Transmission and Distribution Network Augmentations for Solar and Wind Power Injections

SAARC
SAARC ENERGY CENTRE

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02 **Impact of Solar & Wind on Power Systems**
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SAARC

Why Renewable Energy Matters for SAARC

Energy Security

- South Asia imports over 20% of total energy.
- Greater use of local renewables reduces import dependence.
- Less exposure to fuel-price volatility and supply shocks.

Reliable & Inclusive Power

- Solar, wind, mini-grids and distributed generation.
- Power for remote, island and dispersed communities.
- Supports reliable, affordable electricity for all.

Economic Opportunity

- Creates jobs and supports local manufacturing.
- Drives investment in operations, maintenance and services.
- Boosts sustainable economic growth.

Climate & Sustainability

- Most SAARC countries have high wind and solar potential.
- Cuts emissions and supports clean energy transition.
- Strengthens regional cooperation for a greener future.

Renewable energy is a strategic pathway to energy security, reliable power and sustainable growth for SAARC.

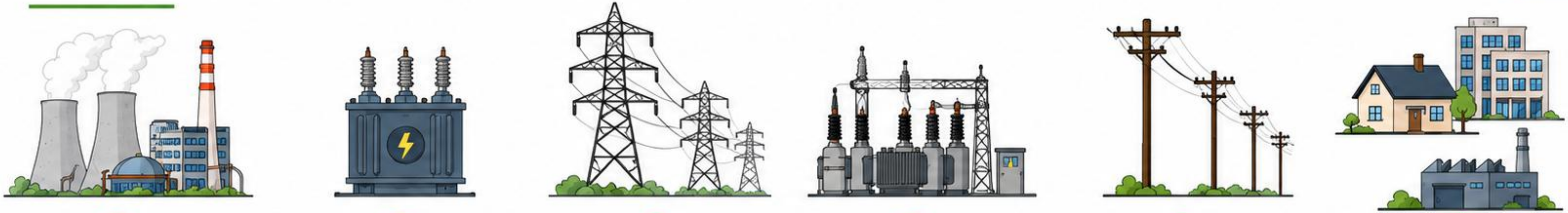
Solar & Wind Penetration in SAARC: Status and 2030 Ambitions

Country	Installed capacity — end 2025		2030 ambition / direction
India	Solar 135.5 GW	Wind 54.5 GW	500 GW non-fossil capacity by 2030.
Pakistan	Solar 3.72 GW	Wind 1.85 GW	30% renewable-energy share by 2030.
Sri Lanka	Solar 2.51 GW	Wind 0.27 GW	70% of electricity generation from renewable energy by 2030.
Bhutan	Solar ~21 MW	Wind ~1 MW	1 GW solar by 2030; wind expansion also planned.

Growing solar and wind penetration will fundamentally change power flows and operating conditions—requiring corresponding reinforcement and modernization of transmission and distribution networks.

Sources: IRENA Renewable Capacity Statistics 2026; national targets/policies of India, Pakistan, Sri Lanka and Bhutan.

How a Conventional Power Grid Works



1 Generation

Electricity is produced at large centralized power plants.

→

2 Step-Up Transformer

Voltage is increased for long-distance transfer.

→

3 Transmission

Bulk power moved over long distances at high voltage

→

4 Grid Substation

Voltage is adjusted at substations before distribution.

→

5 Distribution

Voltage is stepped down and delivered through local distribution networks.

→

6 Consumers

Electricity is delivered to end users.

Key Characteristics

- One-way power flow
- Centralized generation
- Passive consumers
- Limited control at distribution level
- Designed for predictable demand

Conventional grids were designed to deliver electricity from large power plants to consumers — not for large-scale distributed renewable generation.

Operational Challenges of Solar & Wind Penetration

1

Variability & Intermittency

Solar and wind output changes with weather and time, causing fluctuations and rapid ramps in power supply.

2

Balancing & Flexibility

Higher variable renewable energy requires more operational flexibility, reserves and ancillary services to keep supply and demand balanced.

3

Reverse Power Flow

Distributed solar, especially rooftop PV, can send power back through feeders, changing the traditional one-way flow of electricity.

More solar and wind make power flows more variable and less predictable.

Operational Challenges of Solar & Wind Penetration

Voltage & Power Quality

High solar and wind penetration can cause voltage variation and power-quality issues, requiring stronger voltage and reactive-power control.

Network Congestion & Curtailment

Existing transmission and distribution networks can become constrained, leading to bottlenecks and curtailment of renewable generation.

Reliability, Protection & Control

Higher renewable penetration increases the need for real-time monitoring, improved protection and stronger system control.

A cleaner grid also becomes a more dynamic and complex grid to operate.

Solar & Wind Penetration — Need for Grid Augmentation

1 Thermal Loading Constraints

Higher renewable injections can overload transmission lines and transformers, requiring network reinforcement.

2 Voltage & Reactive-Power Constraints

Large wind and solar additions can create voltage-control issues, requiring reactive compensation and voltage-support equipment.

3 System Stability Constraints

Renewable integration must remain within voltage-stability and angular-stability limits for secure operation.

4 Fault-Level Constraints

New generation can increase short-circuit levels, requiring appropriate switchgear, busbar configuration and protection measures.

Network Evacuation Constraints

Large renewable clusters may require new or upgraded transmission lines, substations and transformers to transfer power safely to the wider grid.

Higher solar and wind penetration requires coordinated transmission and distribution reinforcement to maintain system security, stability and reliable power evacuation.

Transmission System Overview

A robust network that transfers bulk power reliably and efficiently from generating plants to load centers.

1. Generation → 2. Step-up Transformer → 3. High-Voltage Transmission → 4. Grid Substation / Interconnection → 5. Step-down Transformer → 6. Distribution / Load Centers

Core Functions

1. Transfers bulk power from generating plants to load centers
2. Interconnects power pools to improve reliability and reduce reserve requirement
3. Enables long-distance transfer using HVAC and HVDC

Major Equipment

- Transformers
- Transmission lines & cables
- Circuit breakers & isolators
- Protective relays
- Shunt/series compensation
- FACTS devices (e.g., SVC, STATCOM)
- Converters / inverters
- Voltage regulators / phase shifters

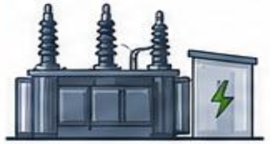
Augmentation in Transmission Network: Transmission System Planning

1. The transmission network must be **assessed before connecting large amounts of solar and wind generation.**
2. Grid studies should **identify where existing lines, substations and transformers may become inadequate.**
3. The network should be planned so that renewable power can be transferred **without compromising system stability and security.**
4. Reinforcement should be selected on both **technical and economic grounds.**

Augmentation in Transmission Network: Increasing Power Evacuation Capacity

1. Existing transmission lines may need to be uprated when renewable power exceeds their transfer capability.

2. New transmission lines may be required to carry power from major solar and wind resource areas to load centres.



3. New substations and additional transformers may be required at major renewable connection points.

4. Stronger network interconnections can improve power-transfer capability and operational flexibility.

Key reinforcement measures include line uprating, new lines, substations and transformers as key reinforcement measures.

Augmentation in Transmission Network: Voltage and Reactive Power Control

1. Large solar and wind injections can change voltage profiles across the transmission network.
2. Additional reactive-power support may be required to maintain acceptable system voltage.
3. SVCs, capacitors, reactors and transformer tap control can provide the required voltage support.
4. Modern wind and solar plants can also support voltage control through their converters and plant controllers.

Strong voltage and reactive-power control is essential for secure and reliable integration of solar and wind power.

Augmentation in Transmission Network: Improving Transmission Monitoring and Control

1. Higher renewable penetration requires better real-time visibility of the transmission network.

2. SCADA and Energy Management Systems should be strengthened for improved system monitoring and control.

3. Wide Area Monitoring Systems can provide better visibility of system conditions across the EHV network.

4. Advanced operational tools can help utilities use existing transmission capacity more effectively and respond quickly to network constraints.

1. Plan the network →
2. Increase transfer capacity →
3. Control voltage →
4. Strengthen substations and protection →
5. Improve monitoring and control

Enhancing Transmission Flexibility & Interconnection

Advanced technologies improve transfer capability, controllability and flexibility for higher renewable penetration.

HVDC Transmission

Bulk power transfer

Transfers large renewable power over long distances efficiently.

FACTS Devices

Power-flow & voltage control

Improves controllability and voltage regulation of AC corridors.

Dynamic Line Rating

Higher use of existing lines

Uses real-time weather and conductor conditions to determine safe line capacity.

Regional Interconnection

Sharing power across grids

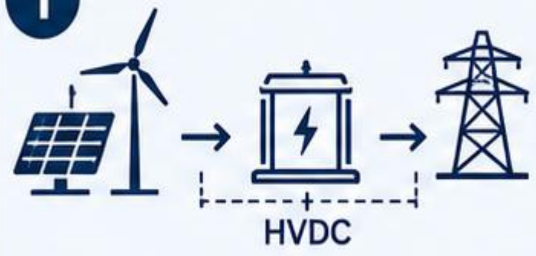
Supports power exchange, reserve sharing and renewable balancing.

More Renewable Energy → **More Flexible Transmission** → **Higher Grid Hosting Capacity**

Transmission augmentation is not limited to building new lines; existing networks can also be strengthened through advanced control, monitoring and interconnection technologies.

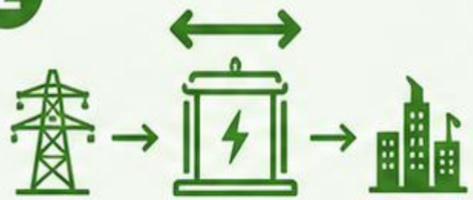
HVDC Transmission as a Strategic Augmentation for Renewable Integration

1



HVDC is useful when large amounts of solar and wind power must be transferred from remote resource areas to major load centres.

2



HVDC provides highly controllable power transfer, helping manage congestion and support flexible grid operation.

3

HVDC is valuable for inter-regional and cross-border transmission, where controlled exchange of renewable electricity is important.

4

HVDC complements the AC grid; it is not a replacement for the entire transmission network.

HVDC is a targeted transmission enhancement that can strengthen renewable-power evacuation, improve controllability and support large-scale solar and wind integration.

Distribution System Overview

1. Power delivery: Delivers electricity from the transmission/ sub-transmission network to consumers at medium and low voltage levels.

2. Voltage step-down: Distribution transformers reduce voltage to levels suitable for local supply.

3. Local supply: Feeders and LV networks distribute electricity to residential, commercial and industrial consumers.

4. Design objective: Maintains acceptable voltage, power quality, reliability and safety.

Distribution networks deliver electricity safely and reliably from substations to end users.

Distribution System: Main Functions & Equipment

1. Power delivery: Supplies electricity locally through MV and LV networks.

2. Voltage control: Maintains acceptable voltage at consumer connection points.

3. Protection & switching: Isolates faults and supports safe network operation.

4. Monitoring & control: Modern systems use automation, SCADA/DMS and smart metering.

Key Equipment in Distribution Systems

- Substations
- Feeders
- Distribution transformers
- Switchgear
- Protective devices
- Capacitor / voltage-control equipment
- Smart meters
- SCADA / DMS

Distributed Energy Resources

Distribution systems increasingly connect rooftop solar, battery storage and other DERs.

Operational impact

High rooftop-solar penetration can cause reverse power flow and new voltage-control requirements in MV and LV networks.

Impact of Solar & Wind Energy on Distribution System

Reverse power flow

When local renewable generation exceeds local demand, power can flow back from feeders toward the substation.

Voltage rise & variation

High solar and wind penetration can increase voltage and cause larger voltage variations along MV and LV feeders.

Feeder & transformer loading

Renewable generation changes feeder and transformer loading patterns and can create thermal or capacity constraints.

Voltage-control settings

Voltage regulators and other control devices may require new settings when power flow becomes bidirectional.

Distribution networks must operate with changing power-flow directions and more dynamic voltage conditions.

Protection, Power Quality and Operational Challenges

Protection coordination

Distributed generation changes fault-current level and direction, making relay, fuse and breaker coordination more complex.

Power quality

Variable renewable output can cause voltage fluctuations and harmonics in distribution networks.

Network visibility

Large numbers of distributed resources require better monitoring, communication and control.

Active management

Higher renewable penetration needs coordinated voltage control, automation and active distribution management.

Higher distributed renewable penetration transforms the distribution grid from a passive network into an actively managed network.

Increasing Distribution Network Hosting Capacity

Assess MV feeders

Check reverse power flow and equipment loading as solar and wind penetration increases.

Reinforce feeders

Expand or strengthen MV and LV feeders where renewable injections exceed network capacity.

Upgrade transformers

Increase or replace transformer capacity where additional renewable generation is connected.

Split overloaded feeders

Feeder bifurcation or trifurcation can redistribute power and relieve heavily loaded sections.

Upgrade conductors

Replace undersized conductors and cables where they limit safe renewable-power transfer.

Distribution upgrades should increase the hosting capacity of feeders, transformers and substations so that more renewable generation can be connected safely.

Strengthening Voltage & Reactive Power Management

Active voltage regulation

High rooftop-PV penetration requires more active voltage regulation on MV and LV feeders.

Volt-VAR Optimization

Introduce Volt-VAR Optimization on high renewable penetration feeders to maintain voltage within limits.

Capacitor banks

Automate and coordinate capacitor banks to provide reactive-power support and improve voltage control.

Smart inverters & storage

Smart inverters support local voltage regulation. Battery storage helps balance feeders with high rooftop-PV.

Coordinated control

Coordinate voltage-control devices with changing and bidirectional power flows, not just one-way supply.

Higher renewable penetration requires the distribution network to move from passive voltage regulation to coordinated and active voltage control.

Distribution Automation & Control

Real-Time Grid Visibility

Monitor voltage, power flow and feeder loading as renewables increase.

SCADA/DMS Expansion

Extend monitoring and control from substations to distribution feeders.

Distribution Automation

Use remotely controlled switches, reclosers and sectionalizers for faster network control.

Smart Meters & Sensors

Provide near-real-time field data for improved operation and planning.

FLISR

Automatically locate and isolate faults and restore supply to healthy sections.

Protection & Reliability

Adaptive Protection

Update protection settings for changing power flows and fault levels.

Digital Relays & IEDs

Enable faster, selective and coordinated fault protection.

Improved Fault Detection

Detect high-impedance and difficult faults more reliably.

Protection Coordination

Coordinate relays, reclosers and DG protection under changing conditions.

Condition Monitoring

Monitor transformers, breakers and assets to prevent failures.

Renewable-rich grids require adaptive protection, rapid fault isolation and improved asset monitoring.

Adding Flexibility through Energy Storage & Demand Response

Battery Energy Storage Systems (BESS)

can absorb excess renewable generation and release it when local demand increases.

Storage reduces reverse power flow, feeder loading and rapid variations in net power demand.

Demand Response

shifts or reduces customer demand to better match high solar and wind generation.

Smart inverters combined with storage

support local voltage regulation and feeder balancing.

Coordinated storage and demand-side flexibility

increase the renewable hosting capacity of the distribution network.

Storage and flexible demand help the distribution network absorb variable renewable generation without relying only on physical network expansion.

From Passive to Active Distribution Network

Passive Distribution Network

- Power flows from the substation to consumers.
- Consumers mainly use electricity only.
- Voltage control and protection are based on one-way power flow.
- Monitoring and control at feeder level are limited.

Active Distribution Network

- Power can flow in both directions.
- Consumers can become prosumers and send power back to the grid.
- Solar, storage and smart inverters help support network operation.
- Smart meters, sensors, SCADA/DMS and automation improve visibility and control.
- The operator can manage voltage, power flow and distributed energy resources in real time.

Renewable integration is changing the distribution system from a passive network into an active, smart and flexible network.

Minigrids: Concept and Relevance for SAARC

1 Localized power system

Has its own generation and local distribution network.

2 Flexible operation

Can work independently or connect to the national grid.

3 Useful for remote areas

Suitable where central-grid extension is costly or difficult.

4 Renewable options

Solar, wind and small hydro can be used alone or in hybrid systems.

5 Supports access and growth

Improves reliable electricity supply and local economic activities.

Minigrids offer a flexible and decentralized way to use local renewable resources and improve electricity access across SAARC.

Smart & Grid-Interactive Minigrids

1 Renewable + storage

Combines renewable generation, battery storage and advanced control.

2 EMS & monitoring

EMS and remote monitoring coordinate supply, storage and demand.

3 Smart metering

Smart and prepaid meters support load control and billing.

4 AI, IoT & smart grid

Digital tools improve efficiency and system performance.

5 Grid-ready & islanding

Can connect to the main grid and safely isolate during disturbances.

Smart minigrids combine renewable energy, storage, digital control and grid interactivity for reliable local power supply.

Challenges for T&D Network Augmentation in SAARC Member States

Network and Technical Challenges

Limited and aging grid capacity
Lines, substations, feeders, transformers and conductors need strengthening.

High losses and reliability problems
Reduce efficient operation of transmission and distribution networks.

Limited monitoring and automation
Weak SCADA, communication and control systems reduce grid visibility.

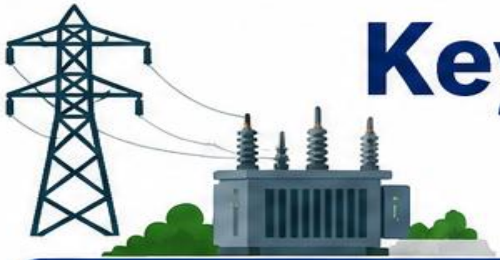
Planning and Implementation Challenges

Weak data and system studies
Limited forecasting, network models and hosting-capacity studies slow proper planning.

High investment needs
Financing constraints can delay grid expansion and modernization.

Policy and institutional gaps
Weak regulations, coordination and skilled workforce can slow implementation.

SAARC Member States need stronger networks, better digital control, improved planning, adequate financing and stronger institutional capacity for successful T&D augmentation.



Key Challenges for T&D Network Enhancement in SAARC

Policy, Financial & Institutional Challenges

Financially weak utilities
limits investment available for grid expansion and modernization.

High capital and operating costs
of transmission reinforcement and interconnection remain a major investment barrier.

Limited private-sector participation
and uncertainty in investment frameworks constrain modernization of power networks, particularly distribution systems.

Different regulations
for transmission access, pricing, market access and dispute resolution hinder coordinated regional network development.

Institutional coordination remains fragmented
common technical standards, data-sharing protocols and clearly defined roles for system operators and regulators are needed.

T&D enhancement in SAARC requires not only stronger physical infrastructure, but also **harmonized grid codes**, **standardized technical data**, **coordinated protection and control**, **sustainable financing** and **stronger regional regulatory cooperation.**

Cross-Border Grid Interconnection for Renewable Integration in SAARC

Regional power sharing

Surplus power in one country can support demand in another.

Wider-area balancing

Regional diversity helps balance variable solar and wind power.

Better use of transmission capacity

Coordinated scheduling improves power transfer across networks.

Harmonized grid operation

Common grid codes and data sharing improve secure operation.

Regional power pool

A shared market can support exchange, pricing and balancing.

Sharing power → **Better balancing** → **Higher renewable integration**

Cross-border interconnection can make the SAARC power system more flexible by sharing power across countries, improving balancing and supporting higher renewable integration.

Way Forward — Scaling Minigrids Across SAARC Countries

1. **Plan with the national grid:** Use minigrids where grid extension is costly or difficult.
2. **Set clear rules and standards:** Define licensing, tariffs, grid connection and grid-arrival rules.
3. **Promote grid-ready minigrids:** Use renewables, storage, smart meters and remote monitoring.
4. **Plan for future demand:** Support homes, businesses and other productive uses.
5. **Improve financing:** Use suitable funding and risk-sharing mechanisms to attract investment.
6. **Build technical skills:** Strengthen training for design, operation and maintenance.
7. **Strengthen regional cooperation:** Share standards, policies, experience and successful models across SAARC.

SAARC should move toward planned, grid-ready and financially sustainable renewable minigrids linked with national energy planning.

Conclusion

1 Plan solar and wind with T&D expansion:
Strengthen transmission corridors, substations, feeders, transformers and power-evacuation infrastructure.

2 Modernize the grid:
Combine physical reinforcement with SCADA/DMS, automation, smart metering, communication, monitoring and storage.

3 Use proactive, data-driven planning:
Improve renewable forecasting, network modelling, hosting-capacity studies and coordinated system operation.

4 Promote minigrids:
Complement central-grid expansion in remote, island and weak-grid areas, with clear future-interconnection rules.

5 Strengthen cross-border interconnection:
Harmonize grid codes, standardize technical data, coordinate system operation and develop regional power-trading mechanisms.

6 Create enabling policy and regulation:
Provide clear interconnection standards, tariffs, licensing, grid-arrival rules and institutional coordination.

7 Mobilize finance and build capacity:
Sustainable financing, skilled workforce, knowledge sharing and regional cooperation are essential for implementation.

SAARC's renewable-energy transition requires stronger and smarter national grids, grid-ready decentralized systems, greater regional interconnection, and coordinated technical, regulatory and financial action.