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Modernising and Transforming the Grid

Indian Power Sector in 2047

At GRIDCON 2025, the panel discussion on "Indian Power Sector in 2047" explored the key factors shaping the future of India's power sector, including the role of transmission companies, grid stability, reliability and resilience, technological advancements in transmission, and policy and regulatory changes.

Mr Padam Prakash, Partner, PwC, moderated the session. The panellists for the session were Mr Naveen Srivastava, Director (Operations), POWERGRID; Mr Reshu Madan, CEO, Sterlite Power; Mr Hemant Jain, Member, CEA; Mr S.C. Saxena, Director (Market Operations), Grid India; and Mr Subir Sen, Executive Director, POWERGRID.

The discussion focused on the transformation of India's power sector by 2047, highlighting the technological, regulatory and infrastructure advancements required to build a secure, sustainable and efficient grid.

Mr Padam Prakash opened the panel discussion by setting the context for the discussion on the future of the Indian power sector in 2047. He outlined four key areas for discussion – role of transmission companies; grid stability, reliability and resilience; technological developments in the transmission sector; and policy and regulatory changes governing the sector.

By 2047, India's estimated economy is projected to reach $30-$35 trillion, with a per capita income of around $14,000 (up from the current $2,500), making a robust and dynamic power sector crucial to support this growth. Further, the distribution segment is expected to become competitive, with discoms turning profitable and offering consumers choice of supply. The electricity demand is expected to nearly double from 250 GW today to around 410-430 GW. The installed capacity mix is expected to undergo a major change, reaching 2,100 GW by 2047, with significant capacity coming from solar and wind. The transmission segment is also expected to see key technological advancements, such as the deployment of 1,200 kV ultra-high voltage transmission, and the addition of 200,000 ckt km of transmission lines and 1,200 GVA of transformation capacity.

Mr Naveen Srivastava reinforced the scale of transformation required in India's power sector by 2047. He noted that out of the projected 2,100 GW of generation capacity by 2047, 1,600-1,700 GW would come from renewable sources, significantly altering the grid dynamics.

He emphasised that with an expected addition of 200,000 ckt km of transmission lines and a surge in transformation capacity to over 4,000 GVA, traditional manual operations would no longer be feasible. Instead, the grid would need to be AI-driven, IoT-enabled and largely unmanned. The volume of data generated by such an extensive infrastructure would necessitate smart transmission lines and substations capable of self-operation and real-time decision-making. Mr Srivastava highlighted that POWERGRID is already advancing in this direction, with 281 substations currently being operated remotely from the NTAMC. POWERGRID aims to transition towards fully digital substations by 2047. The focus is now on predictive maintenance through advanced monitoring technologies, including transformer and breaker condition monitoring.

POWEGRID is also focusing on promoting local manufacturing, ensuring that foreign contractors setting up projects in India must invest in factories within the country. Also, to address the growing challenge of right of way, POWEGRID is implementing Dynamic Line Rating (DLR) systems, making existing corridors and transmission lines smarter to handle additional load.

He stressed that cybersecurity is a critical focus area, given the vast transmission infrastructure network. Investments are being made to strengthen cybersecurity measures, including ensuring that operational technology (OT) and information technology (IT) systems remain separate in order to mitigate cyberthreats.

Mr Reshu Madan highlighted the company's leading role in India's private transmission sector and its international footprint, particularly in Brazil. Sterlite Power has assets worth approximately $10 billion, with $7 billion in India and $3 billion in Brazil. Currently, the company manages 11 operational and under-construction assets valued at around $4 billion.

He emphasised that investment in transmission infrastructure is critical. However, transmission development is lagging behind generation capacity, posing a major challenge for the sector. One of the challenges is the efficiency gap. In India, constructing a 400 kV line takes 1,100-1,200 man-days, while a 765 kV line takes about 1,600 man-days. In comparison, the same work takes 600 man-days in

Thailand, 400 man-days in Brazil, and only 200-250 man-days in the US or Europe.

Speed, innovation and mechanisation are essential for transforming the transmission sector. Sterlite has pioneered the use of heli-cranes in Jammu & Kashmir, as well as drones for projects in the Northeast to accelerate project execution. These advancements have significantly reduced project timelines from 48-60 months to 24-36 months. Looking ahead, reducing dependence on manual labour is important due to skilled workforce shortages.

On the company's plans, he shared that Sterlite Power is making significant investments of Rs 4 billion to expand its conductor production capacity from 110,000 tonnes to 150,000 tonnes. A part of this investment will be used to set up a greenfield plant in Baroda, which will manufacture 400 kV cables. These investments and technological advancements align with the country's growing power demand and the goal of building a resilient transmission network for the future.

Mr Hemant Jain provided the perspective of a technical and planning body, emphasising the importance of a robust power sector in realising India's Vision 2047. He stated that as India approaches 100 years of independence, a strong power infrastructure will be a critical pillar of the country's progress. He acknowledged POWERGRID's leadership in developing the interstate transmission system (ISTS) and recognised the contributions of private transmission players, particularly Sterlite Power and others, in strengthening the sector. This collaborative effort, he noted, enabled India to meet a peak demand of 250 GW last year, with an expectation to reach 270 GW this year.

Mr Jain highlighted that by 2047, India's installed capacity is projected to grow fivefold, with nearly 90 per cent coming from non-fossil fuel sources, including renewable energy and nuclear power. However, he pointed out an important distinction: while installed capacity is expected to grow five times, energy demand and peak load will increase only threefold. This indicates a shift in the energy mix, with a reduced reliance on conventional thermal power and a greater share of variable renewable energy. This transition poses a significant challenge in maintaining grid reliability. The evolving energy system will require careful planning and coordination among central, state and private sector players to ensure stability. Mr Jain appreciated the collective efforts of stakeholders in reaching the current stage, where India can confidently meet its energy and peak demand requirements. Looking ahead, he emphasised the need for continued collaboration to address the challenges posed by an increasingly RE-driven grid.

Regulations are essential to maintain the health and operability of the power system to serve consumers effectively. He acknowledged that while India's interstate transmission system has evolved and continues to do so, the real challenge lies in integrating intra-state transmission networks. Their seamless coordination is crucial for a well-functioning power sector.

He stressed that the harmonisation of regulatory processes is essential to ensuring that investors have clarity on compliance requirements and approval procedures before entering the sector. A cohesive regulatory framework will help streamline investments and execution timelines. He also highlighted the role of regulatory bodies and statutory entities like the CEA in ensuring that the process remains efficient and investor-friendly, fostering a stable and predictable environment for power sector growth.

Looking ahead, he underscored the critical importance of peak load management, particularly in the context of increasing renewable energy integration and the expected 250 GW of thermal capacity by 2047. He emphasised that peak load management strategies, including flattening the load curve, must become a key focus in future policies and operational frameworks. He suggested that these strategies should be gradually incorporated into regulatory harmonisation efforts to ensure a balanced and resilient grid. He also highlighted the need for a more professional and expert-driven approach to load despatch functions at the state level. Jain called for state load despatch centres to be equipped with capabilities similar to regional load despatch centres, ensuring that holistic load forecasting, generation planning and resource mobilisation are carried out efficiently.

Mr S.C. Saxena highlighted the changing dynamics of power demand and supply due to the increasing share of renewable energy. He pointed out that India recently crossed 65 GW of solar generation during daytime, and managing this peak has not been a challenge. However, the real issue arises during non-solar hours, when the entire 65 GW of solar generation disappears. This shift has led to a redefinition of peak demand periods, making non-solar peaks more significant and challenging than ever before. As more solar capacity is added, meeting daytime demand will become easier, but ensuring resource adequacy for non-solar hours will be critical. To address this, new rules and regulations have been introduced, mandating resource adequacy studies up to a 10-year horizon. This includes reserve planning, ensuring not just demand fulfilment but also contingency preparedness. He cited a recent example where 7-8 GW of solar power was lost in an instant due to cloud cover, emphasising the need for robust backup mechanisms.

On the transmission side, he noted that traditional power flows have historically been east to west, east to north and east to south, based on the placement of conventional power resources. However, with the rise of renewable energy in western, northern and southern India, electricity transmission flows are changing. This shift requires significant upgrades and modifications in transmission infrastructure to efficiently integrate and manage variable renewable energy sources.

He highlighted out that traditionally, the northern region was an importing zone, serving as a major demand centre. However, recent data revealed that during solar hours (10 a.m. to 6 p.m.), the entire northern region is now exporting power, a fundamental shift from historical trends. This shift introduces new challenges in transmission operations, particularly the emergence of bidirectional power flows that change on a diurnal basis. Managing these dynamic flows will be critical, as they could lead to congestion issues across the transmission network. He acknowledged that congestion events are already occurring intermittently, underscoring the need for proactive grid management strategies.

Mr Saxena also talked about the importance of flexibility in power generation, given the increasing share of renewable energy in the mix. With renewables set to dominate by 2047, all other energy resources – including thermal – must become more adaptable. While the share of thermal power is expected to decline, he projected that some level of thermal generation would still be necessary in 2047.

Mr Subir Sen outlined the roadmap for India's power sector transformation by 2047, emphasising the need to reimagine and elevate the sector to meet dual energy goals – ensuring energy security and progressing toward net-zero emissions by 2070. He noted that by 2047, 90 per cent of electricity generation is expected to come from non-fossil fuel sources, making energy independence a key objective.

Mr Sen highlighted three critical challenges – what he termed the "three A's" – that must be addressed to build a sustainable and resilient power sector. These are adequacy, accessibility and affordability. To meet these objectives, he stressed the need for significant expansion of transmission infrastructure, covering bulk transmission highways at the interstate and intra-state levels, as well as deeper penetration into the distribution network. The integration of advanced technologies is essential to ensure that the grid operates synchronously and efficiently. He advocated for a "smart" power system – one that can sense meaningfully and respond in real time – enabled by the internet of energy (IoE) integrated with the internet of things (IoT).

Mr Sen emphasised that the future grid must minimise human intervention by leveraging digitalisation, artificial intelligence (AI) and machine learning (ML) for both construction and asset management. Predictive analytics will play a crucial role, allowing automated corrective actions to prevent faults before they occur. He pointed to digital substations as a key component in managing the increasing share of renewable energy, which is inherently variable and intermittent. A major shift, he explained, will be the transition from grid-following inverters to grid-forming inverters, which will enhance grid stability and security. Additionally, energy storage will be crucial, particularly pumped storage hydropower, which is expected to grow from 4.7 GW at present to 116 GW by 2047. Other energy storage technologies, including battery energy storage systems, are projected to reach 47 GW by 2032.

Mr Sen concluded by stating that achieving these goals will require equal focus on digitalisation, decentralisation and automation, ensuring a resilient, efficient and future-ready power system for India. He also highlighted the importance of nuclear energy in India's future energy mix, with 100 GW of nuclear capacity expected to come online. He underscored the need for clean, green and lean development as well as the optimisation of existing assets to enhance their utilisation.

He proposed innovative solutions for lower voltage levels (132-220 kV), such as photonic coatings on conductors and high-capacity conductors, to improve transmission efficiency. Additionally, he emphasised the significance of medium-voltage DC (MVDC) systems, which should be developed alongside high-voltage DC (HVDC) systems (500 kV, 320 kV, 800 kV). He pointed out that even 33 kV and 66 kV DC systems could be valuable, requiring advancements in software and infrastructure. Regarding urbanisation and industrialisation, he noted that India's population is expected to reach 1.7 billion by 2047, making it difficult to build new transmission infrastructure. MVDC networks and underground cable systems will be necessary for power distribution in densely populated areas.

Mr Sen highlighted the importance of offshore wind energy, citing projects in Tamil Nadu and Gujarat, where 10 GW has been identified for development by 2032. Offshore wind power will require dedicated AC-DC transmission infrastructure, undersea power cables and transnational grid interconnections for optimal resource utilisation. He noted that the development of undersea grids and deep-sea power transmission would require extensive research and investment. He also discussed the key role of public-private collaboration in R&D to drive innovation, demonstration and deployment of new technologies.

Finally, Mr Sen outlined four key priorities for India's power sector – energy security and net-zero transition by 2047, smart and efficient transmission networks, AI-driven cybersecurity with a zero-trust approach, and capacity building for emerging technologies. He emphasised the need to modernise transmission infrastructure with 1,200 kV ultra-high voltage AC, HVDC, MVDC, and energy storage solutions while ensuring supply chain security. He proposed the PQRS framework – prioritise action plans, ensure quick implementation, enhance reliability and response, and uphold safety standards.

Global Trends in Energy Transition

The panel on "Global Trends in Energy Transition" featured a discussion among Mr B.V.R. Mohan, Director (Projects), POWERGRID; Mr Luke Robinson, Executive Director, International System Operator Network, AEMO, Australia; Mr Michael Timofeev, Chief Executive Officer, StorEn, UAE; Ms Bani Varma, Director (IS&P), Bharat Heavy Electrical Limited; Mr Joji Sebastian, Vice-President and Head, Operations (Domestic), Power T&D, Larsen & Toubro; and Mr A.K. Rajput, Former Member (Power System), Central Electricity Authority.

The session was moderated by Mr Hitesh Chaniyara, Partner, PwC. He noted that the energy sector is transforming around four key themes: decarbonisation, decentralisation, digitalisation and disaggregation. India, one of the fastest-growing energy markets, is leading this shift, balancing energy security, economic growth and sustainability. India has set ambitious goals, including 500 GW of non-fossil fuel capacity by 2030, 50 per cent renewable energy generation, a 1 billion tonne reduction in carbon emissions and achieving net-zero emissions by 2070. Achiev-

ing these targets requires scaling up renewable capacity, modernising the grid and integrating energy storage solutions.

Mr B.V.R. Mohan highlighted that the transmission sector in India has evolved from simply connecting generators and loads to becoming a vital, vast and reliable grid network. It has transformed into a marketplace for buying and selling electricity and has positioned India as one of the largest transmission utilities globally, ensuring that no power is wasted. With the rapid rise of renewable energy project deployment, there is pressure to match this with growth in transmission capacity and timelines. The challenge is not just the shorter gestation periods of renewable power projects, but also the intensity and speed at which these transmission projects must be developed. This rapid pace of development is putting stress on the entire supply chain, encompassing transformers, insulation boards and high voltage direct current (HVDC) systems.

The government's production-linked incentive (PLI) scheme aims to address some of these challenges, but the increased demand for resources, such as the workforce needed for transmission line erection and fitting, is further compounded by the simultaneous growth in the renewable energy sector. Both sectors rely on the same limited resources, adding strain to the overall system. Another major challenge is securing the right of way for transmission projects, which involves addressing landowner and farmer concerns about the value their land contributes to the transformation. The government is taking active measures such as new guidelines to resolve this issue. To meet the growing demand, ramping up manufacturing capacities and skilling the workforce is essential. POWERGRID is making progress in this area, but collaboration across all sectors is necessary to move forward effectively.

Mr Luke Robinson highlighted that the Australian Energy Market Operator (AEMO) manages two separate synchronous systems: the National Electricity Market, stretching 5,000 km across Australia, and a system in Southwestern Australia. The East Coast system has a mix of coal, gas, hydro and renewable energy, and has achieved 75 per cent renewable penetration, while the West Australian market operates with 82 per cent renewable energy. Both regions have seen significant growth in renewable inverter-based resources. A standout case is South Australia, where the installation of synchronous condensers has reduced reliance on gas-fired generation, allowing the system to sometimes operate with 100 per cent of the load coming from rooftop solar alone. AEMO also plays a key role in system planning, helping meet Australia's net-zero emissions targets and addressing challenges such as forecasting, inverter-based resource integration and power system modelling.

He mentioned that distributed energy resources have become the largest generator in the East Coast system, requiring increased visibility and control. He emphasised the importance of learning from global experiences, such as integrating data centres, offshore wind and large-scale battery systems to avoid common challenges. He also highlighted the importance of developing robust power system models for planning, operational studies and real-time analysis. Key lessons include defining roles and responsibilities for managing distributed energy resources, ensuring systems are future-proofed and implementing emergency backstop procedures. He stressed the importance of operational readiness, thinking ahead to monitor system stability and investing in people. AEMO's Operations Academy fosters collaboration between operational staff and back-office teams, providing valuable insights into areas requiring improvement.

Mr Michael Timofeev emphasised that his company specialises in designing battery storage systems, primarily using CATL products for the DC side. The demand for energy storage systems is increasing as they play a crucial role in balancing the grid by acting as both generator and load. They are especially vital for managing the intermittency of renewable energy sources such as solar and wind, providing smooth load distribution and storing excess energy for use during high-demand periods such as mornings and evenings. Additionally, decentralised energy storage solutions are important for enhancing the output of transformers in substations and supporting demand response for individual or commercial consumers. In recent years, India has made significant progress in implementing energy storage, but challenges remain in fully realising these standards.

The goal is to make these storage systems operational 24/7, which requires establishing service centres across India, potentially with partners such as POWERGRID, who operate the country's largest power lines. He concluded by stressing that energy storage is essential for achieving energy transition and maintaining balance in the power system.

Ms Bani Varma stated that equipment manufacturers play a crucial role in strengthening India's transmission infrastructure, especially in integrating renewable energy sources. She highlighted the growing gap between supply and demand, with increasing pressure to expedite projects despite shortages in critical raw materials and components. However, she expressed optimism that industry capacity will scale up within the next two years.

She emphasised the need for standardisation, urging broader adoption of standard equipment specifications by both central and state entities. Additionally, she underlined the importance of new technologies such as STATCOM, synchronous condensers, HVDC and UHVAC transmission in ensuring grid reliability, availability and stability. She pointed out that synchronous condensers are particularly essential in renewable-rich regions lacking conventional generators. Further, she stressed that a strategic mix of indigenous innovation and technology transfer is necessary, suggesting that PLI schemes could incorporate incentives for in-house technology development. She highlighted the shortage of skilled manpower, particularly at the artisan level, calling for industry-wide efforts to enhance workforce training. On HVDC advancements, she noted that these technologies are critical for large-scale renewable energy evacuation, especially from the resource-rich western and southern regions. She stated that India already has significant HVDC experience, with BHEL successfully executing a few HVDC projects and securing new contracts.

Mr A.K. Rajput highlighted the importance of policy-driven planning and skilled manpower in achieving energy transition. He stressed that India's power infrastructure must adapt to evolving climate conditions, as equipment traditionally designed for 40-45°C must now withstand extreme temperatures ranging from -20°C to 55°C. He suggested that the standards agencies should reassess equipment specifications to enhance robustness. He also underscored the need for clear objectives, defined targets and fixed timelines to ensure a structured energy transition, cautioning against a fragmented approach. Addressing supply chain bottlenecks, he emphasised the necessity of funding and developing a skilled workforce.

Mr Rajput further stressed indigenous R&D and innovation in conductor materials, advocating for a lifecycle-based evaluation of transmission projects to optimise resource utilisation and minimise carbon emissions. He pointed out that congestion issues in transmission planning must be addressed through strategic reconductoring and augmentation of critical infrastructure, particularly in urban centres such as Delhi. On offshore wind and solar transmission, he noted that India is in the early stages of offshore wind development, with identified sites and initial plans underway. He emphasised the need for domestic subsea cable manufacturing and the gradual build-up of technical expertise before large-scale deployment. He advocated for a phased approach, allowing India to gain operational experience before scaling up.

Mr Joji Sebastian noted that energy transition is the defining challenge of the decade, driven by India's commitment at COP26 to achieve a 45 per cent reduction in greenhouse gas emissions by 2030 and ensure that 50 per cent of its energy generation comes from renewable sources. He emphasised that this ambitious target, which also involves achieving 500 GW of green energy by 2030, is shaping the future of India's power sector, particularly its transmission infrastructure. He stressed that the scale and pace of this transformation are unprecedented, requiring a fundamental shift in how transmission projects are executed. He stated the critical role of manpower upskilling, automation and mechanisation in accelerating project timelines, with L&T actively implementing advanced construction techniques. Additionally, he highlighted the importance of a resilient supply chain, noting the current shortages in capacity and the need for import substitution in key components such as electronic surface releases and subsea cables.

He also pointed out that a robust policy framework with a strong social engagement component is essential for a smooth transition, moving beyond right-of-way challenges to a more holistic, community-driven approach. He said that as new technologies and energy storage systems become integral to the grid, digital solutions will be crucial for optimising energy management. L&T is investing significantly in digital transformation to enhance the efficiency of transmission networks. Lastly, he highlighted the unique Indian mindset of resilience and innovation, stating that the country's "can-do" attitude will turn challenges into opportunities and drive the energy transition forward.

Planning, Design and Operation of Offshore Transmission Network

In the plenary session on "Planning, Design and Operation of Offshore Transmission Network", Mr Wessel

Bakker, Business Director, Offshore Power Grids, DNV, the Netherlands, discussed the global energy outlook up to 2050, prospects for offshore renewable energy systems and key concepts for connecting offshore renewable energy with the main grid. He also highlighted the challenges and recommendations from an Indian perspective.

According to DNV's annual Energy Transition Outlook report, the global electricity system is projected to undergo a dramatic transformation by 2050. The world will see an estimated 55,000 utility-scale plants, 12,000 onshore wind farms and 5,000 offshore wind farms, each averaging between 300 MW and 400 MW, as well as around 1.3 billion electric vehicles. Offshore wind is expected to become a dominant energy source, both in fixed and floating configurations. By then, the electricity demand and supply will more than double and a large chunk of the power requirement will be met by renewables. Solar power will also grow very rapidly. Meanwhile, a significant number of fixed and floating offshore wind projects will come up. Further, electricity systems will become larger but also more efficient. In this landscape, strong regional power collaborations will be essential for improved cost economics and overall decarbonisation. India is also planning international and regional transmission collaborations through cross-border and offshore transmission links with countries in Asia, ASEAN and other regions, which will be important for the region's overall future energy security.

In addition, India has significant plans in the offshore wind space and has started implementing its first offshore wind farms. Offshore wind development sites have been identified in the states of Tamil Nadu and Gujarat, and a total potential of 37 GW of offshore wind capacity has been identified for development by 2030. These projects will require adequate offshore transmission networks to connect them to the national grid.

There are many different concepts for developing offshore transmission networks, particularly for offshore wind projects. Nearshore offshore wind projects are located at a distance of up to 100 km from the coast. For India, which is beginning its first offshore wind power development, nearshore projects are the first step towards offshore power grids. In this case, using a 66 kV cable is the current norm. However, the industry is moving towards 132 kV, which will require fewer array cables. Developing offshore wind projects farther offshore, beyond 100 km, will require more advanced transmission technologies to connect them to the main onshore grid. These projects are large, with capacities of 1-2G W, and require HVDC technologies for transmission. There are many such contracts underway in the Netherlands and Germany.

Further, when transmission interconnections are being planned for a particular region, an offshore wind farm can be inserted to create hybrid interconnections. A key advantage of this concept is that offshore wind can be transmitted to regions with the highest demand for greater profitability. Meshed transmission grids can also be created for offshore wind power evacuation for greater efficiencies and system reliability. Another concept is the hub-and-spoke model of development, which enables smarter offshore wind and transmission project development. Further, artificial energy islands, floating offshore substations and subsea substations are being developed in different parts of the world.

However, supply chain constraints, vessel availability and skilled workforce shortages are critical bottlenecks in offshore transmission integration. Addressing these challenges requires early investment in industry capacity building and policy support. Additionally, regulatory harmonisation across regions is necessary for international offshore grid integration.

Advances in DC Technologies

Dr Marcio Szechtman, Director General, CEPEL, Brazil, spoke about the advancements in high voltage direct current (HVDC) technology over the years, highlighting its evolution from an emerging solution to a crucial component of modern power grids, enabling efficient long-distance transmission and renewable energy integration.

Before 1972, HVDC applications using mercury-arc valves were limited to 450 kV. The introduction of thyristors revolutionised the technology, allowing higher voltages and power transmission. In the 1970s and 1980s, the AC versus DC decisions were based on costs, with HVDC proving advantageous for long-distance transmission. However, during the 1990s, project deployment was slow, with frequent converter transformer failures raising concerns about HVDC's viability.

He stated that the 2000s marked a major turning point. The emergence of voltage source converter (VSC) modular multilevel converter (MMC) technology in 2006, which was particularly suited for undersea and underground cables, helped in overcoming the ±800 kV voltage barrier. Several major projects in China and India were subsequently taken up. Unlike line-commutated converters (LCCs), VSC eliminated communication failures and used insulated gate bipolar transistors instead of thyristors.

Early VSC systems faced limitations, but the introduction of MMC allowed full control of active and reactive power, improving grid stability. The elimination of large AC filter yards reduced the land footprint, further facilitating multi-terminal direct current (MTDC) systems and DC grids in China, Italy and Japan.

Countries such as China, India and Brazil have adopted different HVDC expansion strategies based on their energy needs. China developed single bi-poles ranging from 5,000 MW to 8,000 MW, enabling large-scale power transmission. India has implemented a single bi-pole line with two 3,000 MW converters in parallel for optimal efficiency. Brazil has developed two independent 4,000 MW bi-poles with interconnected routes to enhance system reliability.

Another key ultra high voltage direct current (UHVDC) project was the hybrid Yunnan-Guangxi ±800 kV HVDC project, which was commissioned in 2020. It integrated LCC and VSC technologies in a three-terminal system, transmitting 8,000 MW over 1,489 km. Another project, the Changji-Guquan ±1100 kV UHVDC system, holds the world's highest voltage rating, significantly improving transmission efficiency.

Overall, he stated that HVDC's evolution is steering towards architectures resembling AC grids. The Zhangbei ±500 kV HVDC demonstration project in China integrates wind, solar and hydro energy over a wide area. Multi-terminal interconnections, higher power ratings and multi-voltage DC levels necessitate advanced DC/DC converters, signalling a shift toward grid-like HVDC networks.

Medium voltage DC applications are advancing, enhancing renewable energy integration and local transmission. The Xinjiang Renewable Energy DC Collection Project is testing an MMC using integrated gate commutated thyristors at ±500 kV and 200 MW, while the Qinghai Photovoltaic DC project has deployed a ±15 kV/60 MW MCC concept to assess compatibility with larger ±500 kV/2000 MW systems.

Dr Szechtman emphasised that HVDC is set for transformative growth, transitioning from isolated projects to large-scale interconnectors that complement AC grids. This is being driven by the global expansion of renewable integration, particularly in China, India and Brazil, with potential adoption in the US. Northern Europe is also shifting from isolated offshore wind projects to hub-to-hub MTDC and DC grids, while DC super grids and overlay networks are poised to enable efficient cross-border transmission. Advancements in DC circuit breakers and switching stations are expected to improve fault clearance and system reconfigurations. Interoperability and regulatory challenges, however, must be addressed to ensure a seamless energy transition.

Global Operational Experiences of UHVAC Systems

Mr Eiichi Zaima, CRIEPI, Japan, spoke about the system aspects of ultra-high voltage (UHV) transmission technologies and operational experiences with UHV transmission lines, including site-testing of substation equipment.

He noted that Japan has over 30 years of operational experience with UHV transmission lines of 550 kV and lower voltages. The country has also carried out verification of substation equipment at test sites.

He further noted that there are plans for the current under-550 kV transmission system in Japan to be uprated in the future, as described in the "Master Plan of Future System Plan in Japan", which is based on operational experiences.

As per the "Master Plan for the Wide-Area Interconnection System Organization for Cross-Regional Coordination of Transmission Operators of Japan", uprating of the voltage to UHV level is expected to not only be effective in increasing the power flow, but also expanding the operational capacity of the Tohoku-Tokyo interconnection project.

The project has been constrained by the need for synchronous stability. Therefore, depending on the expected introduction of power sources and other factors, the operators will consider either strengthening the Tohoku-Tokyo interconnection or uprating UHV facilities ■

System Innovations

Ongoing HVDC R&D continues to push boundaries

The ongoing research and development on HVDC have continued to push the boundaries, aiming to further optimise HVDC systems to meet the growing demands of modern power networks. A look at the key advances in system components…

Converter Stations

The backbone of HVDC systems is the converter, which serves as the interface with the AC transmission system. Each HVDC system has two converters one at each end. HVDC systems take power from an AC networks via a transformer, convert it to DC at a converter station and transmit it to the receiving point by overhead lines or underground cables, where it is turned back into AC using another converter.

At the first HVDC Light test installation in Hallsjon launched in 1997, the converter station was rated at a modest 3 MW and ±10 kV DC, and connected to separated parts of an existing 10-kV AC network.

Converter stations today scale from 80 kV to 800 kV and 100 MW to 4,600 MW, with rated DC currents up to 3,000 A. The use of semiconductor devices, bi-mode insulated-gate transistors and advanced switching algorithms allow for increased current density and low converter losses. Station losses are now under 1 percent per station.

The inherent capabilities of converters also permit continuous and independent control of real and reactive power. With the introduction of HVDC Light (VSC) converters in the mid-1990s, the controllability of HVDC converters took a quantum leap forward, as not just the active power but also the reactive power became fully controllable.

The converter stations of the VSC-based Caprivi interconnector scheme in Namibia, which connects the AC networks of Namibia and Zambia through 950 km of overhead lines operating at -350kV DC, are able to provide reactive power capability throughout nearly the entire power transfer range. The active power can be selected from 0 to 300 MW import (power flow from Zambezi to Gerus), and up to 350 MW overload capability at low ambient temperatures, or from 0 to 280 MW export (power flow from Gerus to Zambezi), without power interruption when changing power direction During a DC line fault, the converter stations are temporarily isolated from the AC grid and the DC line by opening the AC and DC circuit breakers to interrupt the fault currents.

While high availability and reliability are key requirements on all converter stations, this has become even more evident in offshore systems given the high costs of maintenance. On the DolWin2 platform, which connects offshore wind farms in the North Sea's DolWin cluster with the German grid and is operated by transmission system operator TenneT, the offshore converter stations have a black-start capability – they can generate a voltage with amplitude and phase controlled as desired. The 320 kV converter station has a 916 MW power transmission capacity, enough to power more than a million households with clean energy. The blackstart feature is especially useful when it comes to starting up an offshore network.

Control and protection

HVDC transmission has always been different from AC transmissions in that the power flow on an AC line is solely determined by the voltage and phase angle difference between the endpoints, whereas the power transfer of an HVDC system is fully controllable and the power flow is determined by the control system. This property is what provides many of the outstanding system features of an HVDC system, but it also requires a very fast and reliable control system.

For instance, semiconductor valves rely on a very fast and reliable automatic control regime to fire the thyristors in the HVDC Classic product, or to fire the on and off signals for the IGBTs in HVDC Light. Electrical and auxiliary systems need to be constantly monitored and controlled to ensure all components work in harmony.

To enable a high degree of integration and handling of all HVDC control and protection functions, the introduction of the first-generation MACH (modular advanced control for HVDC) control and protection system in 1991 by ABB was a key development. MACH acts like the brain of the HVDC link – monitoring, controlling and protecting the sophisticated technology in the stations, managing thousands of operations to ensure the reliability of power supply. The first installation using the MACH system, a cable between Norway and Denmark, was put into commercial operation in late 1993.

The second generation of the MACH system was then introduced in 1999, which combined it with a evolutionary input/output system that was connected only by serial buses, even for the highest speed measurement signals. It was introduced together with HVDC Light, which allowed the first generation of VSC converters to achieve their outstanding performance.

MACH has been extensively used across a range of installations from small, highly demanding HVDC Light links, to large HVDC power transmission systems. It has also been extended to energy storage solutions as well as low- and medium-voltage converter applications such as EV chargers and static frequency converters.

The latest generation MACH has outstanding communication capabilities, and is therefore the ideal platform to implement a fully digitalised HVDC station. All time-tagged events and alarms together with all important measured values are immediately available to the control and protection computers.

MACH continues to evolve to incorporate even higher performance, more integrated solutions, and newer innovations. This is possible owing to its carefully chosen interfaces. This has helped in upgrading several pioneering projects. For instance, the Pacific Intertie project in the US was upgraded to the latest MACH system in 2016. The EstLink 1 project, a 105 km-long subsea HVDC transmission system enabling power exchange between Finland and Estonia is now being upgraded with an advanced MACH control and protection system.

In future, a meshed offshore grid and its integration with the existing onshore grid will require advanced protection and control systems. Each connected HVDC Converter station will have its own dedicated control and protection (C&P) system that governs the internal and very fast C&P functions.

Conductors

As the converter station ratings increased, so too did the powers and voltage levels for which the HVDC cables had to be built. The two main types of cable technology suitable for use in HVDC applications are cross-linked polyethylene (XLPE) and mass impregnated (MI) insulation. The Gotland 1 link featured the first submarine MI (mass impregnated) HVDC cable.

Initially MI cables were regarded as a good choice for the highest ratings. The development of VSC technology was considered as an opportunity to introduce XLPE-extruded insulation cables for HVDC applications in addition to MI cables. Intensive research and development for extruded DC cables took place in early 1990's.

The extruded HVDC cable system technology is appropriate when power needs to be efficiently delivered through populated or environmentally sensitive areas, or in coastal and open-sea applications. The Murray Link cable system was the first modern extruded HVDC cables rated for 150 kV.

HVDC cables consist of a copper or aluminium conductor surrounded by a layer of insulation (the thickness of which is dependent upon the operational voltage), a metallic sheath to protect the cable and prevent moisture ingress and a plastic outer coating. Copper has been the preferred material owing to its high conductivity, minimal electrical losses, and good corrosion resistance properties.

With weight and cost reductions, aluminum conductor use has grown. One of the important submarine power cable projects that used aluminum conductors for the first time was the NordBalt HVDC Cable Link between Sweden and Lithuania commissioned in 2015. The 700 MW, ±300 kV connection that links the electricity networks in the Baltic and Nordic regions is the longest extruded HVDC cable system in the world. It spans 400 km of water under the Baltic Sea with a maximum depth of 125 m. Aluminum conductors were installed and buried in a bundled configuration together with a fibre-optic cable.

In more recent years, the high-voltage power cable market has seen a shift with 525 kV extruded XLPE power cable technology becoming the standard technology for several large cable projects. The 2 GW Dutch projects to be completed between 2028 and 2030 by TenneT would see the deployment of these cables.

HVDC breakers

The relatively low impedance in HVDC grids is a challenge when a short circuit fault occurs, because the fault penetration is much faster and deeper. HVDC breakers that isolate faults and avoid a collapse of the common HVDC grid voltage are one of the key technical elements that make it possible to build an HVDC grid with many terminals with multiple protection zones.

From mechanical HVDC breakers that were only capable of interrupting HVDC currents within several tens of milliseconds, the industry then moved to HVDC breakers based on semiconductors to overcome the limitations of operating speeds. However, these breakers generated large transfer losses, typically in the range of 30 percent of the losses of a voltage source converter station. Further, HVDC faults needed to be cleared in a few milliseconds.

This was ABB's motivation behind developing the hybrid DC circuit breaker. After years of research, a key breakthrough happened in 2012 with the development of the hybrid HVDC circuit breaker. The innovative hybrid design had negligible conduction losses, while preserving ultra-fast current interruption capability of the meshed HVDC grid. By allowing the transmission system to maintain power flow even if there is a fault on one of the lines, a reliable HVDC breaker which was the last missing piece of the puzzle was ultimately realised after several years of development.

The hybrid breaker will be a key component for both offshore and onshore HVDC grids as shares of renewable energy radically increase in the energy system.

The development of the breaker has continued during the past few years, following extensive tests at the component, unit and system-level. The 350 kV hybrid HVDC breaker was in 2020 independently tested by KEMA Laboratories (Netherlands) within the EU-funded PROMOTioN project in front of European TSOs and grid developers, further proving the maturity of the technology. Unlike previous experiments, this test exposed the breaker to realistic system voltage stress after the current interruption and full power dissipation. The demonstration proved the reliable control system, robust component design and safe mechanical design of the breaker. Other HVDC circuit breaker prototypes have also been demonstrated including that of Mitsubishi-acquired Scibreak, a Swedish start-up providing DC circuit breaker concept.

Overall, the improvements being made to individual components and the way they are used within HVDC systems suggest that HVDC transmission systems will continue to gain in functionality and capacity for theforeseeable future. ■

Vision 2030

The way forward for India's clean energy transition

It was at the COP26 global climate summit in Glasgow in 2021 that India set the ball rolling by announcing its intent to achieve net zero emissions by 2070. In addition to this, it announced an ambitious clean energy goal of installing 500 GW of non-fossil energy capacity as a part of the country's clean energy transition journey. At that time (end-October 2021), India had 149.57 GW of renewable energy capacity, comprising 47.67 GW of solar power, 46.51 GW of hydro, 39.99 GW of wind, 10.58 GW of biopower and 4.82 GW of small-hydropower. Meanwhile, nuclear power, another non-fossil energy source, accounted for 6.78 GW of installed capacity, bringing the total non-fossil fuel-based power capacity to 156.35 GW.

Three COPs and just three years later, India has shown remarkable progress in its transition towards clean energy sources. Its renewable energy capacity has expanded by an impressive 54 GW to reach 203.22 GW as of October 2024, which translates to almost 45 per cent of the country's entire installed power capacity. This comprises 92.12 GW of solar power, which has singularly been responsible for around 45 GW of the total capacity additions over these past three years. Wind power capacity has reached 47.72 GW, with 7 GW of capacity additions over the past three years, and nuclear power capacity has reached 8.18 GW. Growth in the other three segments has been more sluggish, with hydropower currently standing at 46.97 GW, biopower at 11.33 GW and small-hydro at 5.08 GW.

Thus, the total non-fossil fuel-based power capacity of the country stands at 211.39 GW at present, with almost a quarter of it having been installed over just the past few years. However, this capacity is significantly short of the 2030 target of 500 GW. The country would need at least 45 GW of new installations every year over the next six years to even come close to this goal.

It is a daunting task, but is not impossible, considering the untapped clean energy potential in India. The solar potential, for instance, is a massive 748 GW, as per the National Institute of Solar Energy. Further, the National Institute of Wind Energy estimates the wind power potential as 695.5 GW at 120 metres and 1,163.9 GW at 150 metres above ground level for just onshore wind. The country has a vast resource of untapped potential from other sources, such as bioenergy and hydropower, as well. In addition, emerging areas such as green hydrogen, solar-wind hybrids, round-the-clock (RTC) renewables, offshore wind and energy storage can give a major boost to the sector with various large projects now under construction. Combined with the right enablers such as grid, land and other infrastructure, transparent policy and regulatory regimes, attractive market dynamics, ready demand for clean energy, and access to finance, the country's abundant renewable energy resources can help meet the target for the clean energy transition.

Against this backdrop, this article will review the progress made during the past year with respect to capacity expansion, key auctions, policies, technology trends and financings, and then follow up with six priority areas or action items for the next six years to reach the 2030 target.

Review of the past year

Growing renewable energy capacity: India's total renewable energy capacity has grown from 132.13 GW as of October 2023, to 156.24 GW as of October 2024, translating to 24.11 GW of new capacity addition during this period. In line with the trends of the past few years, a massive 20.1 GW or approximately 83.37 per cent of the new renewable energy deployment has been in the solar space.

Solar power continues to dominate new capacity additions in the country owing to its versatile nature (rooftop, floating, agriPV, ground-mounted), availability of good resources across the country, attractive cost economics, an expanding market landscape, scalable business models, an enabling policy regime, and increasing consumer awareness and demand. Wind power, on the other hand, is concentrated in a few states in the western and southern parts of the country, and many high-wind sites have already been utilised by older, lower-capacity turbines. Further, the segment has faced challenges due to the greater demand for solar power from both utilities and consumers, disruptions caused by changes in project allocation regimes, and supply chain issues. However, the recent slew of solar-wind hybrids, RTC and firm and despatchable renewable energy (FDRE) projects has given a boost to the wind segment (along with solar power), with wind power offtake expected to increase significantly.

Consumers want quality 24x7 clean power supply, which solar or wind alone cannot guarantee, and thus, a mix of resources is ideal. This is evident from the auctions held in the past one year, as the capacity and number of hybrid auctions have increased to become comparable with solar power auctions. According to Renewable Watch Research, between November 2023 and October 2024, auctions were conducted for 27.93 GW of hybrid, RTC and FDRE capacities, compared to 21.78 GW for solar and 2.65 GW for wind power. Tariffs were also competitive, with hybrid tariffs being in the range of Rs 2.99-Rs 3.60 per kWh versus Rs 2.50-Rs 2.68 per kWh for solar power and Rs 3.56-Rs 3.81 per kWh for wind power. With costs of energy storage systems declining, FDRE tariffs came down to a new low of Rs 4.25 per kWh .

Evolving policy landscape: India's expanding clean energy ecosystem is being supported by continuous policy and regulatory support to sustain renewable energy development and attract both domestic and global players. The year 2024 witnessed policy developments focused not only on standalone utility-scale renewables but also on emerging areas such as green hydrogen, offshore wind, repowering and energy storage, as well as the previously neglected biopower and residential rooftop solar segments. These recent policy developments aim to promote inclusive clean energy deployment, encompassing a variety of consumer categories, technologies and business models.

For instance, in the green hydrogen space, financial incentives were announced for green hydrogen production and electrolyser manufacturing. Meanwhile, various guidelines were announced to support the development of green hydrogen hubs, enable funding for testing facilities, facilitate the procurement of green hydrogen and establish pilot projects in the shipping, steel and mobility sectors.

In the distributed solar space, schemes were launched to encourage consumers to become prosumers. The landmark PM Surya Ghar: Muft Bijli Yojana was launched to incentivise household owners to set up rooftop solar systems, supported by attractive subsidies. Guidelines were also issued for creating model solar villages and electrifying 100,000 households belonging to "particularly vulnerable tribal groups". However, in the solar manufacturing space, there was some uncertainty at the beginning of the year regarding the Approved List of Models and Manufacturers for solar modules.

The previously neglected bioenergy space received a fillip with targeted support for various sub-segments, including incentives for biomass aggregation machinery, updated central financial assistance rates for biomass pellet manufacturing units, and concessional customs duty certificates for bio-compressed natural gas (CNG). Further policy support to promote the bioenergy segment included guidelines for the development of pipeline infrastructure to inject compressed biogas (CBG) in the city gas distribution network, as well as clear mandates for the phased blending of CBG into CNG and piped natural gas. The bioenergy space has historically struggled due to policy paralysis, and these policy initiatives will go a long way in improving investments and tapping the vast bioenergy potential in the country.

In the wind power segment, offshore wind and repowering received the much-needed and long-overdue attention from policymakers. Recognising the country's need to develop offshore wind capabilities, the government announced a viability gap funding (VGF) scheme for 1,000 MW of projects to give a kickstart to the nascent offshore wind industry. As many of the country's good wind sites have been taken up and are being run by outdated, low-capacity wind turbines, the government announced the National Repowering and Life Extension Policy for Wind Power Projects, 2023. This policy offers incentives such as fiscal benefits, micro-siting flexibility and preferential loans for the replacement or refurbishment of older turbines with more efficient models. The policy identifies a repowering potential of more than 25 GW for turbines of below 2 MW capacity. With proper implementation, this could significantly boost India's wind power capacity.

To streamline the integration of such large volumes of renewable energy into the grid, new policies were introduced in the power transmission and energy storage spaces as well. On the transmission side, the National Electricity Plan for transmission was launched and Rs 135.95 billion was sanctioned for new interstate transmission system (ISTS) projects for renewable energy evacuation. As storage becomes a critical part of the renewable energy landscape, guidelines were released for VGF of up to 40 per cent to support the development of 4,000 MWh of battery energy storage systems. Plans have also been announced for a comprehensive pumped storage policy.

Development of new technology: India's renewable energy sector is witnessing growing in-house development of diverse technologies. There has been a significant increase in focus on developing research and development (R&D) capabilities. In the solar power space, developers are increasingly opting for TOPCon and heterojunction technologies like the rest of the world. Encouraged by developers' response to technology upgrades and their requirement for cost-efficient products, domestic manufacturers are also scaling up the production of these technology solutions. Further, manufacturers are now focusing on developing capabilities in vertical integration and the upstream solar supply chain to build self-reliance.

Self-reliance in supply chains is also being developed in the electrolyser and battery energy storage spaces. As emerging segments such as green hydrogen and energy storage witness successive auction successes, resulting in the allocation of large-scale projects, various manufacturers have entered the space with ambitious production plans, utilising the latest technologies. Meanwhile, in the wind segment, where India has a significant domestic manufacturing base, the focus is on developing efficient wind turbines that can cater to the country's low wind speeds.

Another critical area in developing domestic manufacturing capabilities for clean energy equipment is building reliable supply chains for critical minerals. Currently, the production of most critical minerals is concentrated in a few countries, making India dependent on imports of these commodities. Thus, the government has proposed the Critical Mineral Mission to give a boost to the discovery, mining and recycling of these essential raw materials and ensure the security of future mineral supply chains.

With the increasing scale, number and size of renewable energy projects and portfolios, automation has become critical across the manufacturing, design, construction, and operations and maintenance phases. Thus, the automation of various activities and the integration of smart technologies across different clean energy verticals are emerging other important areas of focus. Robots, drones, artificial intelligence, big data, predictive analytics, machine learning tools and advanced digital technologies are being increasingly used to navigate complicated issues more efficiently.

Enabling financing environment: The 63rd edition of EY's Renewable Energy Country Attractiveness Index, released in June 2024, ranks India seventh amongst the world's top 40 markets based on the attractiveness of its renewable energy investment opportunities. The country's renewable energy sector continues to be a top investment destination for global private equity firms, venture capitalists, pension funds, multilateral banks and energy majors from across the world. India's renewable energy sector is now drawing substantial investments from domestic financial institutions as well.

In line with the trend of the past few years, equity infusion and mergers and acquisitions have remained the preferred mode of financing. This signifies that the country's renewable energy market is maturing, and assets are finding good value with buyers. Buyers, on their part, want to quickly expand their renewable energy portfolios and acquisitions may seem uncomplicated when compared to developing new assets from scratch. Some recent big-ticket deals include Brookfield's acquisition of a controlling stake in Leap Green Energy, Reliance Industries' sale of REC Norway, IndiGrid's acquisition of ReNew's 300 MW assets and BluePine's purchase of 369 MW of solar power assets from the ACME Group. On the services side, Suzlon's acquisition of a majority stake in Renom was a big highlight this year.

Meanwhile, on the debt side, companies were able to raise loans not just through domestic banks but also through multilateral banks, like ENGIE's Rs 14.6 billion loan agreement with the Asian Development Bank (ADB), and Fourth Partner Energy's fundraising from the International Finance Corporation and the ADB. Lenders such as the State Bank of India, Standard Chartered Bank and Tata Capital focused on financing plain vanilla wind and solar projects as well as distributed solar projects.

A key trend in renewable energy financing during the year was the slew of initial public offering (IPO) announcements by companies as awareness grew and the sector found growing acceptance among a variety of investors. Now, both developers and manufacturers are taking the well-established IPO route to raise funds for expanding their capacities. Companies such as ACME Solar, Vikram Solar, Waaree Energies, NLC India Renewables Limited and NTPC Green Energy Limited have already announced or are in the process of announcing their IPOs. This trend is expected to continue as renewables become more prominent in the everyday lives of people.

Road to 2030

The developments mentioned in the previous section are a testament to India's impressive renewable energy growth story. The sector is driven by a strong political will, policy backing, and an enterprising private and public sector ready to capitalise on these opportunities and build up the sector. As India moves ahead in its transition to clean energy, increased collaboration between the private and public sectors will be vital to realising the country's vision and targets. Needless to say, international and regional collaboration, along with continued partnerships, are essential for technology transfer, capacity building, attracting investments and ensuring future energy security. Global and domestic collaboration is especially urgent in four key priority areas to bridge existing gaps and maintain the clean energy growth momentum.

Overcoming T&D bottlenecks: Adequate transmission infrastructure is vital for evacuating renewable power from generating stations to load centres. However, despite significant planning and efforts to quickly expand the transmission system to meet the growing demand, there is a large gap in available capacity and what is required. Since a major portion of the capacity is being developed in a few states such as Gujarat and Rajasthan, there are long queues for getting grid connectivity, going up to years. The withdrawal of the ISTS waiver in June 2025 may lead to a greater focus on the development of intra-state transmission networks, potentially alleviating the current transmission bottlenecks to some extent in the future. Even then, the build-out of ISTS infrastructure needs to be accelerated through better planning and coordination with developers, as well as quick bidding and approval of projects.

Another critical aspect of the power landscape is distribution, and many of the state-owned distribution utilities and their infrastructure are in dire need of reform and upgradation. Major improvements in their technical and financial health are needed to ensure timely payments to generators. This will enable further innovation, adoption of advanced technologies, and aggregator-based discom-anchored projects in emerging areas such as community solar, electric vehicle charging and residential rooftop solar adoption. Only with a strong transmission and distribution (T&D) infrastructure can India meet its renewable energy ambitions and sustain that growth.

Securing supply chains: To grow its clean energy capacity to 500 GW and beyond, India needs to rapidly secure its supply chains through a combination of expansion of domestic capabilities and diversification. Diversification is important, not just from the perspective of supply routes but also alternative technologies. For instance, since China is the primary producer of lithium-ion cells for batteries, alternative battery chemistries can be explored. Similarly, in solar PV, along with crystalline technology, thin film should also be encouraged. Hence, the expansion of R&D activity with bigger budgets and state-of-the-art infrastructure is crucial for the country to develop cost-efficient clean energy technologies ideal for Indian climate and market conditions.

Regarding manufacturing, the sector needs a phased approach to developing capacities at scale across the solar, storage and electrolyser industries. The sudden imposition or removal of tariff and non-tariff barriers can create uncertainty and impact investor confidence. The country's clean energy manufacturing industry is finally showing signs of expanding, and this must be supported by attractive financial and non-financial policy provisions.

Finally, the country needs to take early and urgent steps to secure the supply chain for critical minerals to safeguard the industry from any future shocks, as witnessed during the Covid pandemic and, more recently, in the commodities market. Recycling, sustainable mining and exploration, along with alternative and diverse supply channels for essential minerals, are key to ensuring future energy security.

Policy and regulatory clarity: The country has done remarkably well in developing the right policy frameworks to meet current needs and undertaking course correction as market demands evolve. This has led to the rapid scaling of renewables within a short period, and global players have invested in the Indian market due to its transparent bidding and project allocation processes. However, since power is a concurrent subject, there has been a certain disconnect between the central government's initiatives and their implementation at the state level. This is especially the case in areas such as open access, net metering, green hydrogen and standalone wind power projects. Thus, the right policies exist at the centre, but many states are slow to adopt them and often have their own interpretation of these policies. This can become quite cumbersome for industry players that operate across multiple states. Therefore, better coordination between the central and state agencies with alignment in vision and targets is the need of the hour.

Furthermore, renewable power projects are long-term infrastructure projects with lifecycles going up to 25 years, and developers require policy certainty and visibility to invest in such projects. Thus, policy direction must be supported by clear and long-term regulatory frameworks as sudden flip-flops can deter investors. In addition, penalties should be clearly defined and enforced for stakeholders that breach contracts, with greater accountability across all parties. This will help ensure that quality infrastructure is rapidly built to clean the energy mix. This also necessitates streamlined and faster approvals for land acquisition, grid connectivity, tariff adoption and the signing of power purchase agreements.

Capacity building: Building clean energy infrastructure across all states and different segments such as solar, wind, biopower, green hydrogen, energy storage and T&D will require skilled manpower. Trained and qualified personnel are required not only to construct these projects but also to operate, maintain and improve them over the project lifecycle. Moreover, researchers and skilled technicians are required to innovate and help expand the country's manufacturing facilities. Focused and practical programmes at the school/college level, combined with specialised courses in various clean energy technologies, are essential.

At the organisational level, regular capacity building and upskilling are required to retain the workforce. Further, the expansion of renewable energy requires increased awareness within the financier community, as well as among state-level or municipal-level approval agencies. Continued capacity building efforts at these levels are crucial for sustained progress.

Finally, the local population must be empowered and educated on the benefits of renewable energy adoption. The country's energy transition will be successful only if it is inclusive, just and sustainable. ■

Optimising Infrastructure

Reconductoring solutions enhance transmission capacity

Despite the urgent need for clean power to meet the nation's 500 GW non-fossil fuel capacity goal by 2030, one significant obstacle remains – a transmission infrastructure that can meet this upcoming demand. India's ability to meet its renewable energy and electrification targets is increasingly constrained by bottlenecks in the transmission network.

Reconductoring, which involves replacing the existing conductors with high-capacity alternatives such as high temperature low sag (HTLS) conductors, is emerging as a solution for delivering more power through existing corridors and overcoming the numerous right-of-way (RoW) issues that construction of new lines faces.

Demand factors

Reconductoring involves replacing or upgrading the conductors on existing transmission or distribution lines to increase their capacity to carry electricity. This cost-effective and efficient method optimises the existing infrastructure. Hence, by enhancing capacity without the need for additional land acquisition or long lead times, reconductoring presents a practical and sustainable alternative to the conventional approach of building new transmission lines. It is also a much more practical alternative to constructing new lines, particularly in urban areas and regions facing RoW issues.

While planning for reconductoring, utilities must consider the choice of technology. As per the Central Electricity Authority's (CEA) 2019 guidelines on the rationalised use of high performance conductors, such conductors can be considered for reconductoring of existing lines. High performance conductors should be considered in corridors where power transfer is constrained due to the thermal loading of conductors. In the intra-state transmission system, such conductors are needed at the 220 kV, 132 kV and 66 kV levels. However, high performance conductors may not be cost-effective for HVDC systems at the 765 kV voltage level.

The most commonly used advanced conductors in India include high-temperature low-sag HTLS conductors, high-temperature superconductors, aluminium conductor steel-reinforced cables and composite core conductors. These designs operate at higher temperatures, reduce heat loss and allow for greater power transfer.

Completed/Ongoing reconductoring ISTS projects as per the CEA's National Electricity Plan–Transmission

Details	Voltage	Mode of implementation	State	Status
Reconductoring of the 400 kV Jodhpur (Surpura) (RVPN)-Kankroli S/C line with twin HTLS conductors with a minimum capacity of 1,940 MVA per circuit at nominal voltage (188 km line length); Upgradation of the existing 400 kV bay equipment each at the Jodhpur (Surpura) (RVPN) and Kankroli substations (3150 A)	400 kV	RTM	Rajasthan	Commissioned
LILO of the Pirana (PG)–Pirana (T) 400 kV D/C line at the Ahmedabad substation with twin HTLS along with reconductoring of the Pirana (PG)–Pirana (T) line with twin HTLS conductors with a minimum capacity of 2,100 MVA/ckt at nominal voltage and bay upgradation works at the Pirana (PG) and Pirana (T)	400 kV	RTM	Gujarat	Ongoing (expected: March 2025)
Reconductoring of the Shujalpur (PG)–Shujalpur (MP) 220 kV D/C line (conductor with ampacity equivalent to ACSR twin moose at nominal voltage)	220 kV	RTM	Madhya Pradesh	Commissioned
Reconductoring of the Kolhapur (PG)–Kolhapur 400 kV D/C line with conductor of a minimum capacity of 2,100 MVA/ckt at nominal voltage along with bay upgradation work at Kolhapur (MSETCL)	400 kV	RTM	Maharashtra	Commissioned
Reconductoring of the Parli (PG)-Parli (M) 400 kV D/C line section of above line (at Sl. 1) with twin HTLS conductors (minimum capacity of 1,940 MVA/ckt at nominal voltage)	400 kV	RTM	Maharashtra	Under construction (allocation date: August 25, 2022)
Reconductoring of the Maithon RB-Maithon 400 kV D/C line	400 kV	RTM	West Bengal	Commissioned
Reconductoring of the Jharsuguda/Sundargarh (Powergrid)–Rourkela (Powergrid) 400 kV 2xD/C twin moose line with twin HTLS conductor (with ampacity of single HTLS as 1,228 A at nominal voltage)	400 kV	RTM	Odisha	Ongoing (expected: November 2025)
Reconductoring of the Rangpo-Gangtok 132 kV D/C line	132 kV	RTM	Sikkim	Ongoing (expected: November 2024)
Reconductoring of LILO portion at the Pare end (of the Ranganadi–Naharlagun/Nirjuli 132 kV S/C line) with HTLS (HTLS equivalent to ACSR Zebra) along with modification of 132 kV bay equipment at Pare HEP. Two 132 kV GIS bays at the Nirjuli S/s for termination of LILO of one circuit of the Pare HEP–North Lakhimpur (AEGCL) 132 kV D/C line (with ACSR Zebra) to be provided by POWERGRID	132 kV	TBCB	Arunachal Pradesh	Commissioned
Reconductoring of the Melriat (POWERGRID)-Zuangtui (Mizoram) 132 kV ACSR Panther S/C line with single rating of HTLS conductor of 900A (at nominal voltage) along with a new 132 kV line bay at the Melriat (Powergrid) S/s (of rating commensurate with the rating of HTLS) for termination of this HTLS line	132 kV	RTM	Mizoram	Ongoing (expected: April 2025)
Reconductoring of the Aizawl (POWERGRID)-Luangmual (Mizoram) 132 kV ACSR Panther S/C line with single HTLS conductor rating of 800A (at nominal voltage) along with upgradation of line bay equipment at Aizawl (POWERGRID) end commensurate with the rating of HTLS	132 kV	RTM	Mizoram	Ongoing (expected: April 2025)
Reconductoring of the Loktak (NHPC)–Imphal (POWERGRID) 132 kV S/C line with HTLS conductor (with single HTLS ampacity of 800A at nominal voltage); strengthening of associated structure in the NHPC switchyard	132 kV	RTM	Manipur	Commissioned

Source: NEP

Challenges and considerations in reconductoring

The CEA, in 2023, had released a draft paper on the reconductoring of ISTS lines. One challenge that the paper highlighted was that the process must address several key technical aspects such as acceptable sag parameters, maximum allowable conductor temperatures and the structural health of transmission towers. Special attention is needed for long spans to prevent excessive tension on towers and their foundations. In cases where the load-bearing capacity of the existing towers is insufficient, reinforcements, or even complete replacements, may be required.

Reconductoring multivoltage or multicircuit lines adds another layer of complexity, especially when adjacent circuits must remain operational during the process. Also, reconductoring with advanced conductors may not always be economically feasible. Hence, utilities must carefully assess these factors to determine whether reconductoring with advanced conductors aligns with their technical and financial goals.

Reconductoring has pros and cons under both regulated tariff mechanisms (RTMs) and tariff-based competitive bidding (TBCB). RTM ensures single ownership, streamlined operations and lower costs with faster execution. TBCB, on the other hand, promotes cost efficiency through competitive bidding. The structural integrity of transmission towers must be assessed for mechanical stress and potential reinforcements. Reconductoring with advanced conductors may expose vulnerabilities in terminal equipment, requiring upgrades to switches, protection systems, and FACTS controllers. Multivoltage lines add complexity, demanding careful planning when adjacent circuits remain operational.

Conclusion

The newly released National Electricity Plan (Volume II, Transmission) has identified important reconductoring projects (see Table). The country operates a vast transmission network. With careful planning, adherence to the CEA's guidelines and prudent use of advanced conductors, reconductoring can overcome these obstacles and play a pivotal role in creating a resilient transmission network. ■

Industry Perspective

Anil Sardana

MD, Adani Energy Solutions Ltd & MD, Adani Power Ltd

The power sector, particularly in India, faces a complex set of challenges as the country stands at the intersection of multi-decadal growth and the transition towards becoming a developed nation. These challenges include India's ambitious growth trajectory, implying a substantial increase in power demand in the coming years. Meeting this soaring demand and providing reliable electricity while adhering to renewable energy targets and maintaining grid stability is a significant challenge. Enhancing grid integration, upgrading transmission infrastructure and investing in energy storage solutions are essential steps to address this issue. Augmenting transmission infrastructure to keep pace with renewable energy deployment is a challenge that needs attention. Alongside, minimising transmission and distribution losses remains a persistent challenge.

The transmission segment will require far greater capacity additions to effectively transmit power from regions with high levels of renewable energy to consumption centres across the country. The private sector is playing a critical role by investing significant capital in the creation of transmission networks, taking advantage of lower global interest rates, reduced risks, the annuity model and extended infrastructure yields. This approach also frees up significant state government resources that can now be allocated for strengthening other social sectors such as health and education.

Dr Praveer Sinha

MD and CEO, Tata Power Company Limited

India has made significant strides in its energy transition, positioning itself as a global leader in renewable energy. This transformation has been driven by government initiatives, financial incentives and declining technology costs. Despite these successes, several challenges remain. One of the primary obstacles is the intermittency of renewable energy sources such as solar and wind, which can lead to fluctuations in supply. Addressing this issue requires a focus on developing round-the-clock solutions such as pumped hydro, small modular reactors and large-scale energy storage systems.

The expansion of transmission networks and green power corridors is also necessary to accommodate the increasing generation of renewable energy. In this regard, grid stability remains a concern, as the existing infrastructure is struggling to keep pace with the increasing share of renewables. The deployment of energy storage solutions, such as battery energy storage systems and pumped storage projects, is crucial for addressing these intermittency issues, although their high costs and scalability limitations remain hurdles that must be overcome. At the same time, grid modernisation is essential for managing the integration of renewable energy and other distributed energy resources. This will require substantial investment in smart grids, advanced metering infrastructure and automation technologies to ensure reliable and efficient power distribution.

Pratik Agarwal

MD, Sterlite Power Transmission Limited

No system is complete without a robust transmission network. One of the key requirements of the transmission grid is the expansion and modernisation of infrastructure to help achieve India's target of 500 GW of renewable energy by 2030. As more wind and solar projects come online, the grid must evolve to handle increased electricity volumes and ensure efficient power evacuation, especially in renewable-rich states. Transporting power over long distances through HVDC will be a game changer. As land becomes a scarce resource and right-of-way (RoW) issues become more complex, upgrading existing corridors will be necessary. To this end, planners should consider RoW width reduction technologies such as HTLS and monopoles. Grid flexibility and resilience are also critical, requiring advanced energy storage solutions, FACTS devices and smart grids to manage the intermittency of renewables and enhance stability. Decentralisation and digitalisation are emerging trends as smaller-scale renewables and rooftop solar demand a more intelligent grid capable of real-time monitoring and automation to optimise performance and prevent disruptions.

India's power sector is on the cusp of a significant transformation. With peak demand projected to exceed 400 GW by 2031-32, there is an urgent need for a robust and expanded power infrastructure. The disruptions caused by electric vehicles, smart buildings, green hydrogen and data centres will only continue to drive up demand.

Harsh Shah

CEO, IndiGrid

India's energy future depends on a modern, resilient and efficient power grid. As we transition towards a renewable energy-driven economy, upgrading our transmission infrastructure is not just an option; it is a necessity. The integration of large-scale renewable energy projects requires a flexible and intelligent grid that can handle variability while ensuring uninterrupted power supply. Battery energy storage solutions have emerged as an effective and efficient way to circumvent renewable energy intermittentcy and facilitate grid stability.

Additional investments in digital technologies, real-time monitoring and automation will enhance grid stability, reduce losses and optimise power flow. Furthermore, with rising energy demand and ambitious renewable energy targets, expanding interstate transmission corridors is critical.

Strengthening our grid will accelerate industrial growth, improve energy access in remote areas and support India's net zero aspirations. We must also focus on grid resilience against extreme weather events, ensuring reliability in the face of climate change. Public-private collaboration, policy support and technological innovation will play a pivotal role in this transformation. A robust transmission network is the backbone of India's power sector, and its modernisation is key to achieving energy security and sustainability for the nation.

N. Venu

MD and CEO, India and South Asia, Hitachi Energy

Grid modernisation will play a pivotal role in realising the energy transition. Each clean gigawatt we add to the energy system needs to be balanced with an increase in grid capacity and flexibility to ensure security, reliability and resilience. Power electronics and advanced control systems will play an important role in this effort. Renewables, grid edge technologies and digitalisation will drive the evolution of future power systems. The future of the grid lies in the adoption of new technologies such as big data analytics for predictive maintenance, artificial intelligence, robotics and virtual reality/augmented reality for better operations and maintenance of the transmission network. India's energy industry is experiencing significant shifts, with a strong emphasis on renewable energy growth, energy storage solutions, digital transformation and decentralised energy systems. Challenges relating to grid integration and stability, infrastructure development, complex regulatory environments and environmental impacts are prominent. Collaboration among all stakeholders is crucial for addressing these challenges because they are bigger than one individual, company or nation. Creating synergies, partnerships, and innovation will be critical to advancing a sustainable energy future for all.

Sandeep Zanzaria

MD and CEO, GE Vernova T&D India Limited

The Indian power sector is not just a national story; it is part of a global trend towards energy transition. The integration of renewables into the energy framework is a part of the rapidly evolving global ecosystem.

As more renewable energy sources are integrated into the grid, we face several challenges due to variability, particularly on the technology and grid stability fronts. The variability inherent in renewable energy generation affects the overall stability of the grid and requires innovative solutions to manage it effectively. Technologies such as HVDC systems will be critical in this process. HVDC not only facilitates long distance renewable energy transmission, it also stabilises the grid by managing power flows more effectively.

We will also need to invest in technologies such as STATCOM for voltage and reactive power management. STATCOM helps maintain grid stability, ensuring that voltage levels remain within acceptable limits, especially during peak demand periods or sudden fluctuations in generation.

As grids become more complex, optimising power flow will necessitate enhanced digital solutions. At the substation level, effective maintenance and monitoring of assets will be critical.

Guilherme Mendonca

CEO, Siemens Energy India, Chairman, Siemens Gamesa India

India's ascension to become the world's fifth largest economy marks just the beginning of its ambitious journey toward Viksit Bharat by 2047. As the nation approaches a GDP of 7 trillion USD, its transition to clean energy stands as the backbone of sustainable growth. The target of 500 GW of renewable energy by 2030 demands a remarkable transformation of power infrastructure – doubling the transmission grid built over a century in less than a decade. This mammoth task includes 1,000 GVA of transformation capacity and advanced technologies like HVDC VSC, STATCOMs and SYNCON, which efficiently transport massive energy blocks while integrating renewable sources. SF6-free switchgears and biodegradable ester transformers further minimize environmental impact. Digitalization and AI bring intelligence to the grid, optimizing power flows and enabling predictive maintenance. Through these innovations, India isn't just addressing energy challenges – it is making significant strides towards a sustainable and clean energy future.

Siemens Energy is deeply committed to India's long-term growth, driving the energy transition through the 'Make in India' initiative by leveraging our manufacturing and talent footprint – for India and the world.

Key Statistics

Power demand and cross-border energy trading

Power and peak demand during the year

Month	Power demand (MUs)	Month	Peak demand (MW)
April 2024	144,403	April 2024	224,181
May 2024	155,346	May 2024	249,856
June 2024	152,650	June 2024	244,529
July 2024	150,030	July 2024	227,479
August 2024	144,271	August 2024	216,486
September 2024	140,725	September 2024	230,613
October 2024	139,217	October 2024	219,179
November 2024	123,813	November 2024	207,513
December 2024	129,656	December 2024	224,189
January 2025	137,177	January 2025	237,378
April 2024-January 2025	1,417,215	April 2024-January 2025	249,856
April 2023-December 2024	1,359,193	April 2023-December 2024	243,271

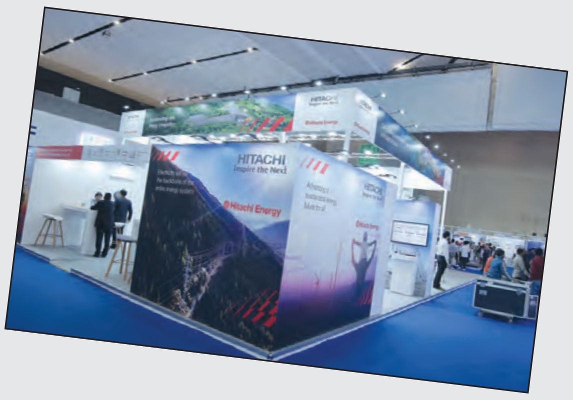
Source: Central Electricity Authority

India's power trade with Bhutan, Nepal, Bangladesh and Myanmar

Month	Bhutan		Nepal		Bangladesh		Myanmar	
	Energy exported (MUs)	Energy imported (MUs)	Energy exported (MUs)	Energy imported (MUs)	Energy exported (MUs)	Energy imported (MUs)	Energy exported (MUs)	Energy imported (MUs)
April 2024	86.47	18.58	346.08	-	694.34	-	0.76	-
May 2024	51.37	68.17	271.84	3.92	655.55	-	0.74	-
June 2024	-	520.23	20.51	152.32	709.14	-	0.87	-
July 2024	-	1,225.84	-	476.74	747.37	-	0.91	-
August 2024	-	1,228.79	-	506.71	719.38	-	0.87	-
September 2024	-	1,219.89	-	494.67	634.75	-	0.75	-
October 2024	-	918.96	-	283.29	695.63	-	0.8	-
November 2024	12.24	125.37	37	212.2	698.58	-	0.71	-
December 2024	187.39	-	58.6	1.56	521.28	-	0.72	-
January 2025	158.13	-	252.02	-	674.7	-	0.67	-
Total	**495.6**	**5,325.83**	**949.03**	**2,131.41**	**6,750.72**	**-**	**7.80**	**-**

Source: Monthly Operation Report, Grid Controller of India

Snapshots from Day 2



GRIDCON 2025

Agenda: Tuesday, March 11, 2025 (Day 3)

VENUE – PALASH HALL – C

6th Floor: Plenary Sessions & Panel Discussions

Time	Agenda
09:30-10:30	**Plenary Session:** Disaster Resilient Infrastructure Design of Transmission Lines by Pierre Van Dyke, Hydro-Québec, Canada
10:30-11:30	**Plenary Session:** Battery Energy Storage Systems by Michael Timofeev, StorEn, UAE
11:45-12:30	**Panel Discussion 4:** Green Finance and Investment Sustainability in Power Transmission
12:45-13:30	**Panel Discussion 5:** Digital Transformation and Skill Development in Power Transmission
14:30-15:30	**Plenary Session:** Grid-Forming Converter and Inverter Technologies by Mikael Halonen, Hitachi Energy, Sweden
15:30-16:30	**Plenary Session:** Digital Transformation of Utilities by Dr Tom TurBushe, EPRI International, France

VENUE – PALASH HALL – B

6th Floor: Poster Presentations

Time	Agenda
10:00-12:00	Poster Presentations
14:30-16:30	Poster Presentations

VENUE – PALASH HALL – A

6th Floor: Women in Energy Event

Time	Agenda	Remarks
09:30-12:30	**Panel Discussions:** 10:00 -10:45 11:00 -11:45	 **Panel Discussion 1:** Breaking Barriers and Building Bridges: Advancing Gender Equality in Power Sector **Panel Discussion 2:** The Power of Women: Modernization and Innovation in the Energy Landscape
14:30-16:30	**Next Generation Networking (NGN)** NGN Overview: Saravana Balamurugan, CIGRE-India NGN Chairman NGN Experience: Ms Amanda Olson, Vice President, Burns & McDonnell, CIGRE NGN Awardee in 2020, Editor of CIGRE Electra Magazine	

12:30-15:00: Lunch - Exhibition Hall 1A & Amaltas Hall

19:00-22:00: Gala dinner along with cultural programme

VENUE – PALASH HALL – C

6th Floor: Valedictory Session & Awards Presentation

Time	Agenda
16:30 -17:30	Valedictory Session and Awards Presentation **Chief Guest:** Secretary (Power), Govt. of India

MEDIA AND KNOWLEDGE SUPPORT

POWERLINE | Global **Transmission** Report

Picture Courtesy: shutterstock images