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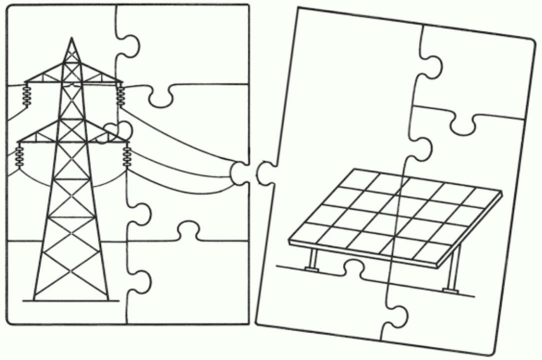

The uncounted solar gigawatts:

Distributed solar mapping and grid impact analysis in Pakistan

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Preface

Pakistan's energy landscape is changing faster than the data systems meant to govern it. Distributed solar has expanded at a pace that has outrun official estimates, net-metering records, and grid planning assumptions, leaving utilities and policymakers making consequential decisions on an increasingly incomplete picture of the system they are responsible for managing.

This study was undertaken to begin closing that gap. HeraldX developed and applied a proprietary AI and geospatial model to quantify distributed solar at feeder level across one of LESCO's most solar-saturated grid stations. Renewables First brought deep power systems expertise to assess what that solar is actually doing to the network, through rigorous PSS/E simulation benchmarked against Grid Code 2023 criteria.

The results are telling. At a single grid station in Lahore, actual installed solar capacity was found to be nearly double the registered figure, with reverse power flow and transformer loading already operating well beyond what official data would suggest. Alongside these findings, the study delivers a replicable, feeder-agnostic analytical framework that any DISCO in Pakistan can deploy. We offer it as a starting point and welcome engagement from utilities and policymakers working toward a data-driven, reliable grid.

We are grateful to the experts whose contributions helped shape the methodology, validate the findings, and ensure this work meets the standards expected of rigorous, policy-relevant research. We are particularly thankful to the power sector experts and organisations who participated in the consultative session on 15 April 2026 and shared their insights and feedback on the initial findings. Notwithstanding the rigour applied throughout, this study has limitations that must be considered when interpreting its results and informing future research in this area.

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Summary for policymakers

Pakistan's electricity system is undergoing a fundamental transformation. Millions of households and businesses have installed rooftop solar panels, driven by high electricity prices and unreliable supply. Yet the institutions responsible for managing the grid, distribution companies, system operators, and regulators, have limited visibility into how much solar has actually been installed and where. Official net-metering records capture only a fraction of the total, leaving a significant and growing share of installed capacity entirely outside the data systems on which planning and investment decisions depend.

HeraldX and Renewables First set out to quantify that gap through this study. Using its proprietary artificial intelligence (AI) model and satellite imagery, HeraldX mapped distributed solar installations across one of LESCO's most solar-intensive grid stations in Lahore. The analysis found 177MW of actual installed capacity against an indicative registered figure of 95MW, nearly double. The scale of disparity is consequential. It represents solar capacity that is physically present, affecting how power flows, how transformers load, and how voltage behaves. Yet planners and operators cannot see any of it.

Our modelling reveals that under actual solar penetration, reverse power flow and transformer loading more than doubled compared to what official data would suggest. While exploring potential remedial measures, our analysis suggests that battery storage can provide partial relief, but it is not a complete solution and introduces its own trade-offs. The findings make clear that the data gap is not a future concern; it is an operational reality today.

The methodology developed for this study is replicable and can be deployed across any distribution company in Pakistan without bespoke development, using available satellite coverage and network data. Several organisations have already expressed interest in extending this work. Pakistan's grid cannot be planned on data that no longer reflects our *rooftop reality*. Our distribution companies, the regulator, and policymakers must prioritise accurate solar visibility as a foundation for reliable grid operations, sound infrastructure investment, and a managed energy transition that works for all consumers.

Study overview: From data gap to grid intelligence

The status quo

A widening data gap on distributed solar capacity...

- Pakistan's distributed solar capacity is estimated at 38GW, nearly double the official figure of nearly 20GW and far exceeding the licensed net-metered capacity.
- The majority of BTM[1] solar capacity remains invisible to utilities, distorting load profiles and undermining the demand forecasts on which operational and strategic decisions are made.

...leads to sub-optimal grid planning and operations

- Unaccounted solar is already driving reverse power flows, voltage fluctuations, and unpredictable network behaviour that operators are struggling to manage without accurate data.
- Investment and dispatch decisions are being made on a grid picture that is materially incomplete, misaligning infrastructure priorities and exposing the grid to significant risks.

How we closed the gap

AI-driven solar quantification

- HeraldX's proprietary AI and geospatial model processed high-resolution satellite imagery to detect and quantify distributed solar at feeder level, providing granular visibility that net-metering data alone cannot offer.
- Trained exclusively on Pakistani rooftop imagery and validated against ground-truth data, the model delivers reliable, decision-grade solar capacity estimates across diverse urban settings.

PSS/E-informed grid simulation

- A 2025 base case network model for the 132KV Old Defence Grid Station was simulated across two scenarios, LESCO's indicative 95MW[2] and HeraldX's AI-estimated 177MW, under daytime and night-time conditions.
- Evaluated against Grid Code 2023 criteria, results reveal how unaccounted solar is already reshaping voltage profiles, transformer loading, and reverse power flow across the network.

Implications & way forward

A replicable framework for the sector

- The AI and PSS/E methodology is feeder-agnostic and deployable across any DISCO in Pakistan with available network data and satellite coverage.
- Several public organisations, including DISCOs and central planners and operators, expressed direct interest in replicating this analysis, a clear signal that the sector recognises the data gap and is ready to act.

Urgent need for data-driven planning

- Accurate visibility into distributed solar is no longer optional; it is a prerequisite for reliable grid operations, sound investment, and forward-looking regulatory design.
- The cost of planning on incomplete data grows with every megawatt that goes unregistered, and the window for proactive intervention is narrowing with the tremendous growth of distributed solar PV across the country.

Note: 1) Behind the meter. 2) Indicative number only, shared by the Lahore Electric Supply Company (LESCO) for simulation purposes.

1. Introduction

Introduction

Distributed solar is reshaping Pakistan's grid faster than the data can track; this study sets out to close that gap and deliver a replicable analytical framework to support a well-managed, accelerated energy transition

Problem statement

- Pakistan's power system is undergoing a fundamental shift toward distributed renewable energy, yet a significant gap persists between official and independent estimates of 20GW and 38GW rooftop solar capacity, respectively.
- This invisibility distorts load profiles and demand forecasts, leaving operators and planners reliant on data that no longer reflects ground, or more aptly *rooftop reality* — with operational and strategic consequences that compound over time.
- Unaccounted solar drives voltage fluctuations and reverse power flows at the operational level, while misaligning investment priorities and constraining forward-looking policymaking at the strategic level.

Research objectives

- Demonstrate the scale of the distributed solar data gap between officially reported net-metering numbers and actual installations and provide validated, feeder-level capacity estimates.
- Quantify the grid implications of unaccounted solar through rigorous PSS/E simulation and assess the effectiveness of mitigation options under real network conditions.
- Deliver a replicable, scalable analytical framework that any DISCO in Pakistan can deploy — demonstrating that AI-driven grid intelligence is both technically feasible and institutionally actionable.

Structure of the study

- Section 1 frames the data gap, its operational consequences, and what our integrated AI and power systems approach offers. Section 2 walks through HeraldX's geospatial methodology from satellite imagery acquisition to validated, feeder-level capacity estimates.
- Section 3 presents the grid impact assessment using PSS/E simulations to test network behaviour under registered and AI-estimated solar scenarios. Section 4 brings the findings together, reflects on study boundaries, and makes the case for replicating this framework across Pakistan's distribution network.

Source: HeraldX and Renewables First

An integrated modelling approach

A two-track methodology combining AI-driven solar mapping with power system simulation quantifies distributed solar capacity installations and assesses its implications for grid operations

Distributed solar capacity quantification

GIS mapping

- Region selection in consultation with key stakeholders and high-resolution imagery acquisition.
- Labelling of solar PV modules and rooftops to build a locally calibrated training dataset.
- Rectification of ML model output for optimal accuracy.

ML model estimates

- Training data created using labelled tiles across the LESCO region to build a locally calibrated model.
- Model trained over multiple iterations until convergence, achieving high detection accuracy across diverse urban rooftop conditions.
- Inference run on remaining tiles to automate and accelerate solar PV digitisation at scale.

Grid impact assessment

Network modelling and scenario design

- Develop a 2025 baseline network model for the selected 132 kV grid station.
- Simulate two distributed solar scenarios: registered capacity vs AI-estimated actual capacity.
- Evaluate daytime and night-time operating conditions to capture varying system behaviour.

Operational impacts and mitigation pathways

- Assess voltage profile, transformer loading, and reverse power flow against Grid Code 2023 requirements.
- Quantify the operational implications of unaccounted distributed solar on network performance and reliability.
- Evaluate BESS and targeted grid reinforcement measures to support higher distributed solar penetration.

Source: HeraldX and Renewables First

2. Geospatial mapping and solar capacity estimation

HeraldX workflow: From satellite imagery to solar capacity insights

A five-stage proprietary pipeline — from region selection to validated solar capacity estimates — built on high-resolution satellite imagery and in-house AI modelling

Region selection

Target region identified in consultation with the DISCO to define boundaries of interest

Image acquisition and processing

High-resolution satellite imagery acquired and processed through the proprietary HeraldX pipeline

Detection and labelling of solar PV systems

AI model detects and samples rooftops with solar PV across the region for area measurement

AI/ML model training and validation

100% in-house model trained on labelled Pakistani rooftop imagery; validated against ground-truth data

Distributed solar PV capacity estimates

Validated, feeder-level distributed solar capacity estimates offering much-needed reliability and granularity

Source: HeraldX

Geospatial mapping

From raw imagery to decision-grade capacity estimates — a four-stage pipeline built for the complexity of Pakistan's urban solar landscape

1. Region selection

- Target region defined in close consultation with LESCO, prioritising areas of high solar PV penetration where high-resolution satellite imagery is available and reliable.
- The 132KV Old Defence Grid Station — one of the most solar-saturated grid stations in the LESCO network — was selected as the study area along with its associated 11KV feeders.

2. Satellite imagery processing

- Sub-metre resolution satellite imagery acquired for the selected grid station, ensuring sufficient detail for accurate detection and mapping of rooftop solar installations.
- Imagery undergoes orthorectification, contrast enhancement, and cloud reduction to ensure geometric accuracy and optimal visual quality across the full study area for AI analysis.

3. Labelling and model training

- Solar panels are manually labelled across an archetypal sample of the study area to create a high-quality, locally calibrated training dataset.
- The resulting AI model, trained exclusively on Pakistani rooftop imagery and validated against ground-truth data, delivers reliable, context-specific detection across Pakistan's diverse urban rooftop conditions.

4. Rectification and validation

- Automated detections are systematically reviewed and corrected before finalisation, accounting for real-world conditions such as shading, distortion, and soiling that routinely challenge AI detection.
- This post-processing layer is what converts raw model output into a reliable, spatially-resolved solar capacity dataset that operators and planners can confidently act on.

Source: HeraldX

HeraldX ML model methodology

Pakistan's rooftops don't look like California’s or Canberra’s; our locally trained geospatial AI model uses ground truth annotations and pixel-level segmentation purpose-built for local rooftops and market realities

Ground truth labels

GIS-annotated rooftop and solar panel data collected across a representative Lahore sample

Labels capture the full diversity of Pakistani urban rooftops — varied roof types, shading, and orientations

Segmentation model

Pixel-level model trained to distinguish solar panels from the visual noise of densely packed urban rooftops

Built entirely in-house, with no third-party models or assumptions borrowed from foreign datasets

Inference at scale

Trained model runs inference across the remaining Lahore ROI, automating months of manual digitisation

Each tile processed consistently, eliminating the fatigue and inconsistency of human-only analysis

Capacity estimation

Panel counts translated into solar capacity using a proprietary probability-based wattage assignment model

Panel type determined through a proprietary classification method calibrated against local market data

Panel classification

Each detected panel assigned a wattage category based on probability scores derived from physical area

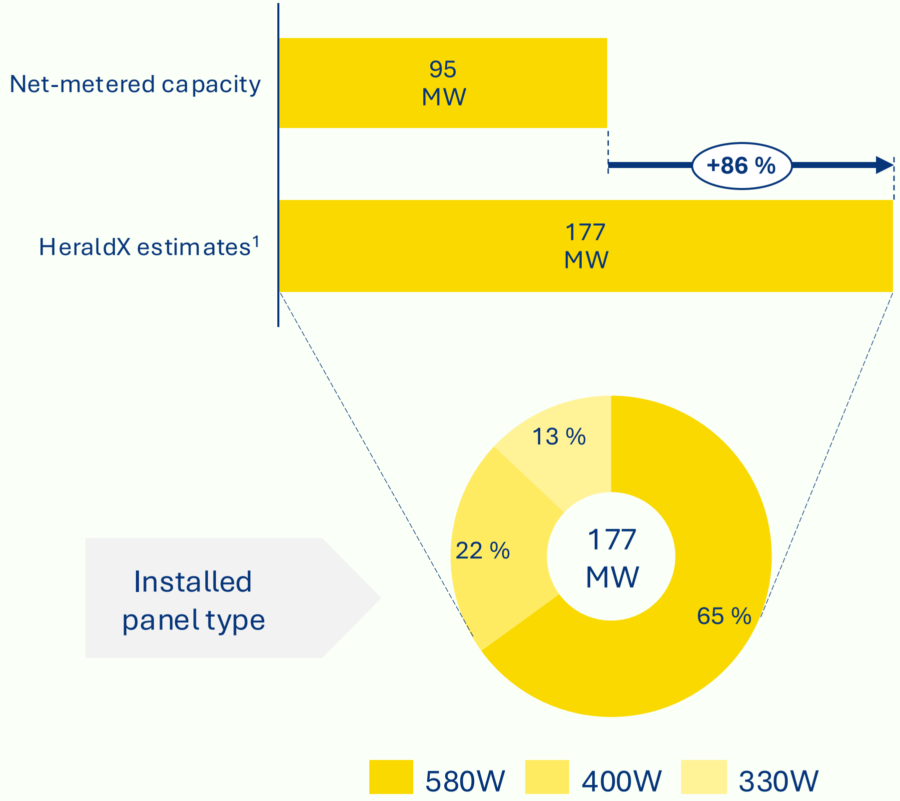
Classification results consistent with Pakistan's current distributed solar import trends

Source: HeraldX

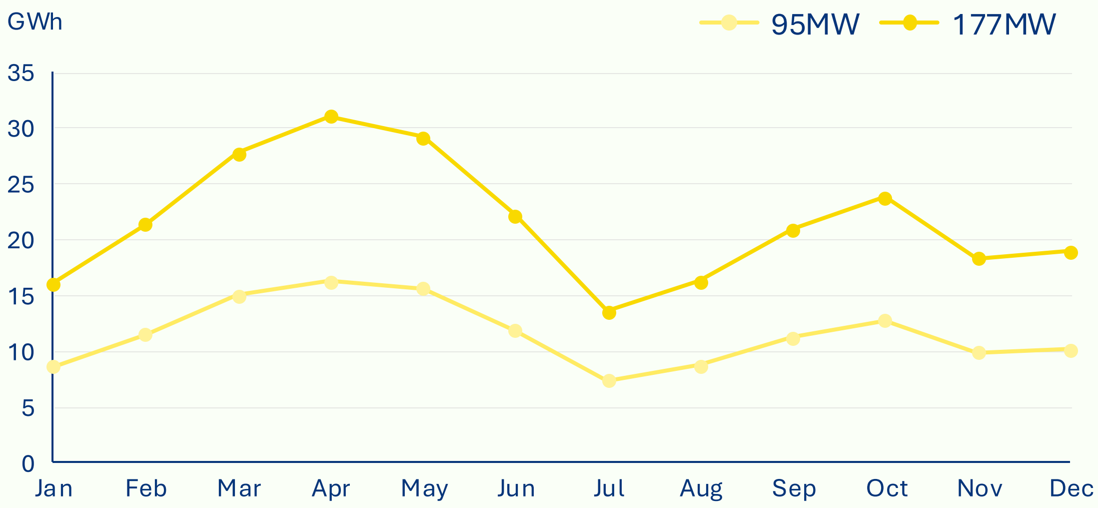
Model output | Capacity and power generation estimates

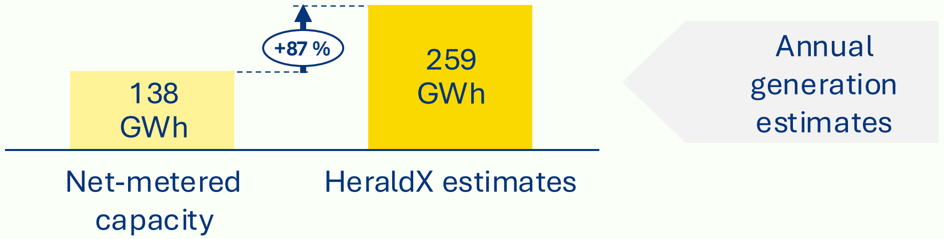
HeraldX estimates 177 MW of installed solar at the Defence grid station, 86% above the indicative licensed capacity, with an annual generation potential of 259 GWh

Installed capacity comparison



Estimated monthly power generation[2] potential





Note: 1) We assume a ±5-10% uncertainty of panel count. 2) Includes all types of solar PV installations, both metered and non net-metered. Generation potential estimates based on Global Solar Atlas assumptions.
Source: HeraldX

3. Grid impact assessment

Grid impact assessment: Analytical framework

Bridging the data gap between what's registered on the grid and what's actually installed — through an end-to-end analytical pipeline built for real world conditions.

1	Data inputs	Grid parameters and demand forecasts from LESCO's Forecast (FY25-35)
2	Baseline network model	Develop 2025 PSS/E model for selected 132kV grid station
3	Distributed solar integration	HeraldX's estimates of solar capacity mapped across 11kV feeders, introducing actual versus registered capacity into the model
4	Scenario development	Two scenarios compared: LESCO's registered capacity (95 MW) vs HeraldX's AI-estimated actual capacity (177 MW)
5	Impact assessment	Voltage profile, transformer loading, and reverse power flow
6	Solutions	Identify actionable mitigation measures and grid reinforcement priorities to support higher DG penetration

Source: HeraldX & Renewables First, LESCO (Energy & Demand Forecast Report LESCO FY2024-35.pdf)

Grid impact assessment: Scenario development

Two capacity scenarios simulated across two time windows to isolate and quantify the grid impact of unaccounted distributed solar

Scenario A — 95 MW
Indicative net-metered capacity

- Reflects solar PV installations formally registered through net metering licenses
- Excludes most of the actual installed capacity, such as behind-the-meter, off-grid, and oversized systems

vs

Scenario B — 177 MW
HeraldX AI-estimated installed solar PV capacity

- Quantifies total installed solar rooftop capacity including BTM, off-grid, and oversized installations
- Spatially resolved at feeder level, allowing direct integration into network modelling

Each scenario simulated across two time windows to capture contrasting system states

Daytime
Maximum solar injection period — highest reverse flow risk

&

Night-time
Solar generation absent — establishing the baseline against which daytime impacts are measured

Evaluation metrics: Each metric evaluated against Grid Code 2023 compliance thresholds

Voltage profile
Tracks nodal voltage levels to assess grid stability under varying solar injection.

Reverse power flow
Measures power flowing back toward the substation — a key DG integration risk.

Transformer loading
Monitors overloading risk at 132/11 kV step-down transformers under high solar penetration.

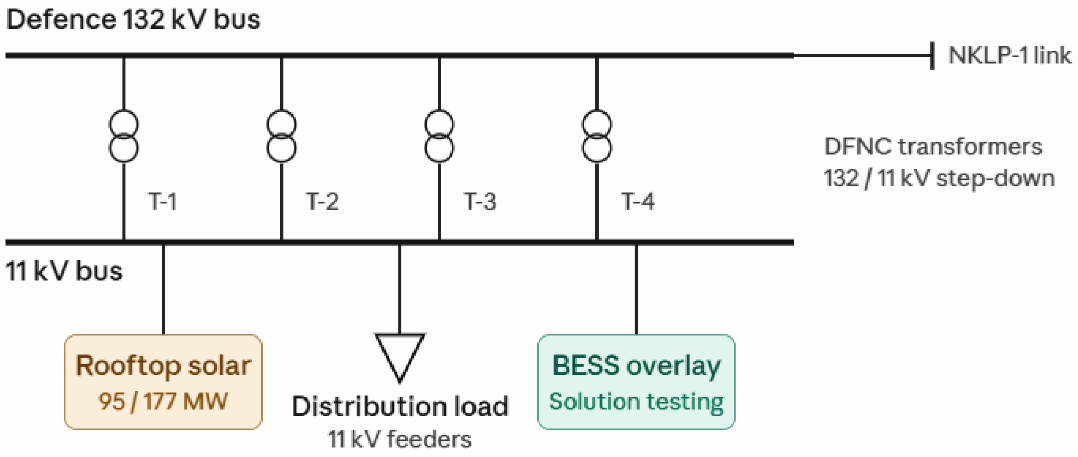
Power factor
Assesses system efficiency, particularly sensitive to the introduction of BESS.

Source: HeraldX & Renewables First, LESCO (Energy & Demand Forecast Report LESCO FY2024-35.pdf)

Grid impact assessment: Impact of unaccounted distributed solar

Comparison of registered and AI-estimated solar scenarios under daytime and night-time conditions

Fig. 1) Single-line diagram of the 132KV Old Defence Grid Station and associated 11KV feeders



DEFENCE 132 kV Bus

Primary transmission interface and the highest voltage point within the study boundary

DFNC Transformers (T1–T4)

Four 132/11 kV step-down transformers — the critical interface where reverse power flow from distributed solar is most acutely felt

11kV Feeders

Distribution feeders where AI-estimated solar capacity is spatially allocated and integrated into the network model

NKLP-1 Link

Interconnection with the wider LESCO network, representing power exchange at the study boundary

Distributed Solar Injection

The two study scenarios — licensed (95 MW) and AI-estimated (177 MW) — integrated at feeder level to simulate contrasting grid conditions

BESS Overlay (Mitigation Scenario)

Battery storage modelled at the 11 kV bus to test mitigation effectiveness against reverse power flow and transformer overloading

Source: HeraldX & Renewables First, LESCO (Energy & Demand Forecast Report LESCO FY2024-35.pdf)

Grid impact assessment: Impact of unaccounted distributed solar

Under actual solar penetration, the grid is already operating outside safe parameters; the data gap is not a planning concern for the future, but an operational reality today

Comparison of licensed vs AI-estimated solar scenarios under daytime and night-time conditions

	Daytime		Night-time
Distributed Solar Capacity (MW)	95	177	0
Power Flow (MW)	-52.2	-118	23.2
Transformer Loading (%)	34	76	17
Voltage Profile (pu)	1.06	1.06	1.03
Power Factor	0.96	0.99	0.92

Reverse power flow more than doubles under AI-estimated solar penetration, from -52.2 MW to -118 MW during peak daytime hours, a reversal of flow magnitude that the network was not designed to accommodate.

Transformer loading jumps from 34% to 76% under actual solar penetration, compared to just 17% at night. The concern is not immediate overloading, but the sharp reduction in operational margin.

Voltage at 1.06 pu under both daytime scenarios, violating the Grid Code 2023. This shows that feeder-level voltage correction is already needed through measures such as inverter Volt-VAR control, reactive power compensation, and targeted network reinforcement.

Please note AI-estimated solar includes net-metered, behind-the-meter, and off-grid systems. Therefore, reverse power flow results represent a modeled system stress condition and should not be interpreted as direct export from all distributed solar assets.

Source: HeraldX & Renewables First, LESCO (Energy & Demand Forecast Report LESCO FY2024-35.pdf)

Grid impact assessment: Impact of mitigation measures

A 10MW BESS delivers technical relief and enables solar-to-evening energy shifting, but overcorrects under registered net-metered capacity, underscoring the need for data-driven storage sizing and dispatch

System performance under registered and AI-estimated solar scenarios following 10 MW BESS integration

	Daytime		Night-time
Distributed Solar Capacity (MW)	95	177	0
Power Flow (MW)	-12.4	-78.4	23.2
Transformer Loading (%)	12	48	17
Voltage Profile (pu)	1.03	1.03	1.03
Power Factor	0.65	0.98	0.92

Reverse power flow reduced from -118 MW to -78.4 MW under actual solar capacity, a 34% improvement that meaningfully reduces operational stress on the network, though notable reverse flow persists and cannot be fully resolved through batteries alone.

Voltage compliance is fully restored across all scenarios, dropping from 1.06 pu to 1.03 pu in both daytime conditions and bringing the network back within Grid Code 2023 thresholds and eliminating the compliance violation identified in the pre-BESS analysis.

Transformer loading falls from 76% to 48% under AI-estimated solar penetration, and from 34% to 12% under registered capacity – a substantial improvement that extends the operational headroom of the DFNC step-down transformers under both scenarios.

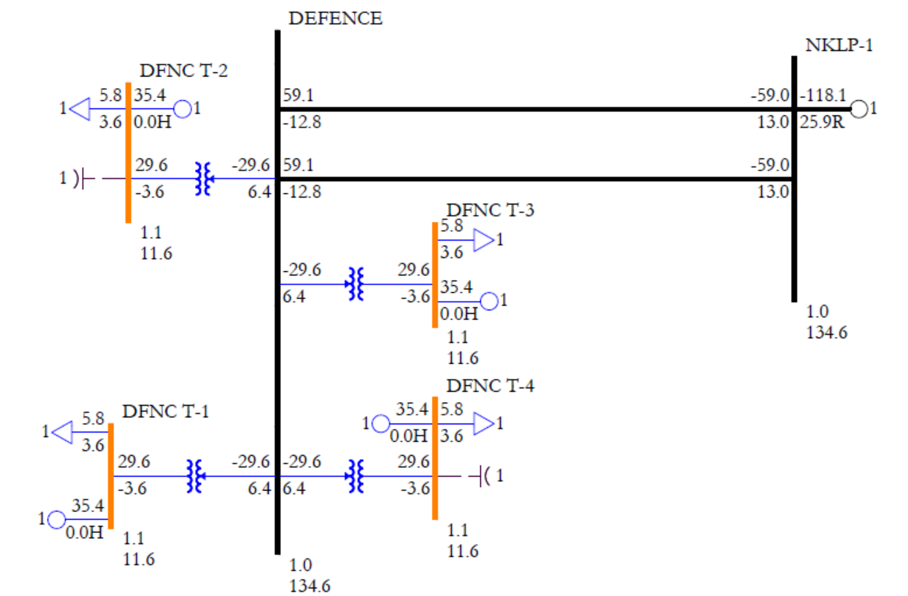
BESS reduces reverse power flow and restores voltage compliance, with a secondary opportunity for evening energy arbitrage. However, under the 95 MW case, BESS alone creates power-factor penalties, signalling the need for complementary reactive power compensation

Source: HeraldX & Renewables First, LESCO (Energy & Demand Forecast Report LESCO FY2024-35.pdf)

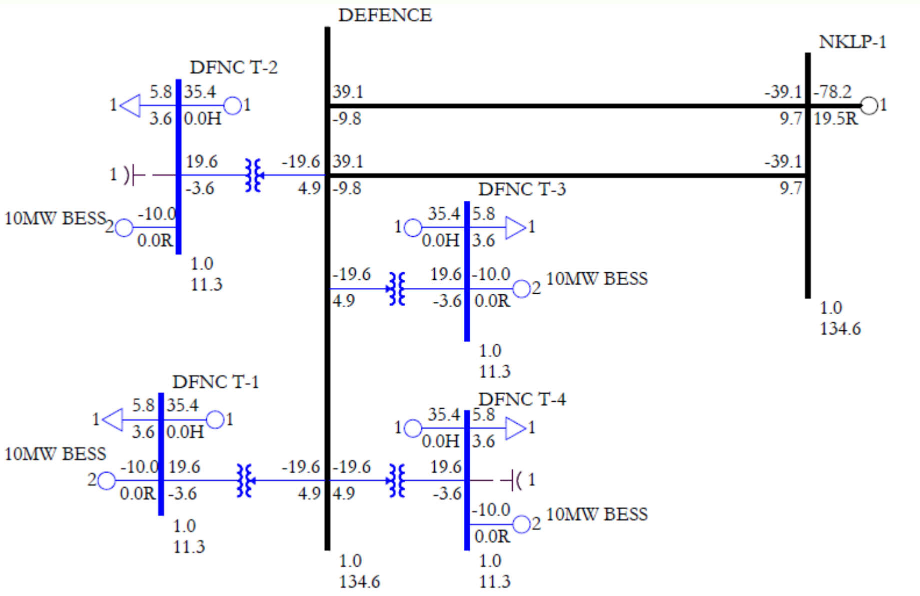
Grid impact assessment: Network simulation outputs

Side-by-side PSS/E load flow outputs showing network behaviour under AI-estimated solar penetration, before and after a 10 MW BESS is introduced at the 11kV bus

PSS/E load flow: 177MW solar scenario, daytime conditions, without BESS



PSS/E load flow: 177MW solar, daytime conditions, 10MW BESS at 11kV bus



- The load flow confirms that BESS reduces network stress, but residual flows remain across DFNC transformers, showing that storage mitigates but does not fully resolve feeder-level impacts.
- The NKLP-1 link exports 118MW of reverse flow into the wider LESCO network, confirming that the grid impact of unaccounted solar propagates well beyond the study boundary.
- The remaining flow pattern highlights the need for targeted reinforcement and LV-level modelling to identify where voltage rise, loading stress, and mitigation needs are likely to concentrate.

Source: HeraldX & Renewables First, LESCO (Energy & Demand Forecast Report LESCO FY2024-35.pdf)

4. Results and limitations

Study results and limitations

When actual solar penetration is nearly double official estimates, the grid planning gap becomes a reliability risk. This analysis quantifies that risk and offers a replicable path forward

Key takeaways

Distributed solar data gap is real and significant

1. HeraldX's AI model estimated 177 MW of installed solar capacity at the 132KV Old Defence Grid Station, nearly double LESCO's registered 95 MW. The difference represents solar that is operationally present but institutionally invisible, with direct consequences for how the network is planned and operated.

Unaccounted solar materially changes grid behaviour

2. Under actual solar penetration, reverse power flow nearly doubled and transformer loading increased from 34% to 76%, both under daytime conditions. Network behaviour is already materially different from what official data suggests, and the gap is widening.

BESS is only a partial solution

3. A 10 MW BESS restores voltage compliance and halves reverse power flow but degrades power factor from 0.99 to 0.65, signalling that storage alone is insufficient and must be complemented by broader grid reinforcement measures.

The AI and PSS/E framework is replicable and ready to scale

4. The methodology developed for this analysis is feeder-agnostic and can be extended to any DISCO with available network data and satellite coverage, making it a scalable tool for system-wide planning across Pakistan's distribution network.

Limitations

Below factors require careful reflection while interpreting the findings

- Analysis confined to the 132KV Old Defence Grid Station and cannot be generalised to other areas without replication.
- Solar capacity modelled as aggregated feeder-level injection, without distinguishing net-metered and behind-the-meter sources.
- Imagery-based detection subject to data currency, geometric distortion, and glare-related constraints.
- Simulations based on representative daytime and night-time snapshots; full-year time series analysis was outside scope.
- Study focused on steady-state power flow; transient and dynamic system responses were not assessed.
- BESS evaluated as an indicative mitigation option only; broader flexibility measures were not modelled

Source: HeraldX & Renewables First

Geospatial mapping limitation

Satellite-based mapping has its limitations, which we have addressed in the best possible manner feasible. We are actively working on further optimisation of our model and would welcome any feedback

Data currency

Satellite imagery captures installations as they appeared at the time of acquisition. Installations added, removed, or expanded between imagery acquisition in March 2025 and analysis in May 2025 may not be reflected, introducing a potential lag in reported capacity figures.

Results are clearly time-stamped against the imagery acquisition date, so figures are interpreted within the correct temporal context. This mitigates misinterpretation but does not account for installations that changed after acquisition. Capacity figures should be treated as accurate to March 2025, not the present day.

Panel geometry distortion

Solar panels captured at oblique angles can shift or overlap in the ML model output, reducing the spatial precision of individual detections. This is particularly relevant for edge cases near feeder boundaries where area and capacity estimates are most sensitive to positional accuracy.

Post-processing rectification identifies and corrects distorted detections manually before results are finalised. This reduces but does not eliminate geometric error. Detections at acute angles near feeder boundaries remain the most challenging to correct and carry the highest residual uncertainty in the final capacity estimates.

Solar reflection and glare

Direct sunlight overexposes panel surfaces and eliminates the visual signature the model relies on for detection. Panels in high-irradiance conditions are prone to missed detections, meaning installed capacity can be understated in areas with high solar exposure.

Imagery acquisition is scheduled to minimise peak-hour glare and residual missed detections are captured during manual rectification. However, heavily glare-affected tiles cannot be fully reco-vered through post-processing alone. In areas of very high solar irradiance, a small degree of undercounting remains possible even after rectification.

Source: HeraldX

HeraldX builds AI-powered platforms for cleaner, more resilient power systems. Using proprietary machine learning and geospatial models, we turn what is happening on the world's rooftops and grids into reliable insights, enabling public and private sector decision-makers to achieve a just energy transition.

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Renewables First (RF) is a think and do tank for energy and environment. Our work addresses critical energy and natural resource issues with the aim to make energy and climate transitions fair and inclusive.

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