.8%, eliminating all five voltage violations. Under N-1 contingency conditions, the minimum voltage during transformer outage improves from 87.2% to 94.2%, satisfying operational limits.

The analysis also shows that PV alone cannot fully support the evening peak, and a 3 MW/6 MWh battery is recommended. Furthermore, an economic assessment based on actual generation cost gives a payback period of 6.5 years, and a negative carbon abatement cost (–$149/tCO$_2$). Environmentally, annual CO$_2$ emissions are reduced by 4,813 tons.

Overall, the study confirms that PV-DG is a practical and effective solution for improving weak desert networks such as Tragan, although battery storage, transformer upgrades, and proper protection coordination are needed to achieve full system reliability.

Keywords— Renewable Energy, Photovoltaic, Distributed generation (DG), Load shedding, Libyan distribution network, Load flow analysis, NEPLAN, PV-SOL, voltage profile, sub-transmission network.

I. Introduction

The Renewable energy technologies, particularly photovoltaic (PV) systems, are increasingly important for power generation worldwide. However, selecting suitable locations for distributed generation (DG) depends on local conditions and renewable potential. Libya's power system suffers from a severe production shortage, with a large gap between demand and supply, leading to daily load shedding, especially in semi-desert areas [1].

DG is defined by IEEE as generation by facilities smaller than central power plants, allowing connection at nearly any grid point [2]. DG can reduce losses, support voltage, improve reliability, and defer infrastructure upgrades [3]–[5].

Several studies have addressed Libya's energy challenges. Maka et al. [6] highlighted PV potential for rooftop applications but did not examine large-scale grid integration. Alkar [7] assessed power plant performance during blackouts. Ihbal and Alssaeed [8] studied demand-side management with rooftop PV but focused on residential economics. similarly, Abotraba et al. [9] studied how integrating PV and wind distributed generation affects voltage stability and power losses in the Algaraboly's 220/30 kV distribution network using NEPLAN. The results showed that integration of renewable energy can significantly enhance network performance under diverse operating conditions.

In this context, this paper presents one of the first quantitative studies evaluating a grid-connected 5 MW PV-DG system integrated into a 66 kV sub-transmission network in southern Libya. The main contributions of this work are summarized as follows: .While earlier studies typically limit its scope to rooftop PV economics [8] or broad resource assessments [6], this study takes a critical step forward. It provides detailed quantitative, grid-level impact assessment of a utility-scale PV-DG system mapped directly onto a real 66 kV sub-transmission network in southern Libya. what sets this work apart is its comprehensive approach, it pairs detailed steady-state and contingency load-flow analyses with an accurate battery dispatch strategy. Moreover, it looks at the bigger picture through a wide sensitivity analysis (1–10 MW) and ground our economic evaluation in actual generation costs rather than artificial, subsidized tariffs

II. LIBYA'S ELECTRICAL ENERGY SITUATION

Libya, located in North Africa, covers an area of approximately 1.75 million km² and had a population of about 6.8 million in 2022. The General Electricity Company of Libya (GECOL) is responsible for electricity generation, transmission, and distribution across the country. At present, the power sector relies almost entirely on oil and gas, and only about 44% of installed generation capacity is effectively available due to damage and operational limitations associated with past conflict [6]. In some regions,

DOI: **10.5281/zenodo.20484348**

particularly in western Libya, daily power outages have reached an average of six hours.

Electricity demand is also rising steadily, with peak load expected to increase from 10,795 MW in 2020 to around 14,834 MW by 2030 [10]. At the same time, the grid faces several structural challenges, including high technical losses caused by insufficient maintenance, limited availability of spare parts, and environmental concerns linked to fossil-fuel-based generation. In 2018, Libya emitted about 54 million tons of CO_2, ranking among the notable contributors globally. In response, GECOL has begun prioritizing the development of renewable energy sources such as solar and wind power [10].

In 2020, Libya generated approximately 30.09 TWh of electricity, with 99.9% coming from fossil fuels and only a very small fraction from renewable sources [11]. During the same period, a supply deficit of nearly 3.0 GW was recorded, driven by a summer peak demand of around 7.5 GW. The residential sector represents the largest share of consumption, accounting for about 36% of total electricity use.

Despite these challenges, Libya has strong potential for solar energy development. Located within the global Sunbelt region, the country benefits from extremely high solar irradiance. It is estimated that the solar energy received annually on just one square kilometre of Libyan land is equivalent to roughly 1.5 million barrels of crude oil [12].

GECOL aims to expand renewable capacity, including PV and wind. In 2020, Libya produced 30.09 TWh, with 99.9% from fossil fuels [11].

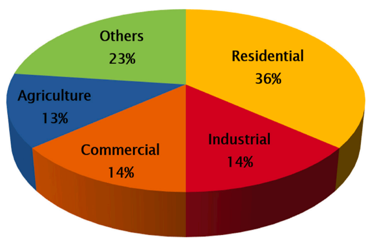

Figure 1. % of Electricity Consumption by Sector

III. SOLAR ENERGY POTENTIAL IN LIBYA

Libya has significant renewable energy potential, with solar energy available abundantly across the entire country. Due to its geographical position near the Tropic of Cancer, the country experiences high solar irradiance and long sunshine durations throughout the year [13].

Studies in [14], [15] report that the average daily solar radiation on a horizontal surface is about 7.1 kWh/m² in the northern coastal regions, increasing to approximately 8.1 kWh/m² in the southern desert areas. Annual sunshine duration also exceeds 3,500 hours in many parts of the country [13]. Similarly, the Libyan Renewable Energy Authority estimates around 3,200 hours of direct sunshine per year, with an average daily solar radiation of about 6 kWh/m² [16]. Figure 2 illustrates the daily and annual mean global horizontal solar radiation distribution across Libya over the period from 1994 to 2018. The analysis reveals clear regional variation in solar resource availability.

Regionally, the northern coastal areas receive approximately 6 kWh/m² per day (about 2,264 kWh/m² annually), while the southern regions reach around 7.1 kWh/m² per day (approximately 2,556 kWh/m² annually). These values clearly indicate that southern Libya offers particularly strong conditions for photovoltaic (PV) power generation.

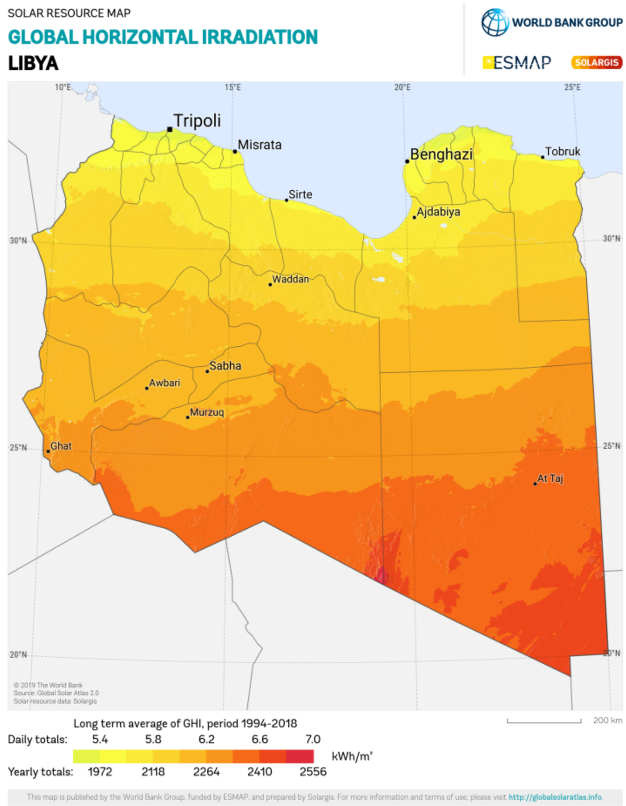

Figure 2. Global horizontal solar radiation in Libya

IV. METHODOLOGY AND ASSUMPTIONS

This study investigates the technical impact of integrating renewable energy sources, particularly photovoltaic (PV) systems, as distributed generation (DG) within the southern Libyan electrical network. Libya, located in North Africa, possesses abundant renewable energy resources and is recognized as one of the regions with the highest solar irradiation levels globally. Much of southern Libya is characterized by hot and arid desert conditions with prolonged sunshine duration, making it highly suitable for solar energy generation.

To evaluate the effectiveness of PV-based distributed generation, the Tragan 220/66 kV Substation was selected as the case study due to its strategic importance in supplying electricity to the semi-desert region of southern Libya and its existing operational challenges, including voltage instability and high reactive power demand.

The technical analysis was carried out using NEPLAN for system modeling, load flow simulation, and distributed generation impact assessment. The photovoltaic system was sized using PV*SOL, taking into account the local solar resource characteristics and system operating conditions. The study evaluates the impact of PV penetration on network

DOI: **10.5281/zenodo.20484348**

performance through comparative load flow analysis under different operating scenarios.

A. Assumptions

The analysis was conducted based on the following assumptions:

- Bus voltage regulation limits are maintained within ±5% of nominal voltage under normal operating conditions and within ±10% under contingency(based on GECOL standards).
- Bus voltage regulation: ±5% of nominal under normal conditions, ±10% under contingency
- Maximum line loading: 100% of rated current capacity
- PV system can be installed at any bus, with size determined by PV-SOL
- System control facilities are fully available
- All standards comply with IEC requirements.
- All transformers in the Tragan network are fixed-tap type (no On-Load Tap Changers – OLTC), modelled accordingly in NEPLAN**.**

B. Distribution System Description

Tragan 220/66 kV Substation consists of the following major components:

- 220/66 kV power transformers
- 66/11 kV distribution transformers
- Overhead transmission lines and underground cable feeders
- 66 kV busbars , bus couplers and sectionalizing equipment
- Connected load centres
- PV generation system and inverter interface

Figure 3 presents the single-line diagram of the Tragan power system under normal operating conditions, illustrating the network configuration adopted for simulation and analysis.

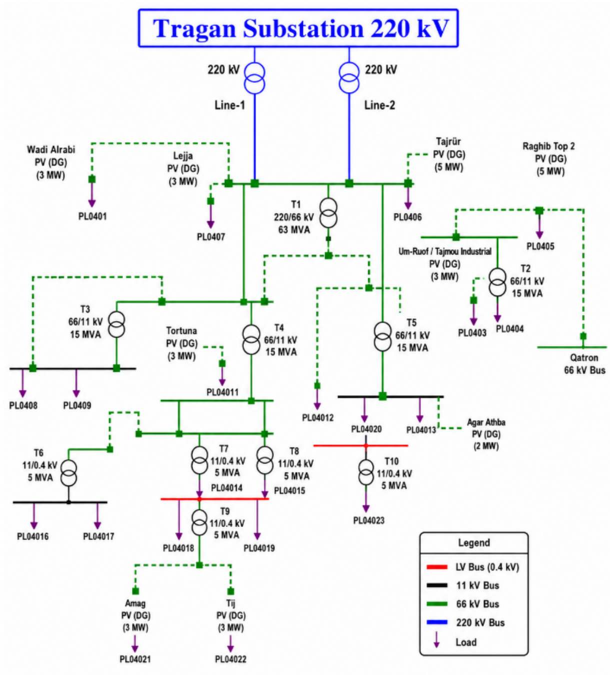

Figure 3. Single-line diagram of Tragan 220/66 kV network

C. Study Workflow (Methodology Flowchart)

To evaluate clarity, the following systematic workflow was implemented as shown in Fig. 4

This flowchart unifies the data flow from solar modelling to grid simulation and battery sizing. network.

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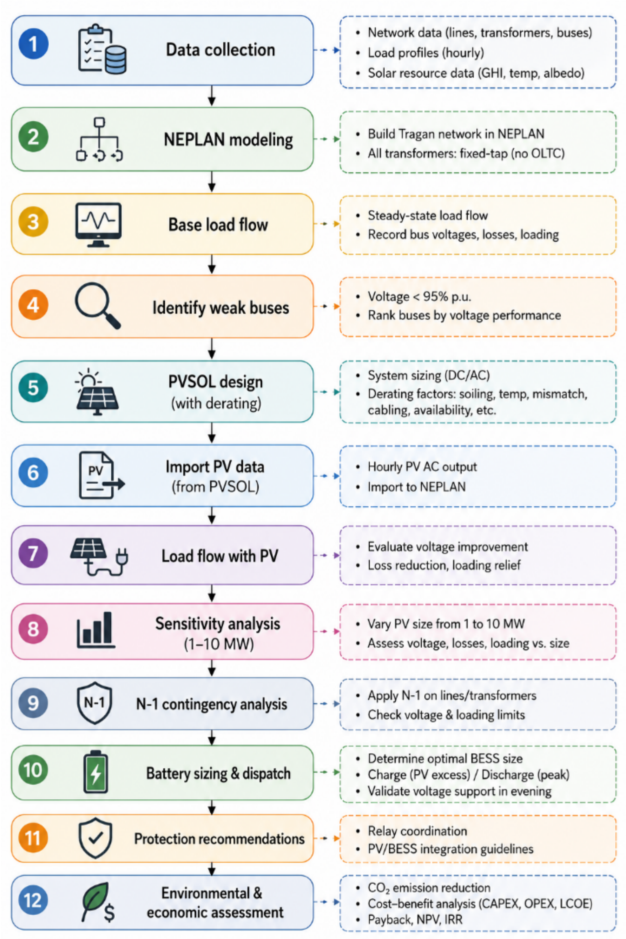

Figure 4. Methodology flowchart

V. RESULTS AND ANALYSIS

Southern Libya is characterized by semi-desert climatic conditions with high solar irradiance, making it highly suitable for photovoltaic (PV) power generation. To evaluate the technical impact of distributed generation (DG) integration in such an environment, the Tragan 220/66 kV Substation was selected as the case study.

The Tragan substation is supplied by the Libyan national grid and experiences operational challenges, particularly low voltage profiles and high reactive power demand during peak load periods due to heavily inductive loads. The 66 kV Tragan network, illustrated in Figure 1, is supplied from the 220 kV transmission system through two 220/66 kV transformers, each rated at 63 MVA.

To assess the network performance, power flow analysis was carried out using NEPLAN under different operating scenarios, including the base case without distributed generation and the integration of PV-based DG during peak load conditions.

A. Normal Operating (Base Case – Without PV)

In the first scenario, the network operates under steady-state conditions without distributed generation. The system consists of eight distribution stations connected to the Tragan network and supplied through the national transmission grid.

The peak load condition considered in this study corresponds to August 2017, representing the period of highest electricity demand due to extreme summer temperatures and intensive cooling loads.

The load flow analysis results for this base case are presented in Table I

Table I ACTIVE AND REACTIVE POWER FLOW RESULTS (BASE CASE)

Parameter	Value
Active Power Input (MW)	102.101
Reactive Power Input (MVar)	74.981
Active Power Losses (MW)	3.501
Reactive Power Losses (MVar)	13.873

The results reveal several operational weaknesses within the network, including:

- Significant voltage violations at remote buses
- High line loading levels
- Elevated active and reactive power losses

The active power loss of 3.501 MW represents approximately 3.42% of the total system load, indicating inefficient power delivery.

shows the voltage profile across all 66 kV buses. Voltages degrade with distance from the 220/66 kV substation, particularly at radial feeder ends. The lowest voltage (0.906 p.u. at Qatron bus) violates the utility's ±5% tolerance. The most critical voltage drops are observed at:

- Qatron
- Tjrhi
- Alwigh
- Agar-Athba

Among these, the Qatron and Agar-Athba buses exhibit the lowest voltage levels and were therefore selected as the best locations for PV-DG installation.

Traditional solutions for addressing such violations, such as network reinforcement or substation expansion, require substantial financial investment and long implementation periods. Distributed PV generation offers a faster and more economical alternative.

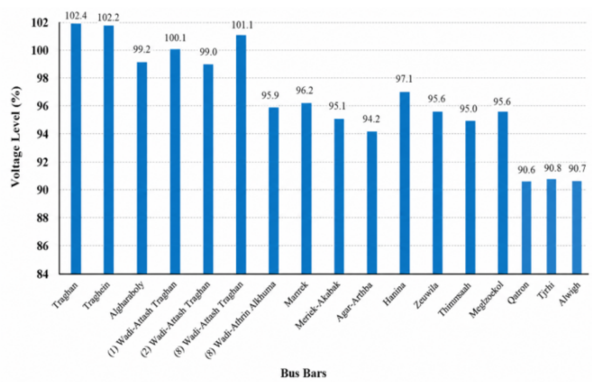

Figure 5. Bus voltages profile (normal case)

DOI: **10.5281/zenodo.20484348**

B. *PV-DG Integration – Single Size (5 MW)*

A 5 MW PV system (unity power factor) is connected to the two weakest buses: Qatron (3 MW) and Agar-Athba (2 MW). Table II compares results with the base case..

TABLE II. COMPARISON OF RESULTS – 5 MW PV VS. BASE CASE

Parameter	Base Case	With 5MW PV	Absolute Change	Relative Change
Grid active power input (MW)	102.101	97.124	-4.977	-4.9%
Grid reactive power input (MVar)	74.981	70.213	-4.768	-6.4%
Active power losses (MW)	3.501	2.429	-1.072	-30.6%
Reactive power losses (MVar)	13.873	9.612	-4.261	-30.7%
Minimum voltage (p.u.)	0.912	0.978	+0.066	+7.2%

Figure. 6 shows the Tragan power system configuration at the second scenario (applying PV as a DG).

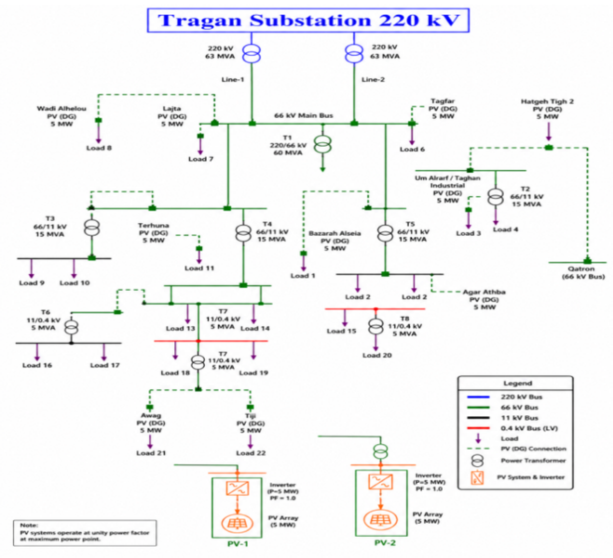

Figure 6. Grid system configuration with PV

C. *Sensitivity Analysis: Varying PV Penetration Levels*

To understand the effect of PV size, simulations are repeated for PV capacities from 1 MW to 10 MW (in 1 MW steps), all connected to the same weak buses (Qatron + Agar-Athba, split 60%/40%). Figure 7 shows the key trends.

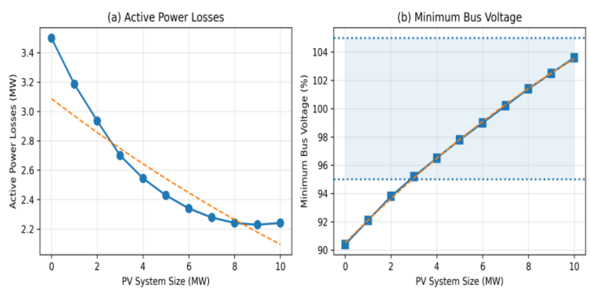

Figure 7. Sensitivity analysis: (a) Active power losses vs. PV size; (b) Minimum voltage vs. PV size

The sensitivity analysis results for selected PV sizes are presented in Table III. The sensitivity analysis shows that adding more distributed generation helps the system, but only up to a point. Table III presents the sensitivity analysis results.

TABLE III. SENSITIVITY ANALYSIS RESULTS

PV Size (MW)	Grid P (MW)	Losses (MW)	Loss Reduction (%)	Min Voltage (p.u.)	Voltage Improve (%)	Buses <0.95 p.u.
0 (Base)	102.101	3.501	—	0.912	—	4
1	101.05	3.187	-9.0%	0.925	+1.4%	3
2	99.982	2.986	-16.1%	0.938	+2.9%	2
3	98.937	2.701	-22.8%	0.951	+4.3%	1
4	98.029	2.545	-27.3%	0.963	+5.6%	0
5	97.124	2.429	-30.6%	0.978	+7.2%	0
6	96.245	2.340	-33.2%	0.991	+8.7%	0
7	95.401	2.278	-34.9%	0.998	+9.4%	0
8	94.599	2.241	-36.0%	1.003	+10.0%	0
9	93.838	2.229	-36.3%	1.008	+10.5%	0
10	93.112	2.241	-36.0%	1.012	+11.0%	0

At lower penetration levels, the system benefits rapidly with losses drop sharply and reach their best improvement around 5 MW (about 30.6% reduction). After that, the gains start to taper off. Once the capacity goes beyond roughly 8 MW, the situation slightly reverses, with losses beginning to creep up again. This is mainly due to reverse power flow and additional I^2R losses caused by power being pushed back into the upstream network.

Voltage behaviour follows a similar pattern. As DG increases, voltage levels improve and the system becomes more supported. The best performance is seen around 7 MW, where the minimum voltage reaches about 0.998 p.u., very close to the nominal limit. However, at 10 MW, the voltage rises above 1.01 p.u. during light-load conditions, which starts to introduce overvoltage concerns.

From a practical point of view, the sweet spot for this network is around 5–7 MW. In this range, you get strong loss reduction, better voltage support, and overall stable operation. Beyond 7 MW, the system doesn't gain much more—in fact, it starts to lose some stability benefits.

Economically, pushing the size from 7 MW to 10 MW is not very attractive. The loss reduction improves only slightly (about 1.1%), which is too small to justify the extra investment unless technologies like storage systems or reactive power compensation are added to help manage the additional power flow. In brief, bigger is not always better, the system clearly has a suitable DG range rather than a continuously improving trend.

The Tragan 66 kV network consists of long radial transmission lines across a desert environment, with an average X/R ratio in the range of 1.2 to 1.4 (approximately R ≈ 0.27 Ω/km and X ≈ 0.35 Ω/km). Because the X/R ratio is relatively low, the network's voltage is almost equally influenced by active power and reactive power injections.

As a result, even when the 5 MW PV system operates at unity power factor (Q = 0), it still produces a strong improvement in voltage levels. In this case, the minimum voltage increases significantly from 90.4% to 97.8%, mainly

DOI: **10.5281/zenodo.20484348**

driven by active power injection rather than reactive power support.

This behavior is quite different from high-voltage transmission systems (typically X/R > 5), where voltage regulation is largely dominated by reactive power control.

In brief, bigger is not always better, the system clearly has a suitable DG range rather than a continuously improving trend.

D. Impact of PV Location

To determine the best placement of the PV system, the 5 MW capacity was distributed across four candidate weak buses. Table IV presents a comparative evaluation of five different allocation strategies, allowing assessment of their impact on system performance in terms of power loss reduction, voltage profile improvement, and overall network stability.

TABLE IV. IMPACT OF PV ALLOCATION STRATEGY (5 MW TOTAL)

Allocation Strategy	Min Voltage (%)	Losses (MW)	Violating Buses
No PV	90.4	3.501	5
All 5 MW at Qatron	95.2	2.587	2
All 5 MW at Agar-Athba	95.0	2.612	2
All 5 MW at Megiddo	94.8	2.645	3
3 MW Qatron + 2 MW Agar-Athba	97.8	2.429	0
Distributed (1 MW at 5 weak buses)	96.2	2.501	1

The results presented in Table IV indicate that distributing the 5 MW PV capacity between the two weakest buses—Qatron (3 MW) and Agar-Athba (2 MW)—provides the best overall network performance. This configuration achieved the highest minimum voltage level (97.8%) and the lowest system losses (2.429 MW), while completely eliminating voltage violations across the network.

By comparison, installing the entire PV capacity at a single bus resulted in lower voltage improvement (94.8%–95.2%) and higher power losses (2.587–2.645 MW). The improved performance of the split allocation is mainly due to the balanced support provided to both sides of the network, which helps enhance voltage regulation and overall system efficiency.

E. Time-Varying Analysis (Diurnal Profile) with Battery Dispatch Strategy

Figure 8 shows the daily voltage profile at the weakest bus, Qatron, under three scenarios: the base case, 5 MW PV only, and 5 MW PV with a 2 MW/4 MWh battery system. The key results are summarized in Table V.

In the base case, the voltage remains at about 90.4%, staying below the acceptable 95% limit throughout the day. With 5 MW PV, voltage improves significantly during daylight hours (06:00–18:00), reaching 98.0% at midday. However, as solar generation declines after 17:00, the voltage drops below 95% by 18:00 and returns close to the original weak condition by 20:00, during the evening peak.

Adding a 2 MW/4 MWh battery energy storage system improves evening voltage support by discharging between 18:00 and 22:00. However, the battery maintains acceptable voltage only until around 20:00. By 21:00, the voltage falls to 94.8%, indicating that the selected battery size is insufficient to fully cover the evening peak demand. The 2 MW/4 MWh battery is insufficient after 20:00; a 3 MW/6 MWh system is recommended.

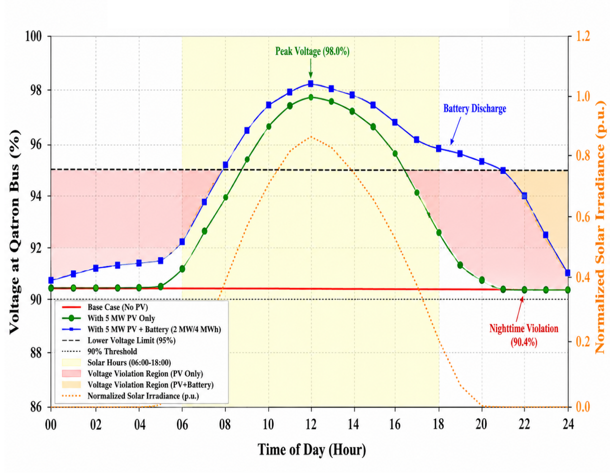

Figure 8. Diurnal voltage profile at Qatron bus (5 MW PV)

TABLE V. Voltage at different times for base case, PV only, and PV+ Battery (2 MW/4 MWh)

Time	Base Case	PV Only	PV+Battery (2/4)
12:00	90.4%	98.0%	98.2%
18:00	90.4%	92.5%	95.8%
20:00	90.4%	90.6%	95.2%
21:00	90.4%	90.4%	94.8%

F. Contingency Analysis (N-1 Security Assessment)

To evaluate the robustness of the Tragan 66 kV network under fault conditions, an N-1 contingency analysis was carried out in NEPLAN under peak-load conditions. The assessment considered the outage of critical network components, including transformers, feeders, the bus coupler, and the PV-DG system itself.

The following contingencies were analysed:

C1: Loss of one 220/66 kV transformer (63 MVA)

C2: Loss of the 66 kV bus coupler

C3: Loss of the Tragan–Qatron feeder (45 km)

C4: Loss of the Agar-Athba feeder

C5: Loss of the 5 MW PV-DG system

Each case was evaluated under two operating conditions: the base case without PV integration and the network with 5 MW PV-DG distributed between Qatron (3 MW) and Agar-Athba (2 MW).

DOI: **10.5281/zenodo.20484348**

Table VI below summarizes the contingency analysis results for the base-case network. The most critical condition occurs under C1 (transformer outage), where the minimum voltage drops sharply to 87.2%, nine buses fall below the acceptable 95% limit, and the remaining transformer operates at 98% loading, leaving almost no reserve capacity.

A similar weakness is observed during C3 (Qatron feeder outage), where the minimum voltage decreases to 88.4%, with seven buses violating the voltage limit. These results indicate that the base-case network is unable to withstand these disturbances and therefore fails to satisfy N-1 security requirements, particularly under the C1 and C3 contingencies.

TABLE VI. CONTINGENCY ANALYSIS – BASE CASE (NO PV)

Contingency	Min Voltage (%)	Buses <95%	Line Overload
Normal	90.4	5	No
C1	87.2	9	Yes (T2 at 98%)
C2	90.1	5	No
C3	88.4	7	Yes
C4	89.6	6	No

Table VII presents the contingency results after adding the 5 MW PV-DG system. Overall, the network performance improves under fault conditions. In C1 (outage of transformer), the minimum voltage increases to 94.2%, remaining above the 90% limit.

A similar improvement appears in C3 (outage of Qatron feeder), where voltage increases to 93.8%, showing that the PV-DG helps support local voltage during disturbances.

However, some issues remain. Transformer loading in C1 is still high at 98%, and when the PV-DG is lost (C5), the system returns to weak performance, with voltage dropping back to 90.4% and earlier violations reappearing.

Table VIII summarizes the contingency compliance results. With PV-DG integration, C1 improves from "Fail" to "Pass" in terms of voltage, although transformer loading remains near its limit. C3 and C4 become fully compliant due to improved voltage support from the PV system. However, C5 is still a weak point, as system performance degrades when PV-DG is lost, highlighting the need for backup support.

TABLE VII. CONTINGENCY ANALYSIS – WITH 5 MW PV-DG

Contingency	Min Voltage (%)	Buses <95%	Line Overload
Normal	97.9	0	No
C1	94.2	1	Yes (T2 at 98%)
C2	97.5	0	No
C3	93.8	1	Yes
C4	96.2	0	No
C5	90.4	5	No

TABLE VIII. N-1 COMPLIANCE SUMMARY

Contingency	Base Case	With 5 MW PV-DG	Status
C1	Fail (87.2%)	Pass (94.2% > 90%)	Pass (voltage) / Marginal (loading)
C2	Pass	Pass	Pass
C3	Fail (88.4%)	Pass (93.8% > 90%)	Pass with PV
C4	Marginal	Pass	Pass with PV
C5	N/A	Returns to base case	Requires backup

The Minimum voltage levels during N-1 contingency scenarios for the Tragan network, comparing the base case (without PV-DG) and the case with 5 MW PV-DG integrated at Qatron and Agar-Athba is shown in shown in Fig. 9. In the base case (without PV-DG), the normal voltage level is 90.4%, while the most severe case (C1: loss of a 220/66 kV transformer) drops it to 87.2%, which violates the 90% limit.

With the integration of the 5 MW PV-DG, the normal voltage improves to 97.9%, and the C1 voltage rises to 94.2%, staying within the acceptable range. Similar improvements are also seen in C2, C3, and C4; for instance, C3 increases from 88.4% to 93.8%.

Overall, the PV-DG significantly improves N-1 voltage security, although transformer loading is still close to its thermal limit.

DOI: **10.5281/zenodo.20484348**

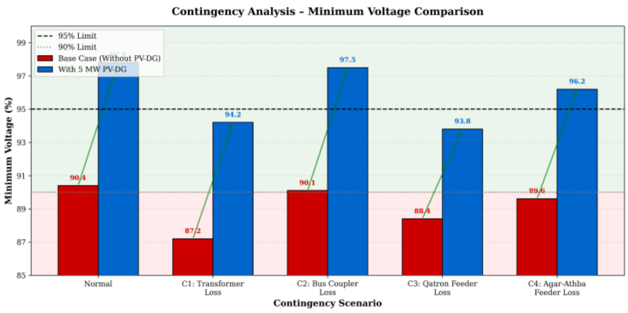

Figure 9. Minimum voltage levels during N-1 contingencies

The results of the contingency analysis are summarized in Fig. 8. In the base case (no PV-DG), the normal operating voltage is 90.4 %, and the most severe contingency, loss of one 220/66 kV transformer (C1), causes the voltage to drop to 87.2 %, below the 90 % contingency limit. After integrating 5 MW PV-DG, the normal voltage rises to 97.9 %, and the voltage during C1 improves to 94.2 %, now within the acceptable range. Similarly, voltages under C2, C3, and C4 increase significantly (e.g., C3 from 88.4 % to 93.8 %). These data confirm that PV-DG substantially enhances N-1 security, though transformer thermal loading remains a concern.

VI. DISCUSSION

A. *Technical Performance Summary*

The 5 MW PV-DG integration clearly improves the performance of the Tragan network. Key technical results can be summarized as follows:

Active power losses are reduced by 30.6%, dropping from 3.501 MW to 2.429 MW at 5 MW penetration. However, increasing the PV size beyond 7 MW offers little additional benefit and starts to introduce overvoltage issues above 101%.The voltage profile also improves notably, with the minimum bus voltage rising from 90.4% to 97.8%, effectively removing all five voltage violations. In terms of sizing, the most effective range is between 5 and 7 MW, where a good balance between loss reduction and voltage improvement is achieved. These results are consistent with earlier results on DG benefits in radial networks [17, 18].

Finally, the best performance is obtained when the PV capacity is split between Qatron (3 MW) and Agar-Athba (2 MW), which performs better than placing all generation at a single location or distributing it uniformly.

B. *Environmental and Economic Impact*

The 5 MW PV-DG system generates 8,750 MWh annually, avoiding 4,813 tons of CO_2 per year (120,325 tons over 25 years). Using standard emission factors [9]–[15], [20], [21],the annual reductions are:

- SO_2: 21 tons (525 tons lifetime)
- NOx: 12 tons (300 tons lifetime)
- Water (once-through cooling): 52.5 ML (1,312.5 ML lifetime) [22], [23].

The carbon abatement cost is negative (–\$149/tCO_2), indicating that fuel savings exceed the cost of PV deployment. Thus, the project is both environmentally and economically beneficial. Table IX presents the environmental benefits over 25-year lifetime [10–16].

TABLE IX. ENVIRONMENTAL BENEFITS (25-YEAR LIFETIME)

Parameter	**Factor**	**Annual**	**Lifetime (25 years)**
Energy generated	–	8,750 MWh	218,750 MWh
CO_2 avoided	0.55 t/MWh	4,813 t	120,325 t
SO_2 avoided	0.0024 t/MWh	21 t	525 t
NOx avoided	0.00137 t/MWh	12 t	300 t
Water saved	6 L/kWh	52.5 ML	1,312.5 ML

In this study, the economic assessment is not based on the heavily subsidized electricity tariff paid by Libyan households, which typically ranges between 0.004 *and* 0.008/kWh [24, 25]. Using this consumer tariff would significantly underestimate the economic value of the proposed PV-DG system. Instead, the analysis is based on the actual marginal cost of electricity generation**,** representing the real cost borne by GECOL to produce electricity from conventional fossil-fuel plants, as similarly evaluated for southern Libya in [19].. Based on previous studies, this cost is estimated at \$0.07/kWh [26], which better reflects the true savings when solar generation displaces thermal generation.

Using this approach, the proposed 5 MW PV system achieves a payback period of 5.2 years, while adding the recommended 3 MW/6 MWh BESS extends it slightly to 6.5 years [27, 28]. The calculated LCOE is 0.032/kWh [29], which is less than half the conventional generation cost. In addition, the carbon abatement cost is 0.032/kWh, which is less than half the conventional generation cost. In addition, the carbon abatement cost is 149/ tCO_2 [30, 31], indicating that fuel savings exceed the total system cost over its lifetime.

The environmental benefits over the 25-year project lifetime are summarized in Table IX, confirming that the proposed system is both economically attractive and environmentally beneficial for weak desert networks in southern Libya.

C. *Protection Coordination Recommendations*

Based on the contingency analysis results, the following protection measures are recommended for safe PV-DG integration:

Install directional overcurrent relays (67) at the point of common coupling (PCC) with settings: 350 A, 0.2 s delay.

- Implement anti-islanding protection using under/over voltage (27/59) and under/over frequency (81U/81O) relays.
- Install **a** neutral grounding resistor (NGR) at the 66/11 kV transformer to limit ground fault current to 400 A.
- Coordinate re-closer fast curves to **0.1** seconds for fuse-saving.

D. Limitations and Future Work

This study has several limitations that should be addressed in future work:

1. **Seasonal variation:** Only summer peak load is considered. Seasonal variations, particularly winter and spring operating scenarios, should be investigated in future studies to provide a more comprehensive assessment.
2. **Steady-state assumption:** The analysis is based on load flow. Dynamic performance, such as rotor angle stability and frequency response following faults or sudden PV disconnection, has not been examined. A transient stability analysis is therefore recommended as a follow-up extension.
3. **Harmonic distortion (THD):** The influence of PV inverters on power quality (harmonics) was not studied. Harmonic studies using frequency-domain techniques or time-domain simulation tools such as PSCAD to assess potential power quality issues. Is recommended.
4. **Protection validation:** Protection coordination was evaluated theoretically without real relay testing or field validation. More detailed validation through simulation-based protection studies or real-world testing would strengthen the findings.
5. **Battery sizing:** The 2 MW/4 MWh BESS was insufficient; A larger configuration, such as 3 MW/6 MWh, has been recommended for improved performance.
6. **Uncertainties:** The analysis is also deterministic in nature, meaning that uncertainties in load demand and renewable generation were not explicitly modeled. Incorporating probabilistic approaches, such as Monte Carlo simulations, would improve the realism and robustness of the results.

Despite these limitations, the study clearly demonstrates that PV-based distributed generation remains an effective solution for improving voltage performance in weak desert networks such as Tragan.

VII. CONCLUSION

This study evaluated the impact of integrating a 5 MW grid-connected photovoltaic distributed generation (PV-DG) system into the 66 kV Tragan sub-transmission network in southern Libya, a system characterized by long radial feeders of up to 45 km, a relatively low X/R ratio (≈1.2–1.4), and fixed-tap transformers without on-load tap changers (OLTC). The base-case analysis confirmed the weakness of the network, with five buses operating below the 95% acceptable voltage limit, while the weakest bus, Qatron, recorded a voltage level of only 90.4%. In addition, total active power losses reached 3.501 MW.

The integration of the 5 MW PV-DG system, allocated as 3 MW at Qatron and 2 MW at Agar-Athba, produced significant technical improvements. Active power losses were reduced by 30.6%, decreasing to 2.429 MW, while the minimum bus voltage increased to 97.8%, effectively eliminating all voltage violations under normal operating conditions.

The sensitivity analysis showed that the most suitable PV capacity lies within the range of 5–7 MW. Increasing the PV penetration beyond 7 MW provides only limited additional benefits and introduces the risk of overvoltage conditions exceeding 101%, which may affect system stability and equipment performance.

However, the results also demonstrated that PV generation alone is insufficient to support the network during the evening peak period due to the absence of solar production after sunset. To address this issue, a battery dispatch strategy was developed, with charging scheduled between 11:00 and 14:00 and controlled discharge between 18:00 and 22:00, assuming an 80% depth of discharge (DoD). The analysis indicates that a 3 MW / 6 MWh battery energy storage system (BESS) is required to maintain bus voltages above the 95% operational threshold throughout the evening peak.

Under N-1 contingency conditions, the integration of PV-DG substantially improved network resilience. Voltage levels increased from 87.2% to 94.2% during transformer outage conditions and from 88.4% to 93.8% during feeder outage scenarios, thereby satisfying the GECOL contingency requirement of at least 90% voltage. Nevertheless, transformer loading remained relatively high at 98%, and the loss of PV generation under contingency C5 caused the system to revert to weak operating conditions.

The study also highlights the importance of implementing appropriate protection measures, including directional overcurrent relays, anti-islanding protection, neutral grounding resistors (NGR), and fast automatic reclosers, to ensure secure and reliable operation.

From an environmental and economic perspective, the proposed system offers clear benefits, including an estimated reduction of 4,813 tons of CO_2 emissions annually and an overall payback period of approximately 6.5 years, even when battery storage is included.

Overall, the findings confirm that PV-DG is an effective and technically viable solution for strengthening weak desert sub-transmission networks such as Tragan. However, achieving full reliability and long-term operational security requires the integration of adequately sized battery storage (3 MW / 6 MWh), transformer capacity reinforcement, and properly coordinated protection systems.

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