High Renewable Energy Penetration: Challenges and Pathways Toward a Sustainable Power Grid

Renewable Energy Uptake in South East Asia

Wind Power Capacity

51.5+ GW

India

Leading regional wind capacity

1.9 GW

Pakistan

Growing wind infrastructure

267 MW

Sri Lanka

Island nation progress

60 MW

Bangladesh

Early stage development

Solar Power Growth

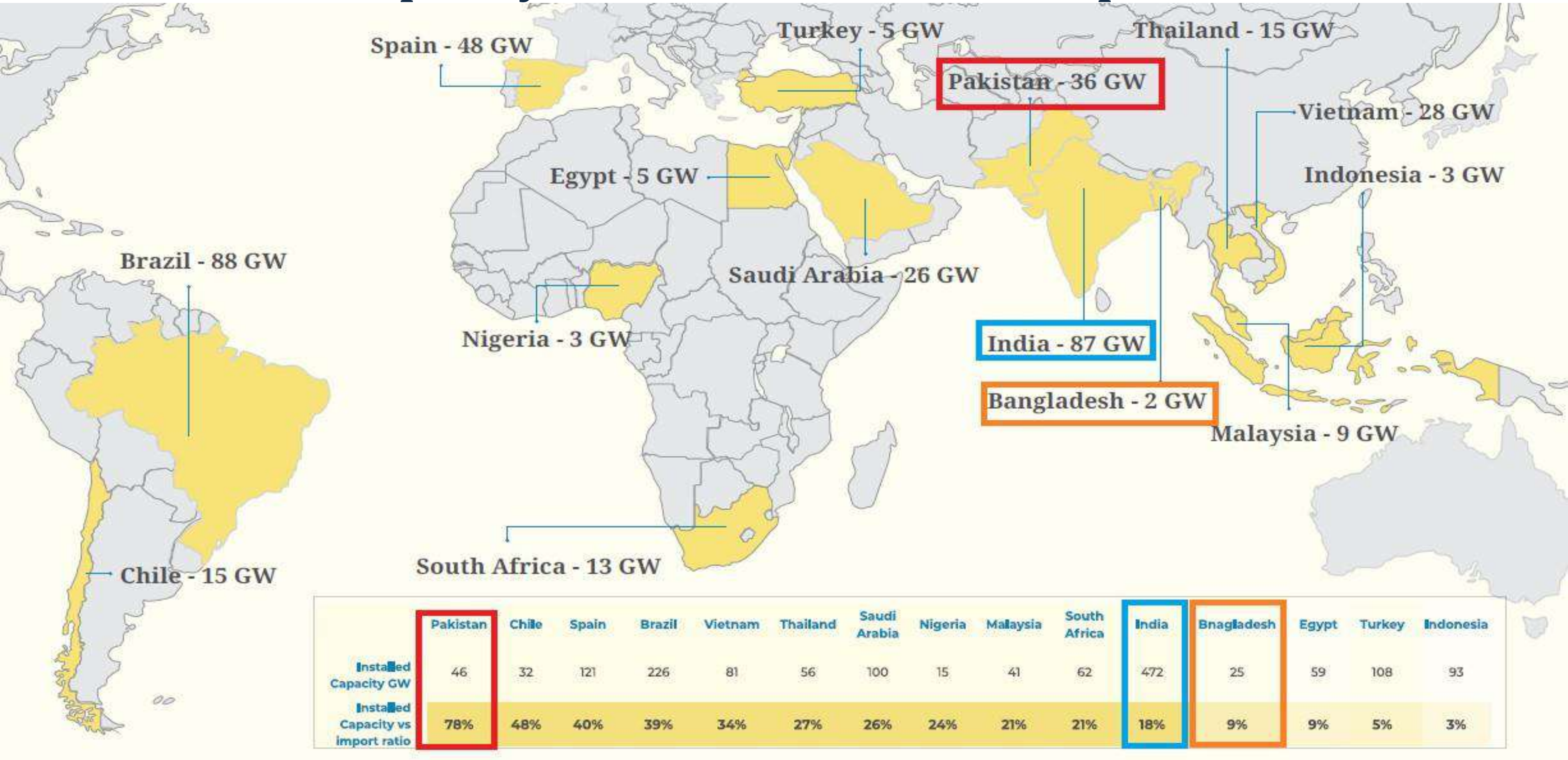
2024 Installed

- **India:** 14+ GW utility-scale
- **Pakistan:** 500+ MW utility, 7+ GW rooftop
- **Bangladesh:** 2 GW
- **Sri Lanka:** 1.7 GW rooftop

2025 Projections

- **India:** 39+ GW total additions
- **Pakistan:** ~25% generation share
- **Bangladesh:** 3 GW target
- **Sri Lanka:** 2+ GW milestone

Installed Capacity vs Chinese Solar PV Imports *(till 2024)*



	Pakistan	Chile	Spain	Brazil	Vietnam	Thailand	Saudi Arabia	Nigeria	Malaysia	South Africa	India	Bnagladesh	Egypt	Turkey	Indonesia
Installed Capacity GW	46	32	121	226	81	56	100	15	41	62	472	25	59	108	93
Installed Capacity vs import ratio	78%	48%	40%	39%	34%	27%	26%	24%	21%	21%	18%	9%	9%	5%	3%

Data Source: Ember and RF calculations

Pakistan's Renewable Surge

Solar Power

500+ MW utility-scale

7+ GW rooftop installations

Wind Power

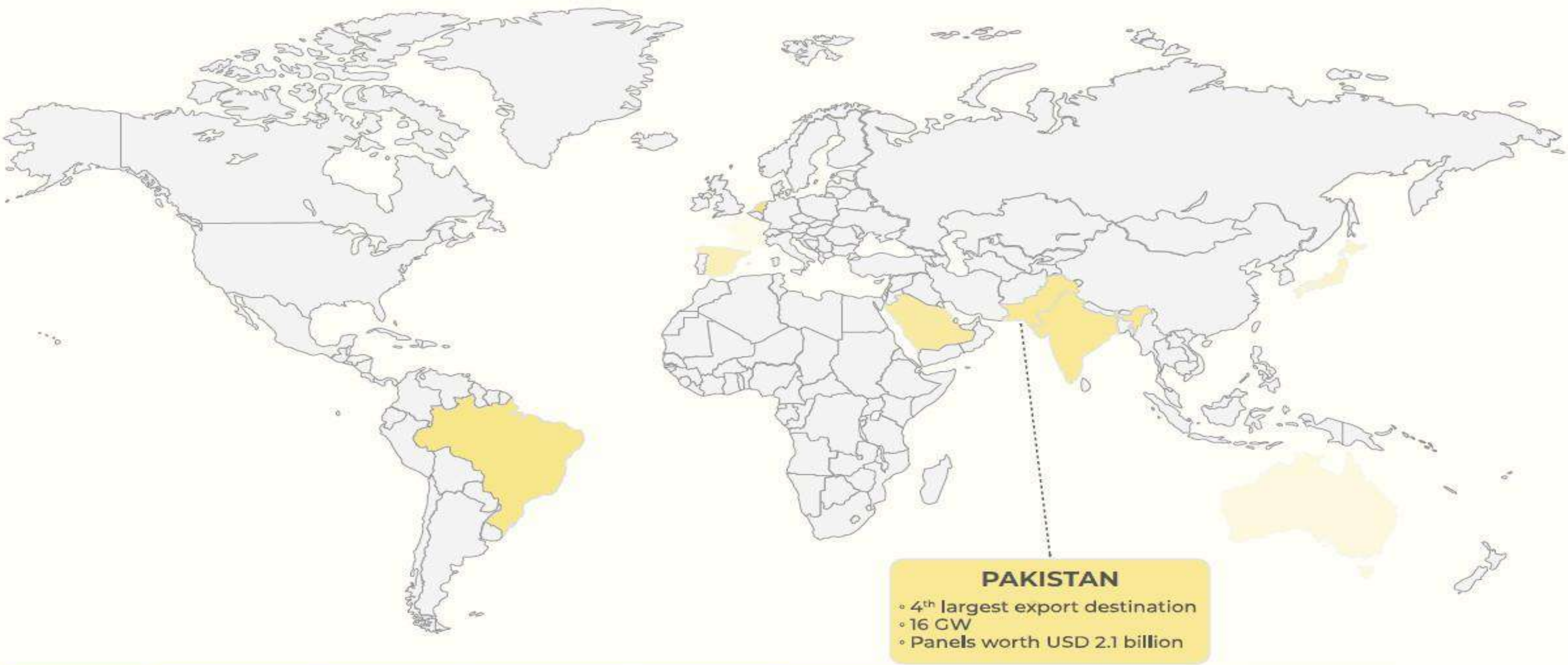
1.9 GW installed capacity

2025

~25% renewable generation share

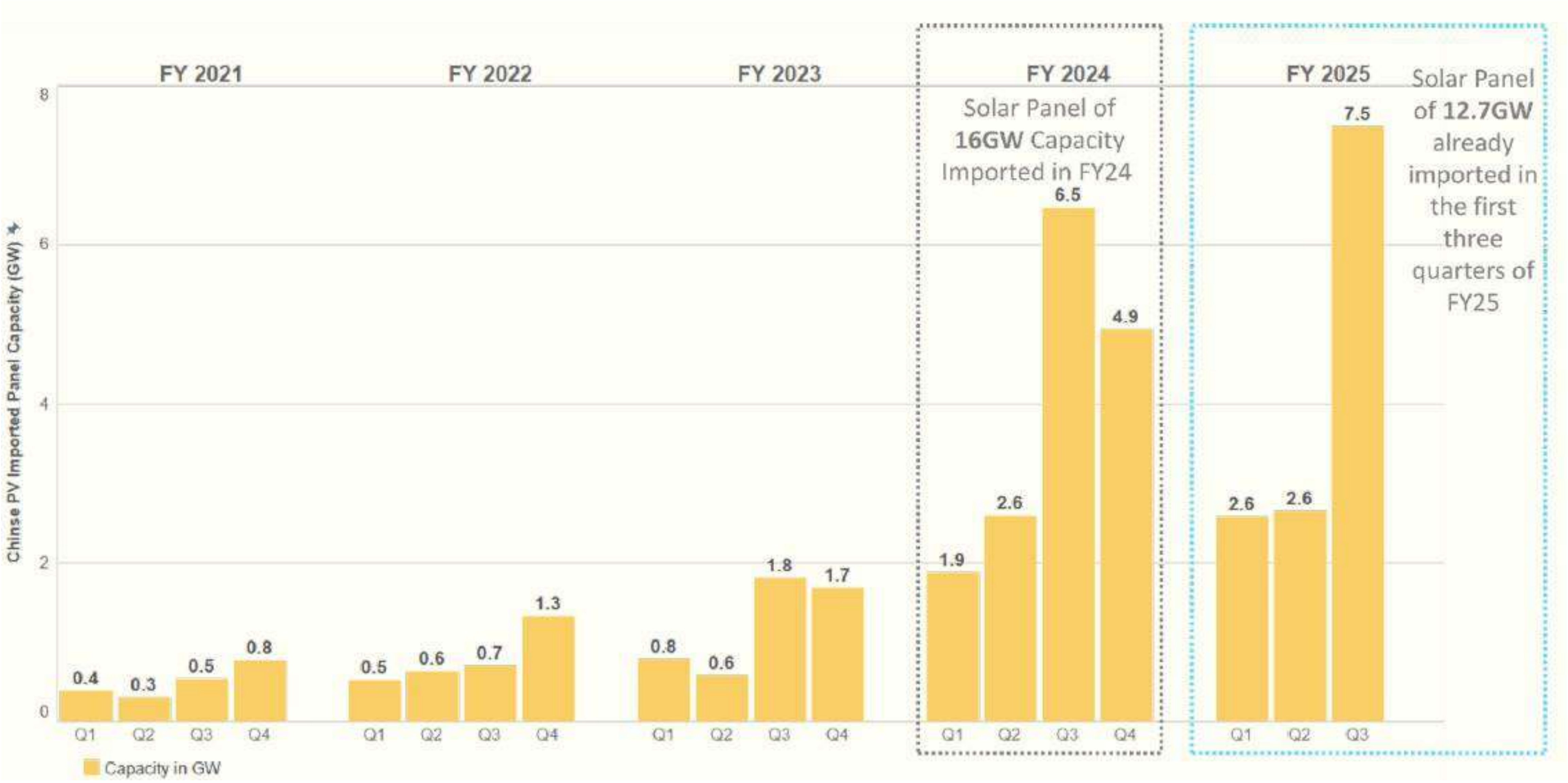
Rooftop solar continues surging

Top 10 Destinations for China Solar PV Exports in FY 2024 (GW)



Netherlands	Brazil	India	Pakistan	Saudi Arabia	Spain	Japan	Australia	France	Greece
41	23	21	16	13	11	7	7	6	5

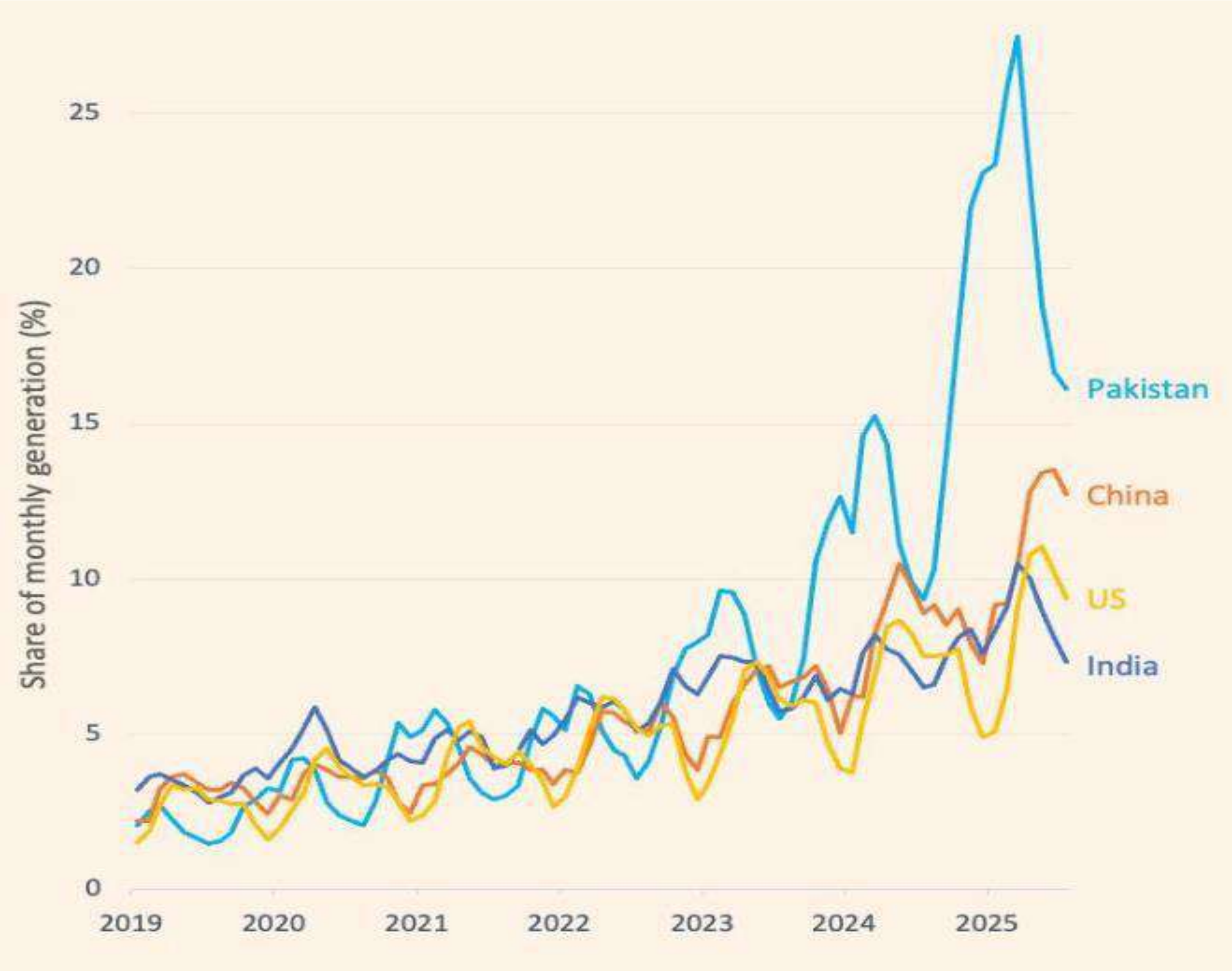
Pakistan Solar panels imports (GW), FY21 - FY25:Q3



Pakistan Solar Share in Monthly Electricity Generation

2% in 2019

Over 25% in 2025



Grid Challenges with Higher Renewable Energy Penetration

Understanding the complexities of integrating variable renewable sources into modern electrical grids

Weather Dependent Generation Creates Instability

Solar & Wind Variability

Weather-dependent output causes unpredictable generation fluctuations

Rapid Ramping

Quick generation changes lead to frequency instability risks

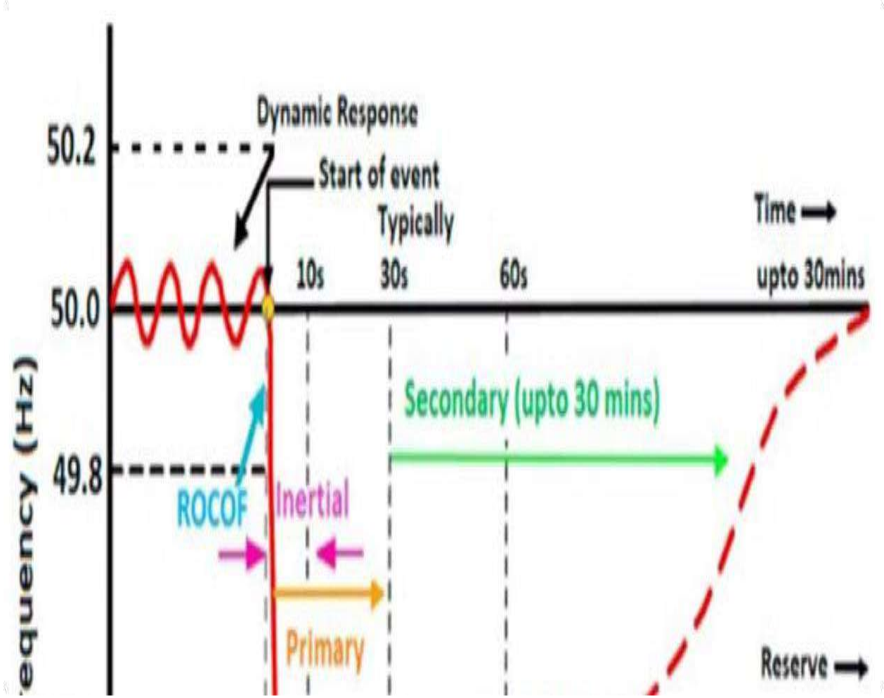
Supply-Demand Mismatch

Seasonal and daily variations don't align with consumption patterns

Grid Stability: From Synchronous to Inverter-Based Generation

Grid Stability Challenges

- Lower system inertia from fewer synchronous generators
- Voltage instability risks in weak grid areas
- Need for synthetic inertia solutions Fast frequency response requirements



Balancing and Reserves Needs

Energy Storage

Batteries and pumped hydro provide crucial backup during low RE periods

Spinning Reserves

Fast-response backup power ready to compensate for sudden generation drops

Flexible Generation

Gas turbines and hydro plants provide rapid response to fill supply gaps

Transmission Bottlenecks & Curtailment

Remote RE Locations

Offshore wind and solar require massive transmission upgrades

Grid Congestion

Limited transmission capacity creates bottlenecks during peak RE generation

Curtailment Losses

Overgeneration forces RE shutdown, wasting potential clean energy and revenue

Advanced Systems: Forecasting & Protection

Weather Forecasting Challenges

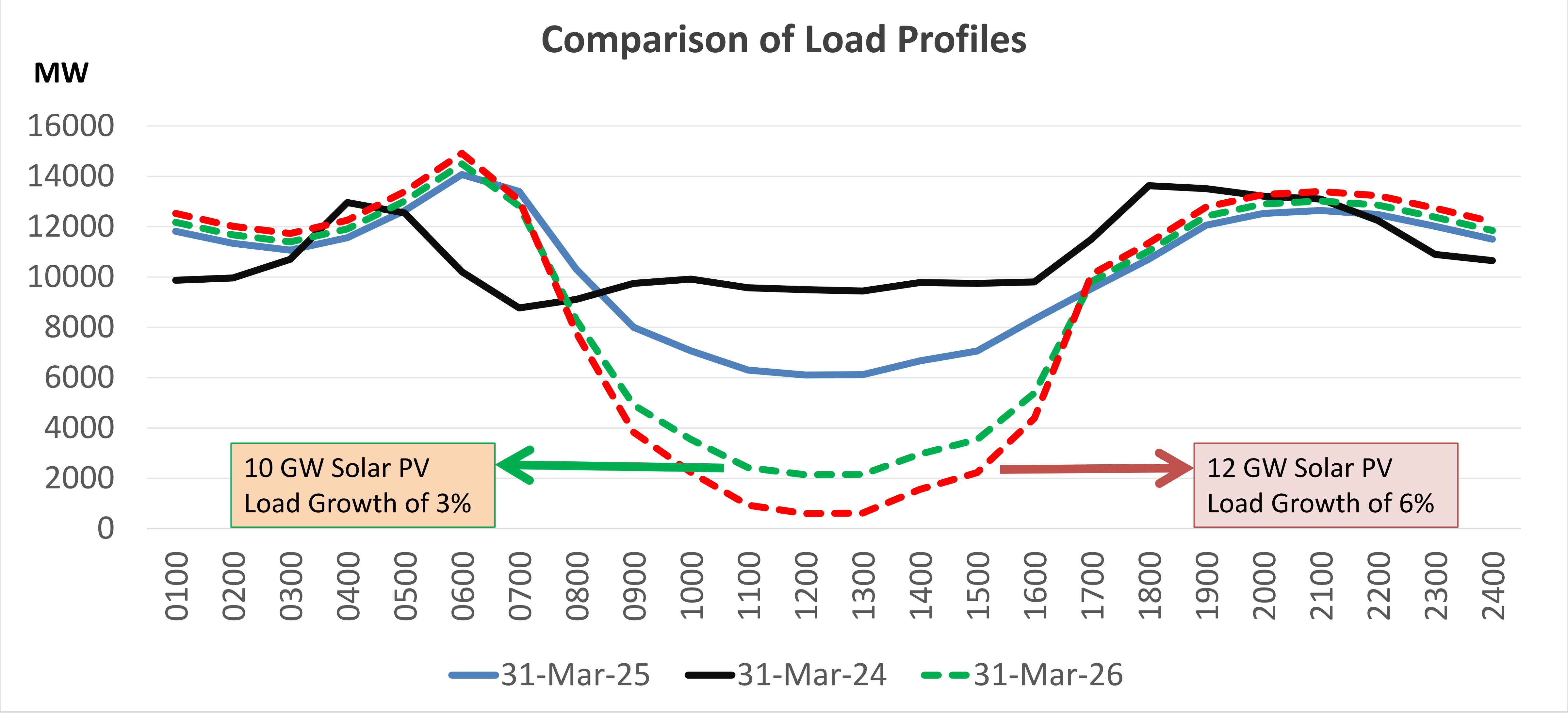
- Accurate RE prediction crucial for dispatch planning
- Weather uncertainty complicates real-time operations
- Day-ahead market planning becomes complex

Protection System Evolution

- Traditional fault detection schemes inadequate
- Advanced digital relaying required
- Grid-forming inverters needed

High Solar Penetration:
Challenges in Pakistan Power Grid

Pakistan: Intra-day Load Profiles

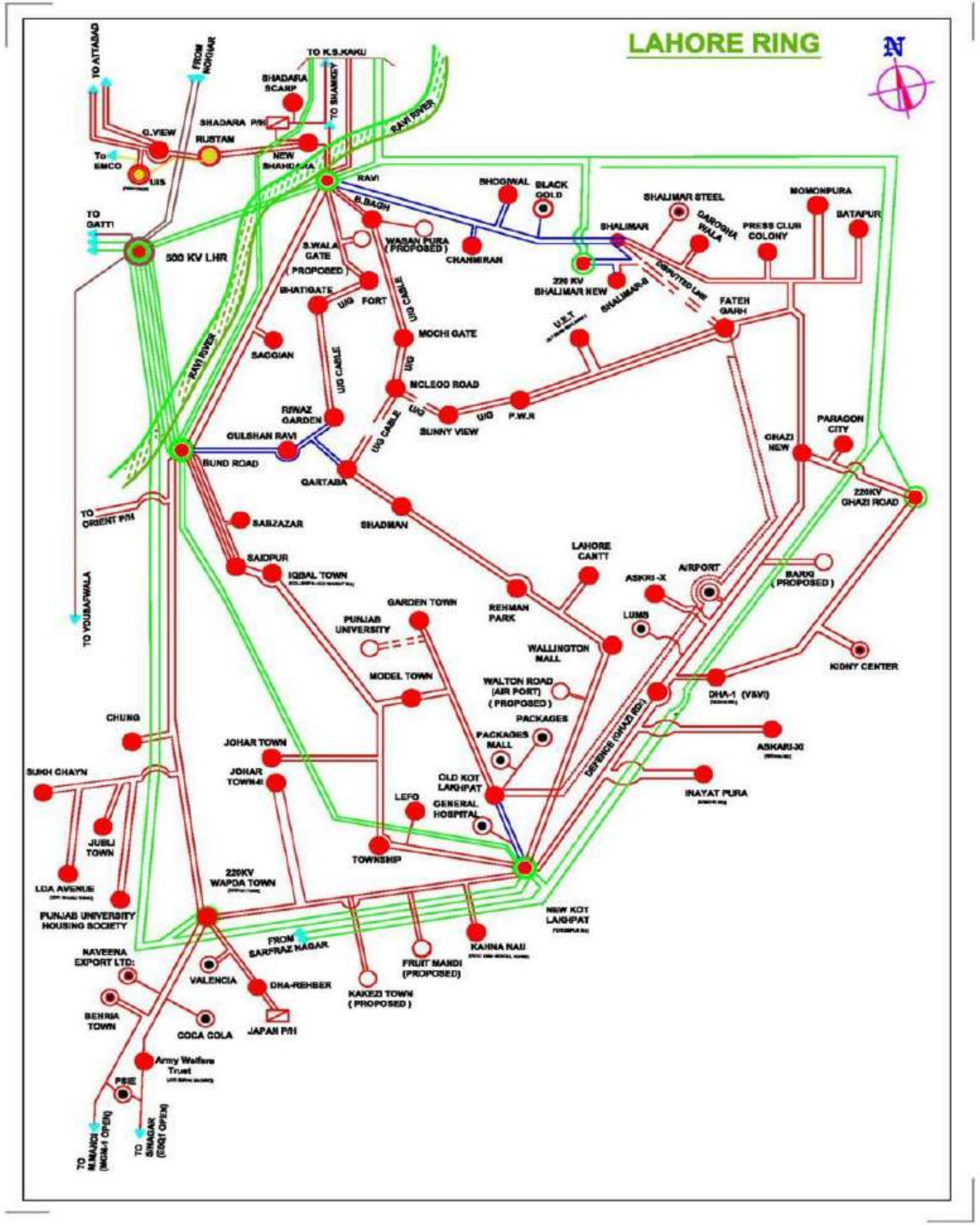


Grid Modernization: High Temperature Low Sag Conductors

- No Right of Way needed
- Double the Power Transfer Capacity without constructing new Line
- Can be operated at High Temperature
- Low Sag

Lahore HTLS Project

- Replacement for 66.5km 132kV Double Circuit Transmission line from ACSR Rail to HTLS conductor
- Project Cost: 8.20 Million US $
- Implementation Period: 2020 to 2023
- Useful life: 30 years



Grid Modernization: FACTS Devices

Advance Flexible AC Transmission Systems (FACTS)

- Enhancing the grid stability
- Increased VRE Integration
- Increase Grid flexibility, Reliability

Lahore SVC Project

- New kot Lakhpat (NKLP) 220/132kV Substation
- Deployment of Static Var Compensator (SVC)
- +450MVAR, -50MVAR
- Implementation Period: 2018 to 2021
- Useful life: 30 years

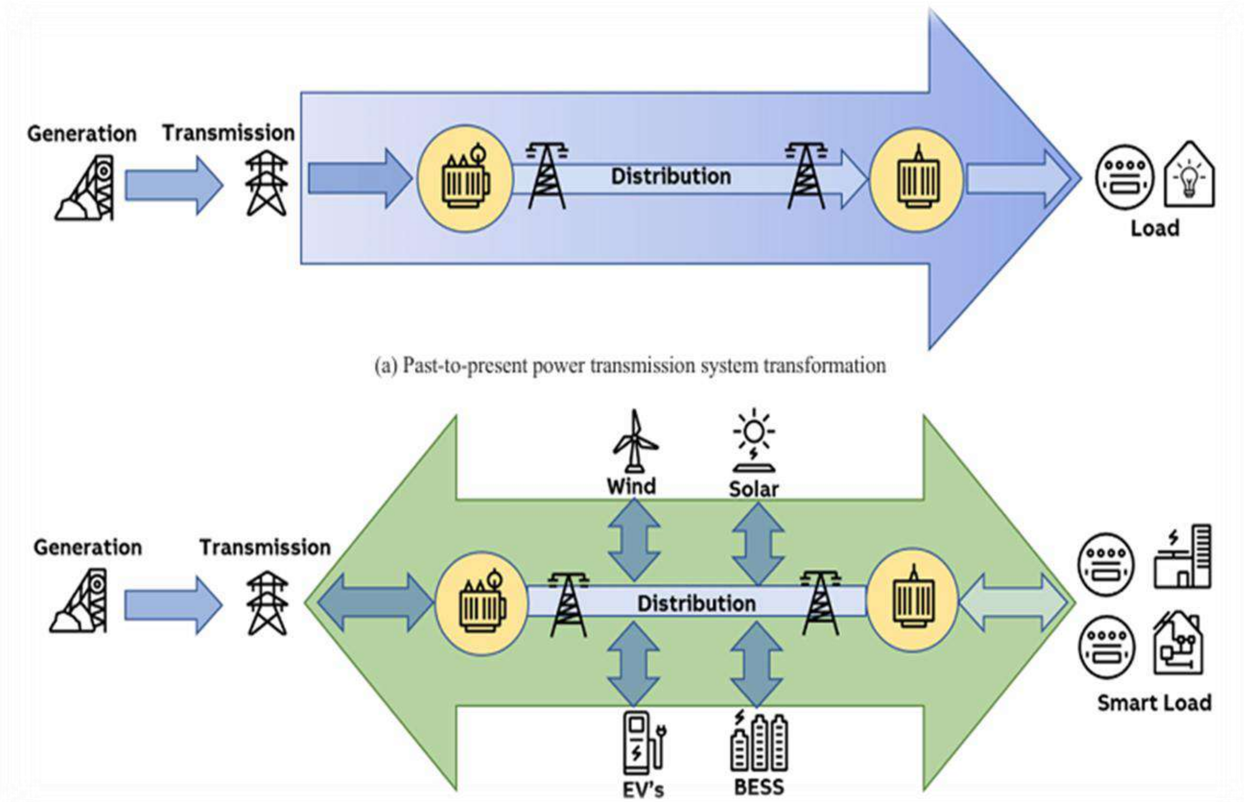
Battery Energy Storage Systems at Substations

BESS: Enhance Grid Stability and Flexibility

- Peak Load Management
- Renewable Smoothing
- Real and Reactive Power Management
- Voltage and Frequency Regulation
- Ancillary Services
- Energy Arbitrage

Solar PV Impact Analysis

132 kV Dera Chahal Grid Station - DHA Lahore



Introduction & Problem Statement

- **132 kV Dera Chahal Grid Station** in DHA Lahore is experiencing significant operational challenges due to widespread adoption of rooftop solar PV systems.

- **Key Problem:** Unforeseen operational issues, primarily characterized by substantial **reverse power flow** during peak solar generation hours.

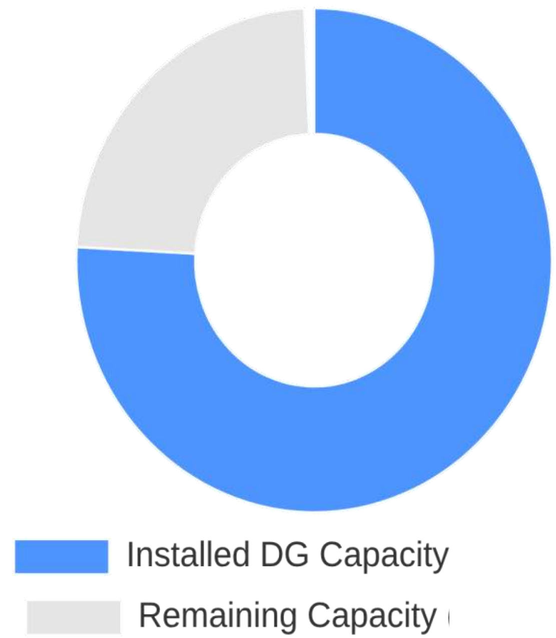
- **Objective:** Provide comprehensive impact analysis on system stability, asset longevity, and operational efficiency.

- This analysis aims to sensitize stakeholders to challenges posed by high solar PV penetration and inform strategic decisions for sustainable grid management.

Grid Overview

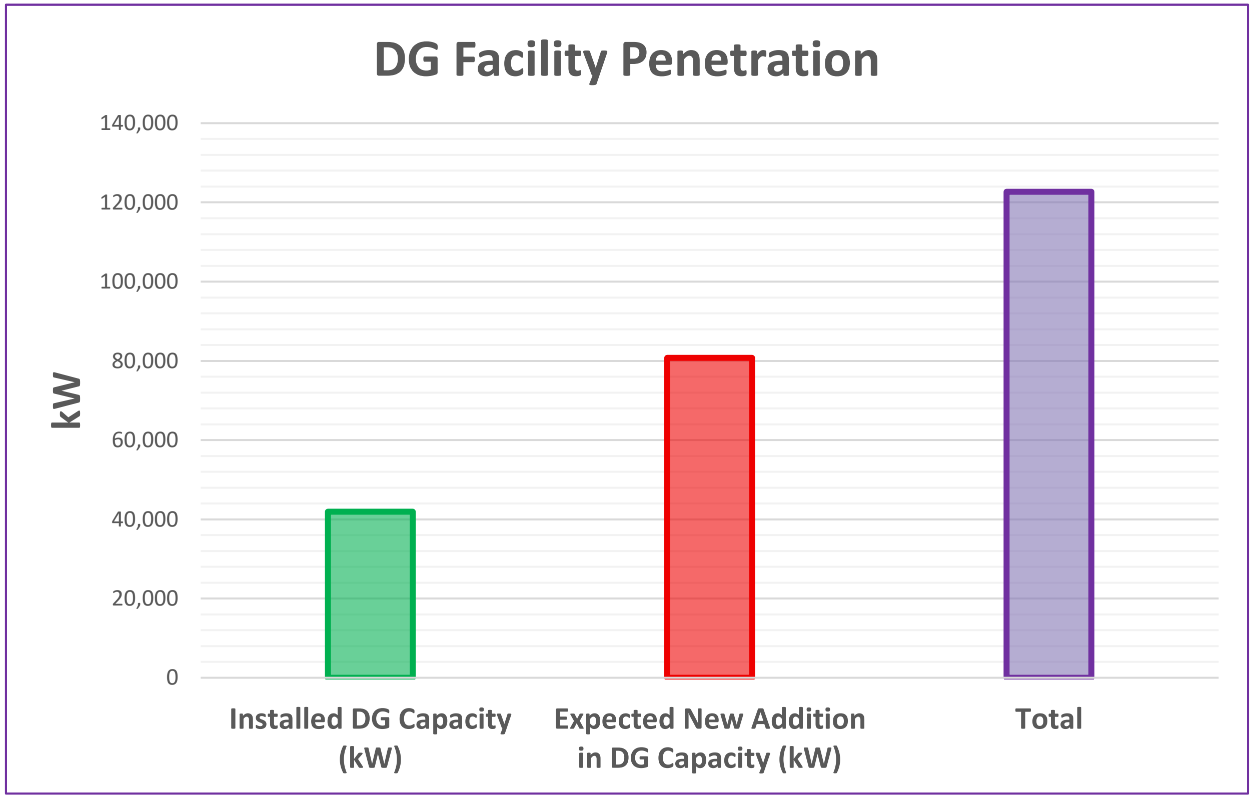
Grid Station Name:	132 kV Dera Chahal Grid Station
Location:	DHA Lahore
Transformer T1 Rating:	20/26 MVA
Transformer T2 Rating:	20/26 MVA
Total DG Capacity:	41.923 MW
Area Characteristics:	Predominantly domestic and mixed-use with high rooftop PV installations

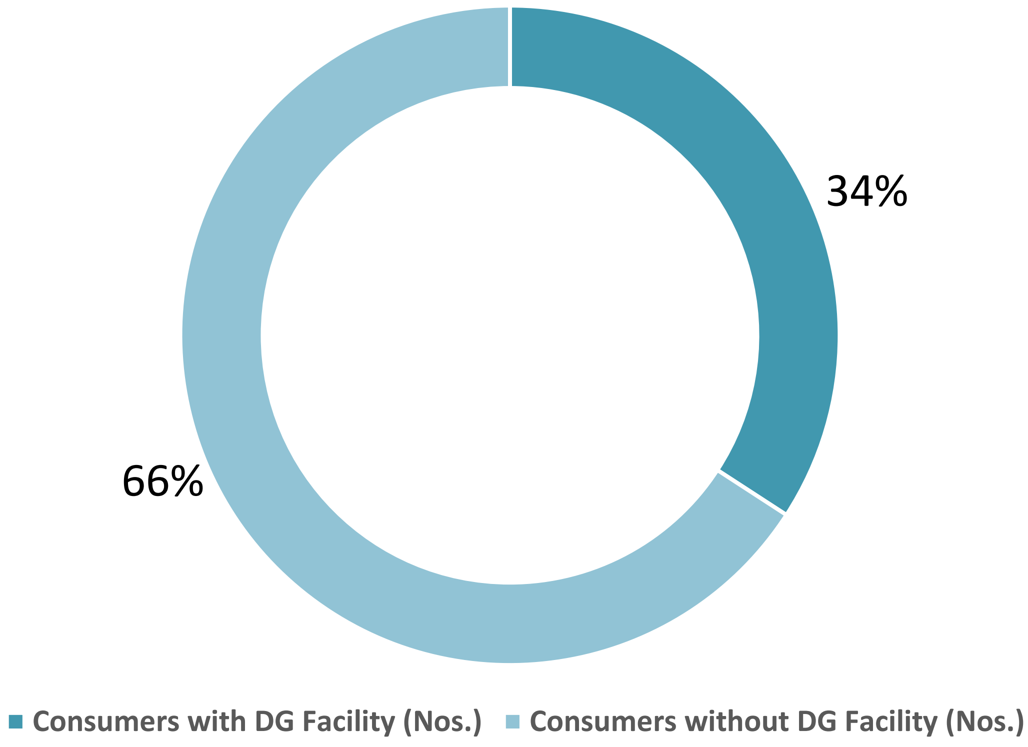
Grid Capacity Utilization



- The grid station has a **total capacity of 52 MVA** with two transformers.
- **High PV penetration** with installed distributed generation capacity of 41.923 MW, which is **89.6% of the total grid capacity**.

DG Penetration Analysis



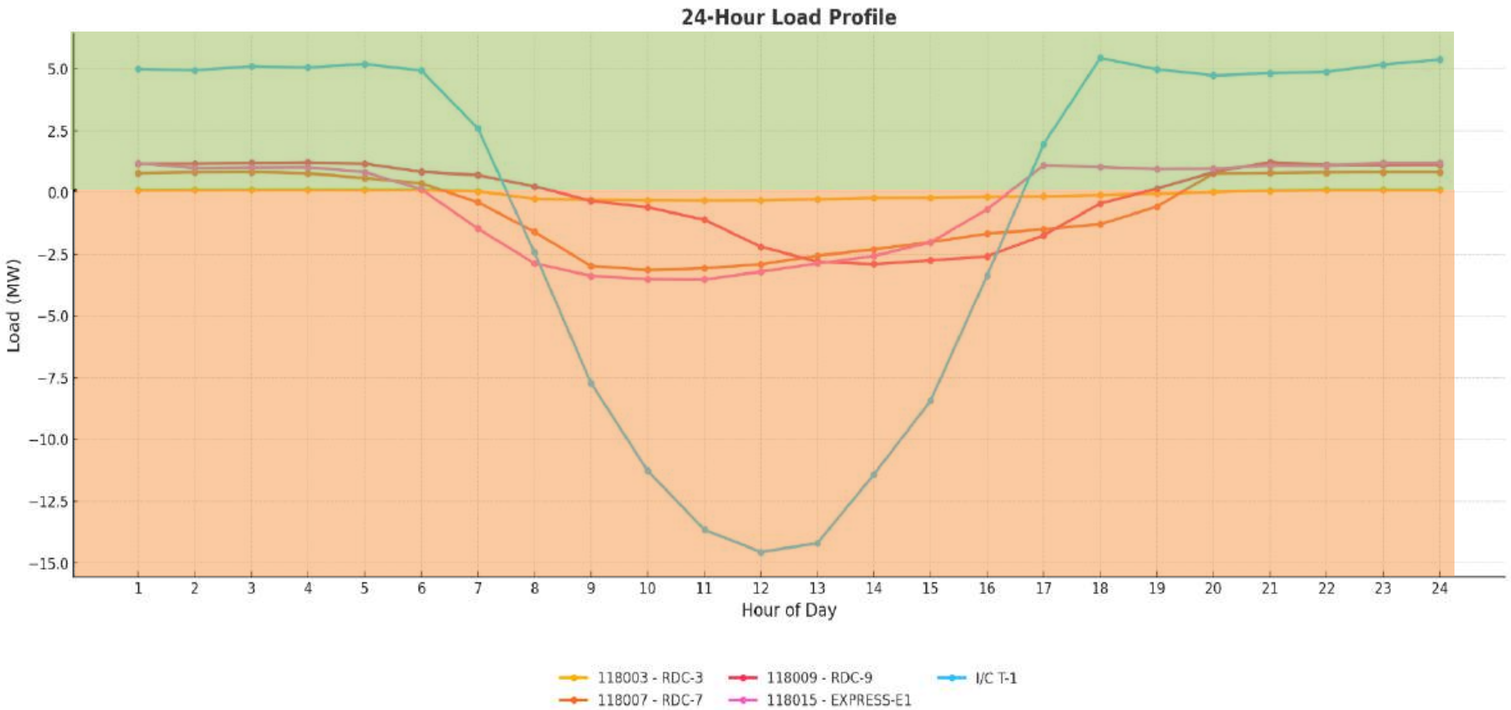


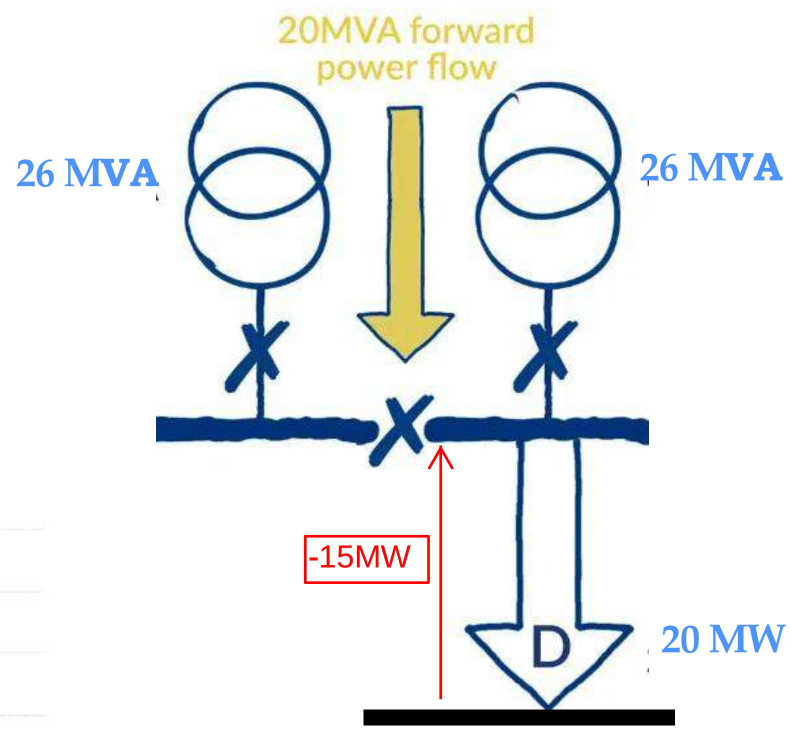
Key Insights:

- **Installed DG capacity exceeds sanctioned load** by approximately 3,259 kW (8.43%).
- **Potential DG growth** is approximately 80,764 kW.
- Top 5 feeders account for **95.5% of total installed DG capacity**, indicating concentrated solar PV deployment.

Active Power (MW) Flow Trends

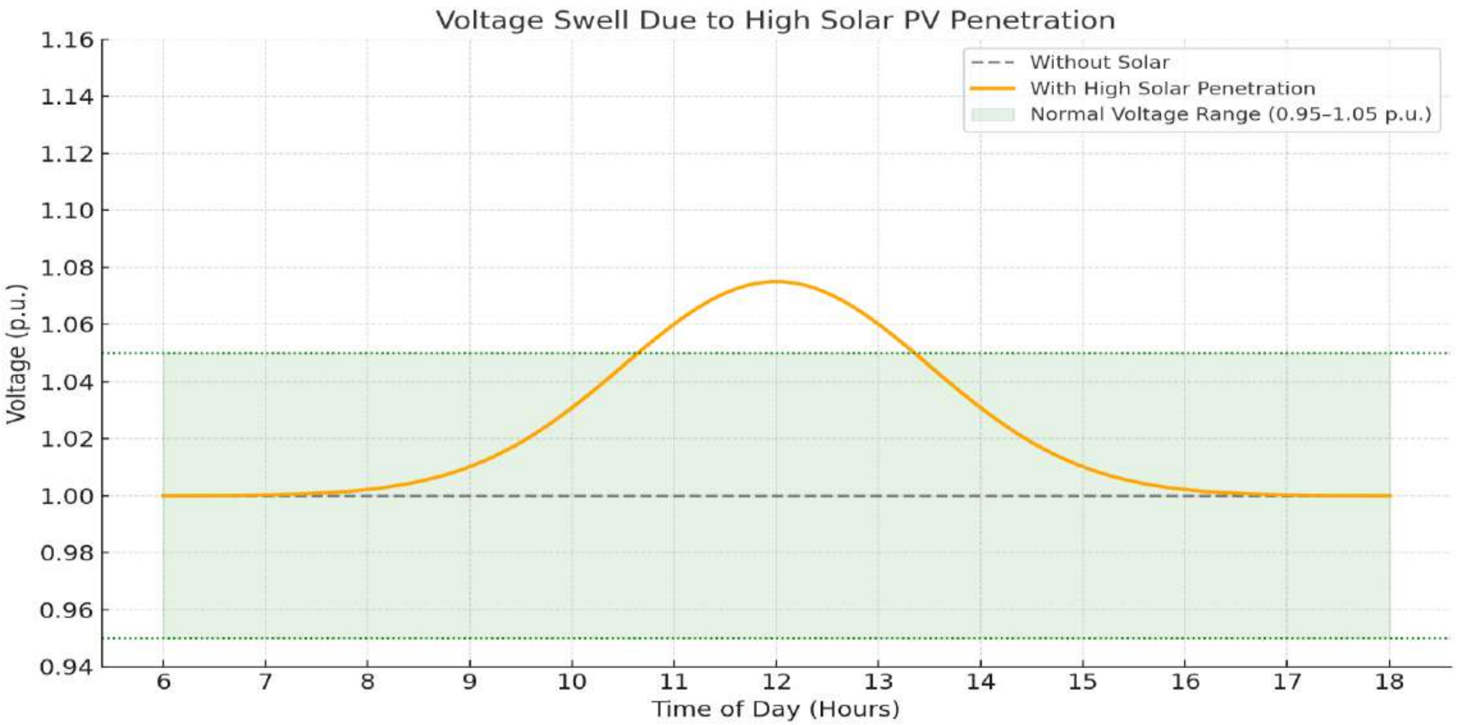
- Grid has transformed from a **conventional load sink** to a **power injection node**.
- **Peak forward load flow:** **+20 MW**
- **Peak reverse power flow:** **-15 MW**
- Most pronounced reverse flow occurs **between 12:30 AM-2:00 PM**





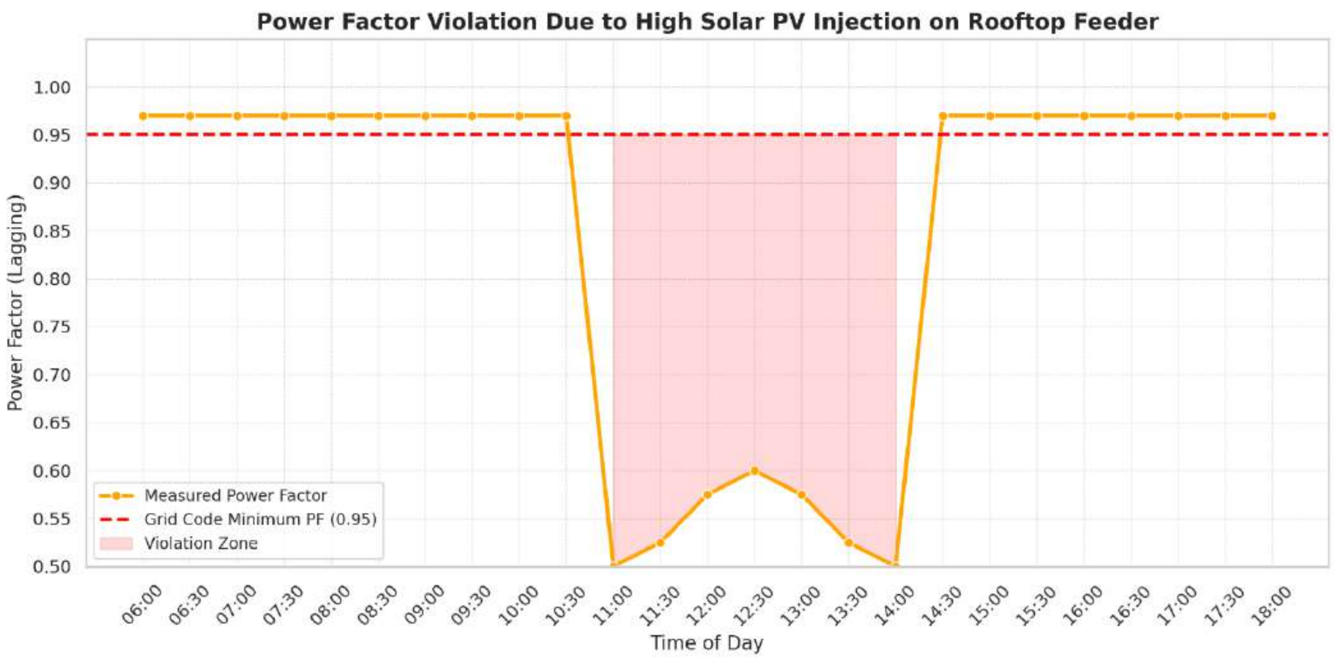
Voltage Trends

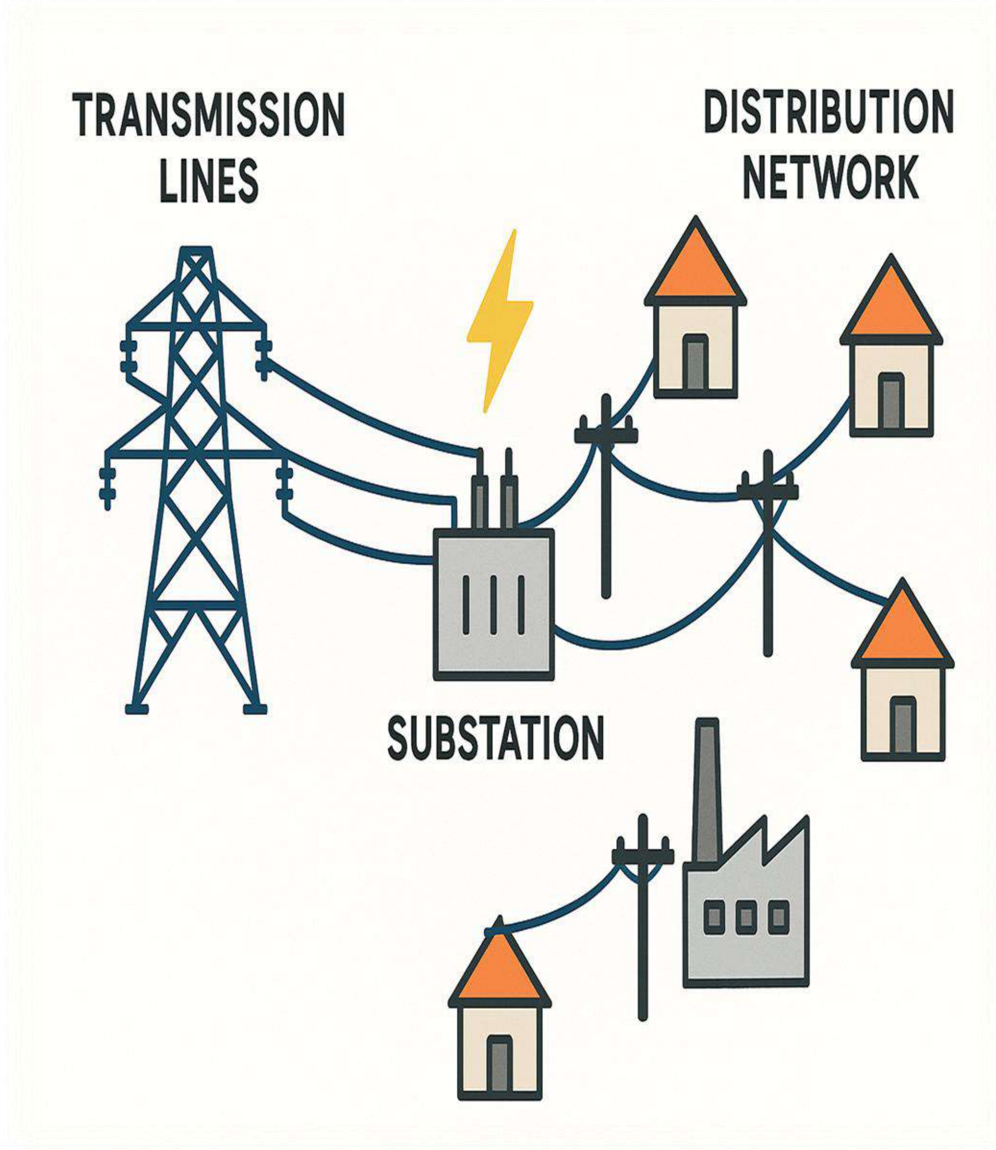
- Feeder and LT network have experienced **Severe Voltage Swells.**
- It led to **tripping of Solar PV Inverters.**
- Acceptable **Range of Voltage (PU)** as per Grid Code: **0.95 – 1.05**
- Most pronounced voltage swell occurs **between 11:00 AM-1:00 PM** because house owners are keep on increasing the inverter voltage cutoff to avoid tripping hence swells are also increasing day by day.



Power Factor Trends

- Transformers are experiencing **PF dips during midday hours.**
- It leads to **Grid instability.**
- Acceptable **Range of PF** as per Grid Code: **≥ 0.95**
- May require mitigation through **reactive power compensation**, **inverter control tuning**, or **local storage solutions**.





Grid Parameters Performance Summary

Grid Station Details		Voltage (PU)		Power Factor		Power Flow (MW)	
Parameter	**Value**	**Criteria**	**Recorded**	**Criteria**	**Recorded**	**Peak Power**	**Reverse Power**
Sanctioned Load (kW)	38,664	0.95 - 1.05	**1.1**	0.95	**0.6-0.9**	20	-15
Installed DG Capacity (kW)	41,923						

Key Performance Issues:

- **Voltage exceeds criteria**: Recorded voltage of 1.1 is above the acceptable range of 0.95-1.05, indicating overvoltage conditions.
- **Power factor below standard**: Recorded power factor of 0.6-0.9 is below the criteria of 0.95, reducing system efficiency.
- **Significant reverse power flow**: -15 MW reverse power flow represents 75% of the peak forward power (20 MW), indicating substantial bidirectional stress on the grid.

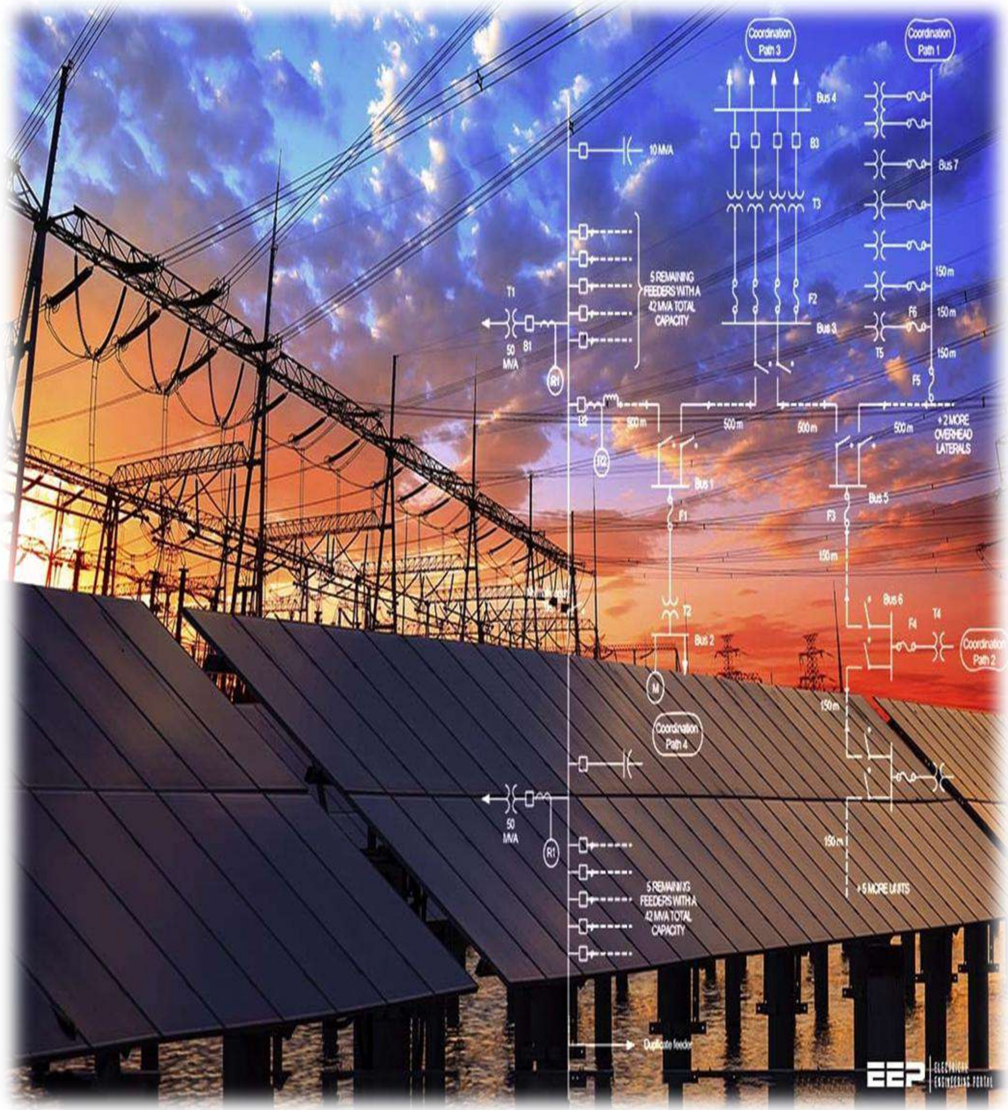
Protection & Coordination Challenges

⚠️ Key Issues Introduced by Reverse Power Flow

- **Directional Fault Currents:**
    - Traditional protection assumes unidirectional current (grid → load).
    - PV generation can reverse current direction, confusing protective devices.

- **Relay Maloperation or Non-Operation:**
    - Non-directional overcurrent relays may fail to detect or isolate faults.
    - Faults might not be cleared if power flows from PV side.

- **Coordination Disruption:**
    - Upstream and downstream device coordination is compromised.
    - Fuse-blowing and relay tripping sequences may be inconsistent.



Impact on Distribution Transformer

- **Reduced Lifespan:** High reverse power flow overloads transformers, significantly shortening their operational life (up to 25%) due to increased winding temperatures and insulation degradation.
- **Increased Losses:** Reverse power leads to higher core and harmonic losses within the transformer.
- **Thermal Cycling:** Fluctuating DER output causes frequent thermal cycling, further degrading insulation and reducing transformer life.
- **Voltage Regulation Issues:** Reverse power can cause overvoltage on the HV side and challenges for traditional tap changers designed for forward flow.
- **Protection Challenges:** Traditional protection relays may experience spurious tripping, and protection coordination becomes more complex due to altered power flow patterns.
- **Design & Operational Adjustments:** Mitigating these issues often requires network reinforcement and specialized control schemes.

Technical Implications

Voltage Rise

Voltage rise beyond statutory limits (approximately **260V at LT side**) has been consistently observed during peak solar generation periods.

Equipment Degradation

Overvoltage leads to **premature degradation** of electrical equipment and poses significant safety risks to connected devices.

Transformer Stress

Transformers designed for unidirectional power flow are now operating in **off-design conditions** as power flows from LT side to HT side.

Protection Miscoordination

Existing protection schemes configured for unidirectional fault currents face **increased risk of miscoordination** due to bidirectional power flow.

- These technical challenges require **immediate attention** to prevent potential system failures and ensure grid stability.

Conclusion & Recommendations

> The 132 kV Dera Chahal Grid Station serves as a **compelling case study** of the challenges faced by urban grids undergoing significant solar excess penetration.

Key Recommendations

- **Battery Energy Storage System** (BESS) needs to be deployed at Grid Scale to cater the reverse flow. (3 scenarios are given on next slides)
- **Careful review** of further Distributed Generation (DG) capacity sanctioning, particularly solar PV.
- Integration with a **holistic understanding** of potential impacts on the existing system.
- Implementation of **adequate grid modernization** and adaptive operational strategies.
- **Proactive management** to prevent infrastructure damage, compromised power quality, and reduced grid reliability.

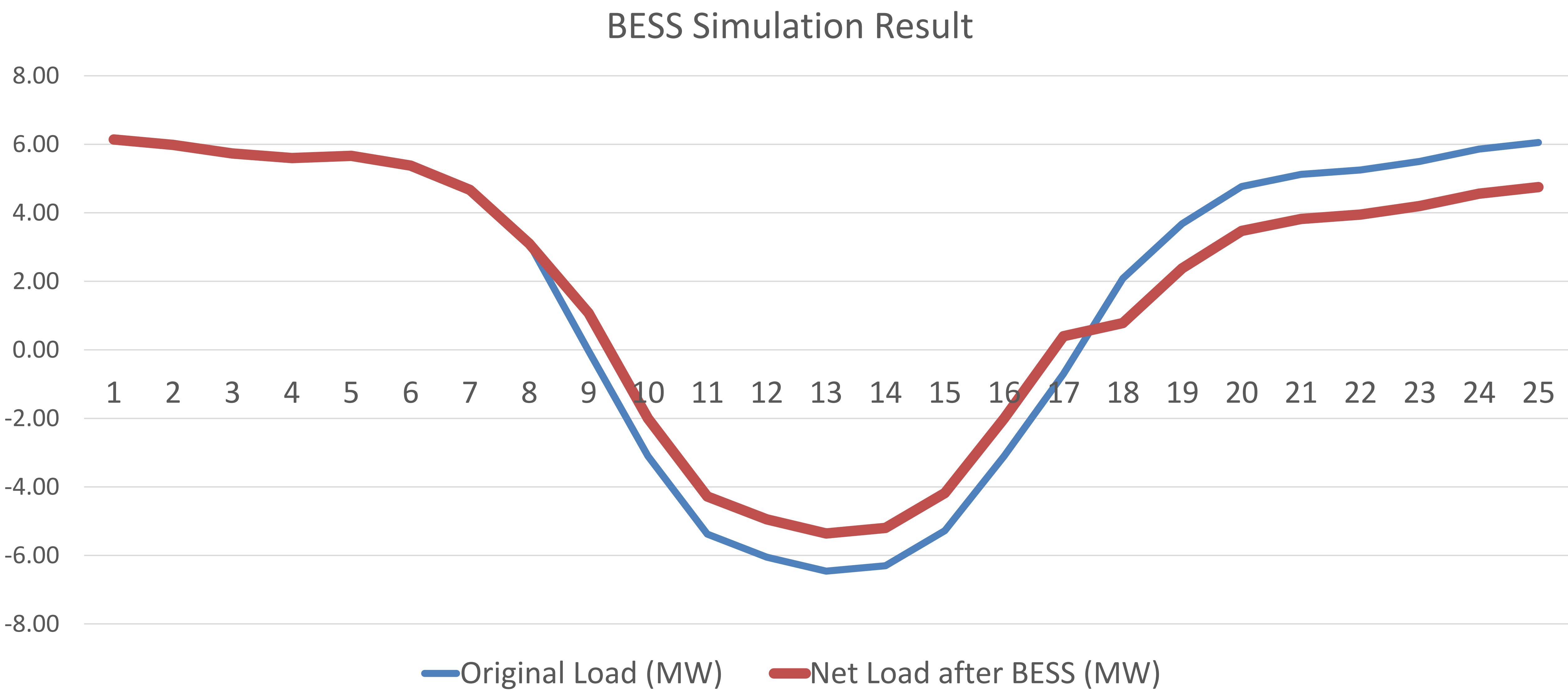
Uncontrolled proliferation of DG without proper planning risks severe damage to infrastructure and compromises grid reliability.

How BESS can solve excess solar issue

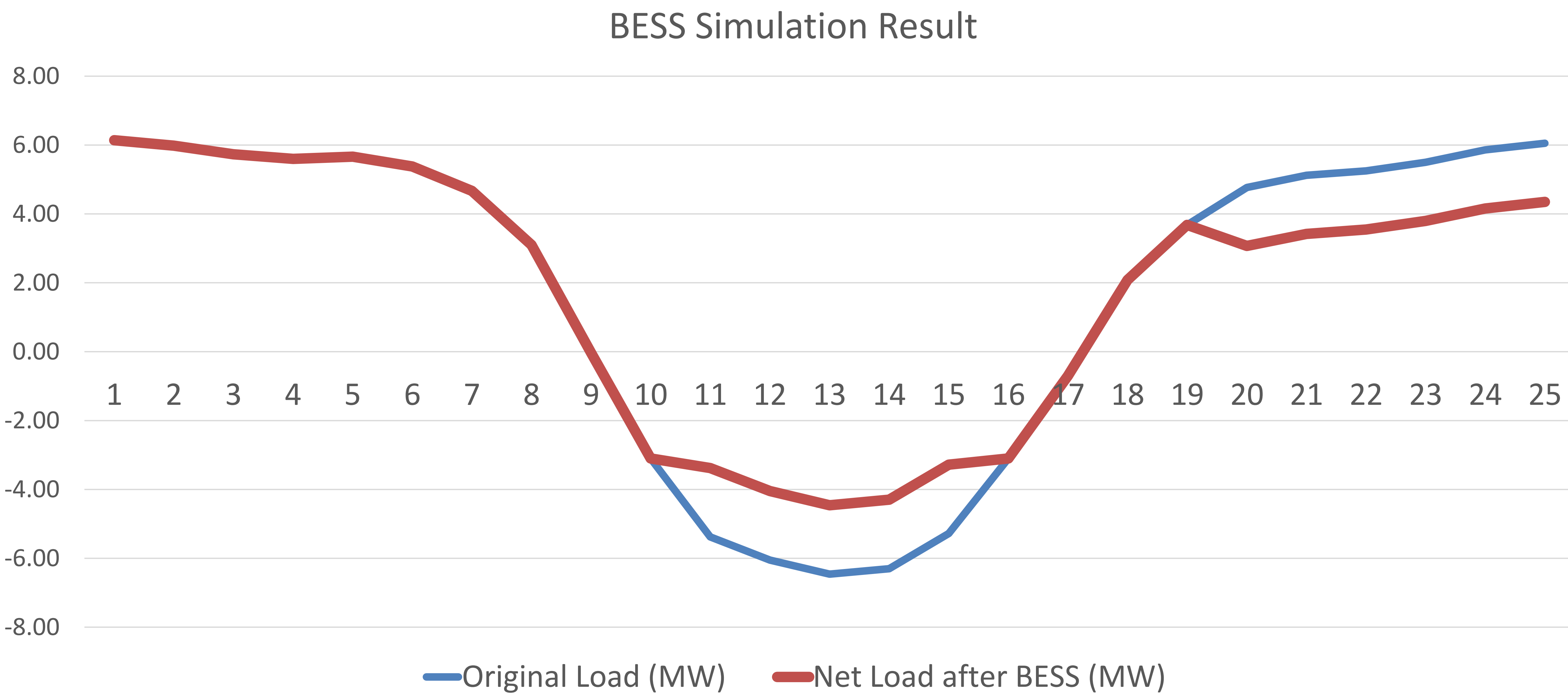
- **Battery Energy Storage System (BESS)** can be deployed at Grid Scale in the switchyard that can act both as **load (Store excess solar power)** and **generator (Deliver low cost power during peak).**

- Three Scenarios are discussed:
  - 10MWh **Grid Forming** Mode
  - 10MWh **Peak Shaving** Mode
  - 28MWH **Best Case** Scenario

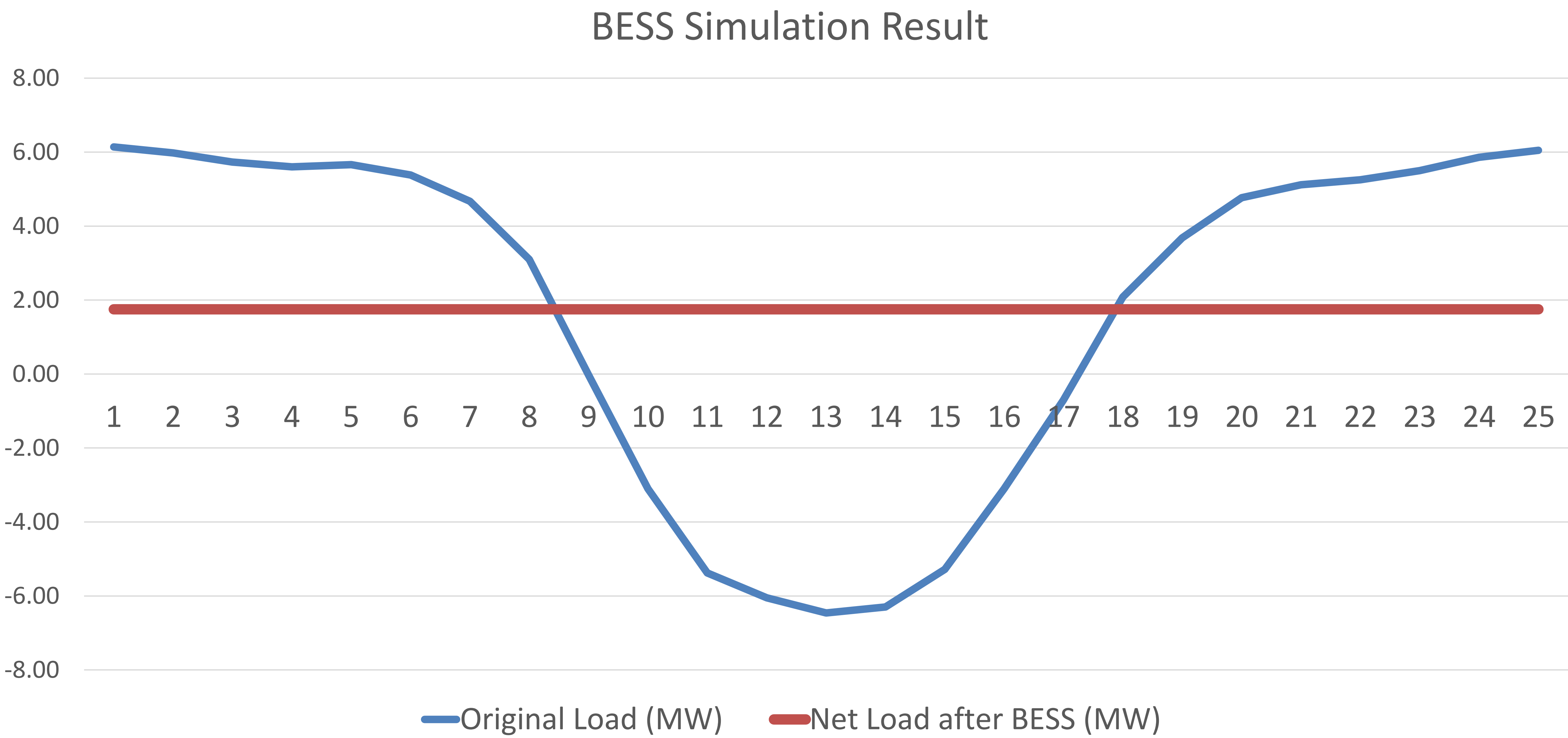
10MWh Battery Simulation Plot (Scenario 1) Grid Forming Mode



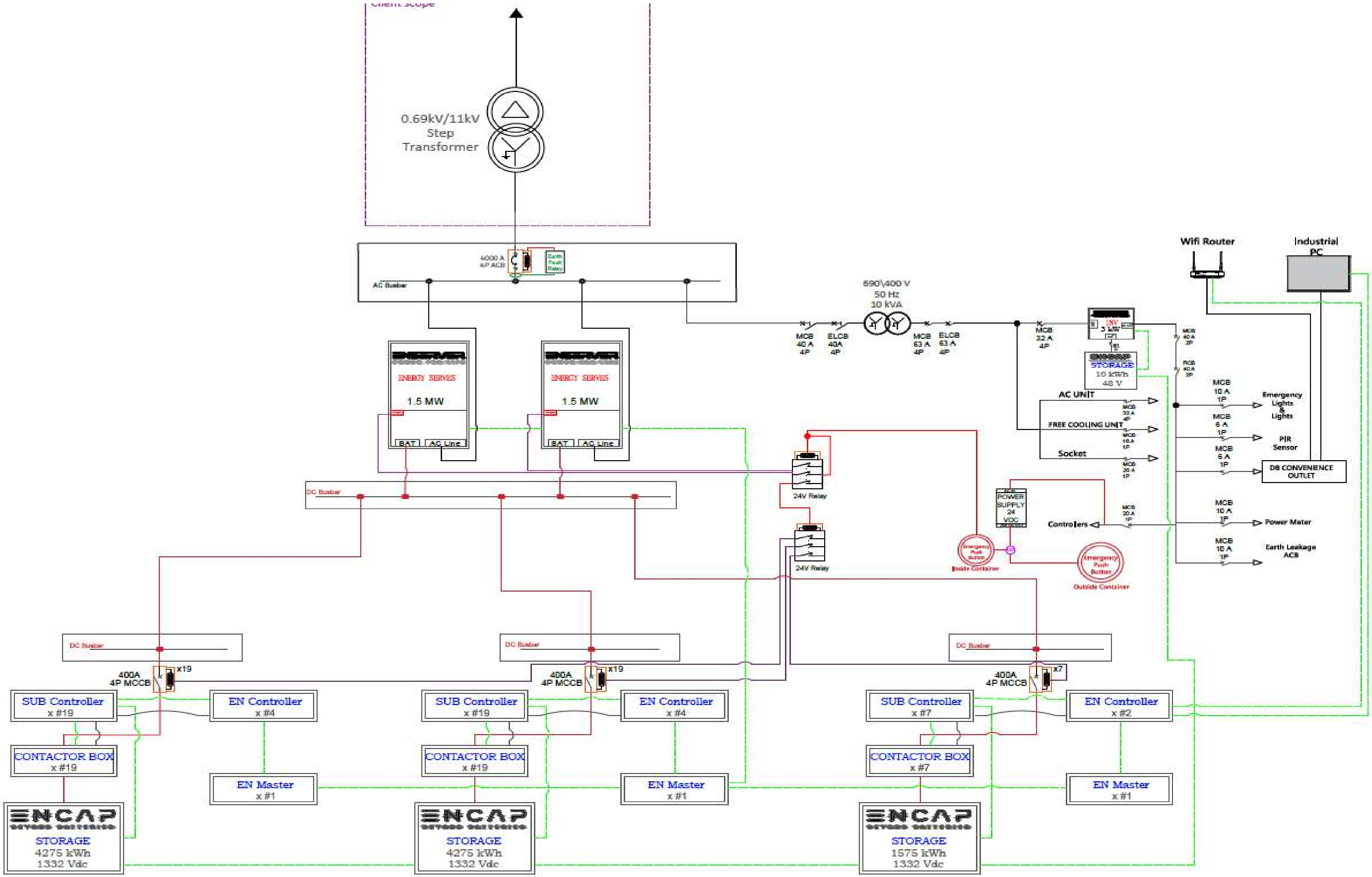
10MWh Battery Simulation Plot (Scenario 2) Peak Shaving Mode



28MWh Battery Simulation Plot (Scenario 3) - Best Case Scenario



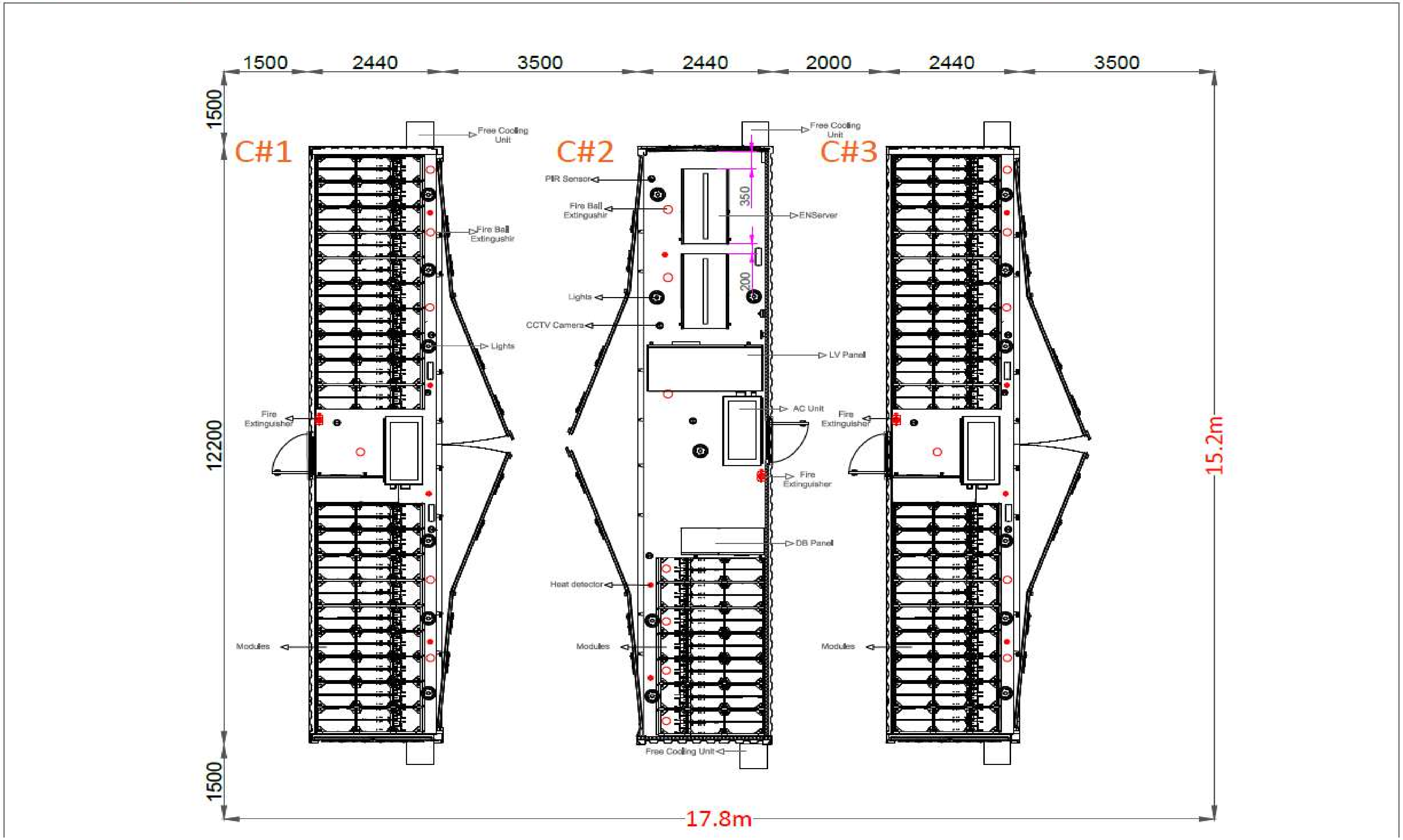
Containerized BESS Single Line Diagram



Project site and Container Layout

System Configuration : 3MW, 10MWh

Required Plot Area : 17.8 m x 15.2m



Thank You