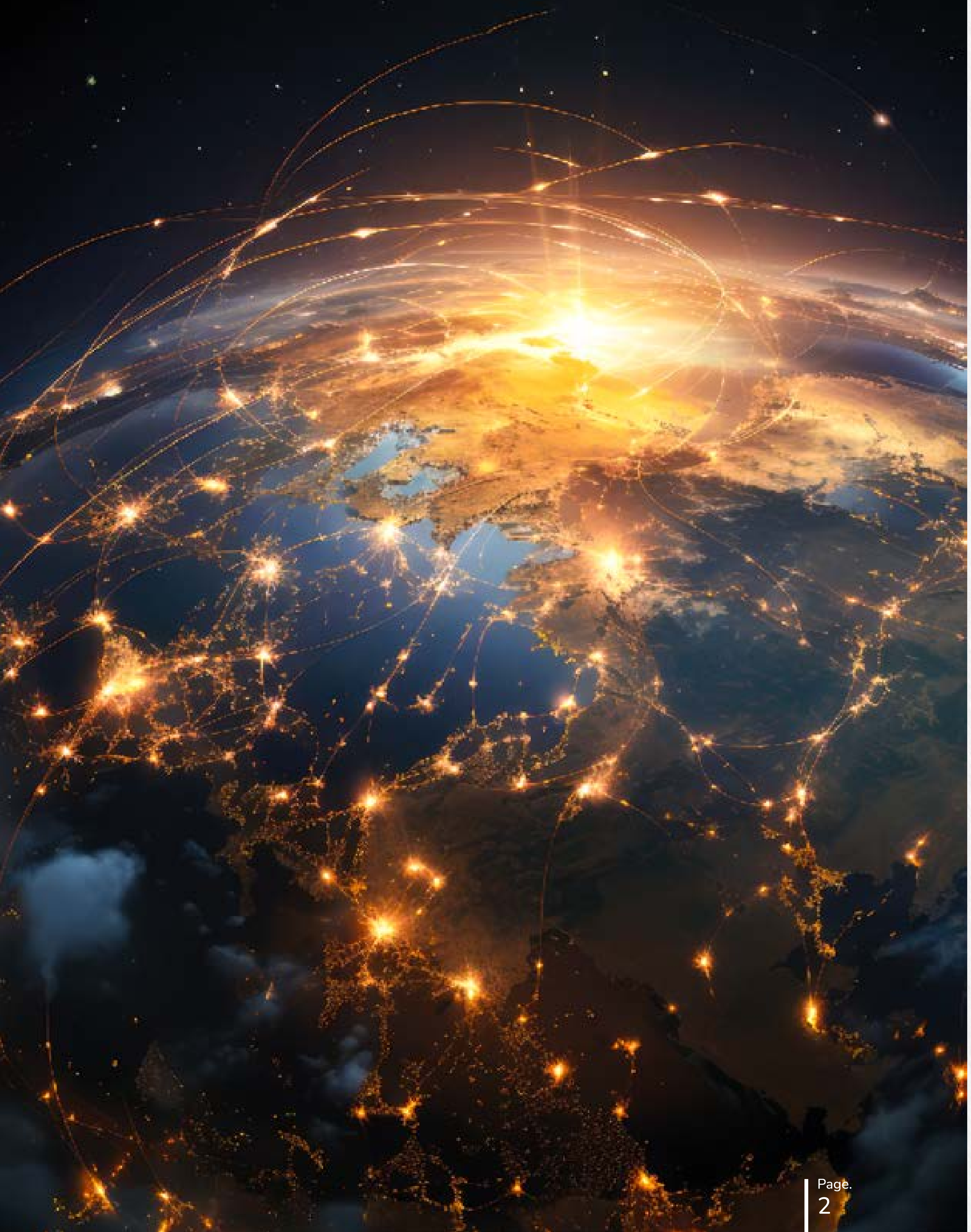
XM Vision

The 2030 Energy Transition Roadmap

20 years
Made by Colombia



1. Introduction

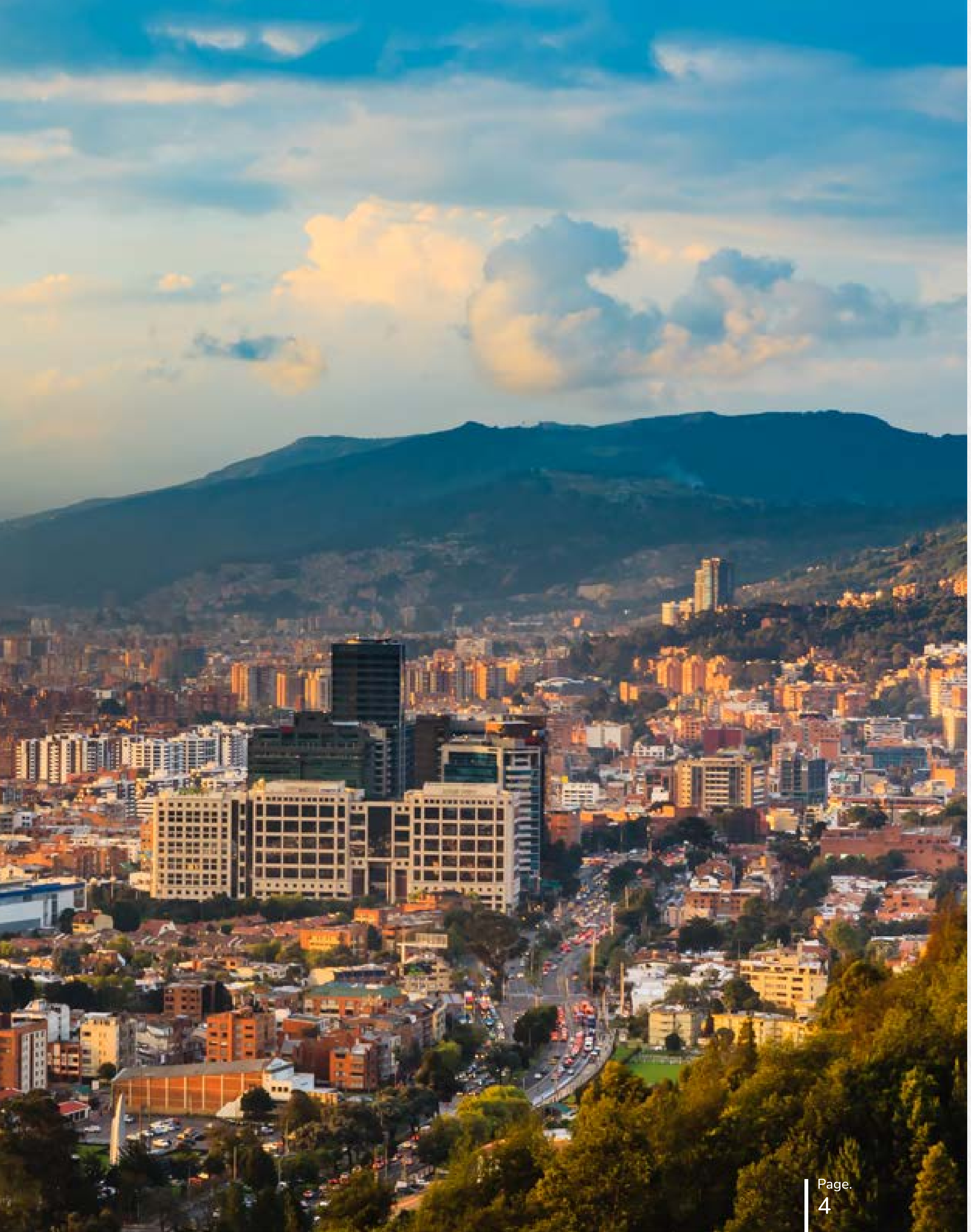
The energy transition presents an opportunity for Colombia to evolve toward a more diversified, sustainable, and resilient electricity system. In a global context where the adoption of non-conventional renewable energy sources (NCRESs) is key to mitigating climate change, Colombia is well positioned to lead this transformation in Latin America. A roadmap provides a structured path for achieving an orderly transition—anticipating challenges, prioritizing actions, aligning capabilities, and supporting informed decisions to ensure a secure, reliable, and efficient process.

Como operador del Sistema Interconectado NacAs the operator of the National Interconnected System (SIN) and administrator of the wholesale energy market (WEM), XM plays a central role in the Colombia's energy transition. Since 2017, in fulfilling its mandate and pursuing a long-term vision, XM has led strategic alliances with research centers, universities, system operators, and government entities. These efforts have strengthened its internal capabilities through the implementation of new processes and the development of new models. Its purpose is to ensure the operation and administration of the SIN, while promoting the development of the country's electrical infrastructure. In addition, XM supports the regulating body by submitting proposals aimed at laying the foundations for the transition.

Building on this experience, XM presents its vision for the roadmap Colombia should follow to achieve its 2030 energy transition goals.

Through a comprehensive approach, the roadmap identifies operational and market needs, required technological developments, and the institutional capabilities necessary to advance a secure, reliable, cost-effective, and sustainable energy transition. **It promotes cooperation among the sector stakeholders and supports the development of new technologies** to efficiently integrate **non-conventional renewable energy into Colombia's electricity system.**

The roadmap is structured around the progressive integration of NCRESs. Each stage drives the adoption of new knowledge, skills, regulatory frameworks, and technologies—promoting an innovative vision and aligning with global best practices in the sector to meet emerging challenges.



2. The Colombian Electricity System

The electrification of various economic sectors—which traditionally have been major energy consumers—is expected to drive a significant increase in electricity demand in the coming years. According to the World Energy Outlook 2024 published by the International Energy Agency, **peak electricity demand is expected to increase up to 80% faster by 2033** in emerging and developing economies, including Colombia.

To meet increases in electricity demand, most of the new generation capability is expected to come from solar and wind resources, connected to the grid via inverters.

https://www.iea.org/reports/world-energy-outlook-2024

In Colombia, the Mining and Energy Planning Unit (UPME) forecasts that electricity demand will increase by nearly 25% by 2033. This growth will be driven by industrial electrification, increased residential consumption, expanded service coverage, and the rise of electric transportation *(see **Figure 1**)*.

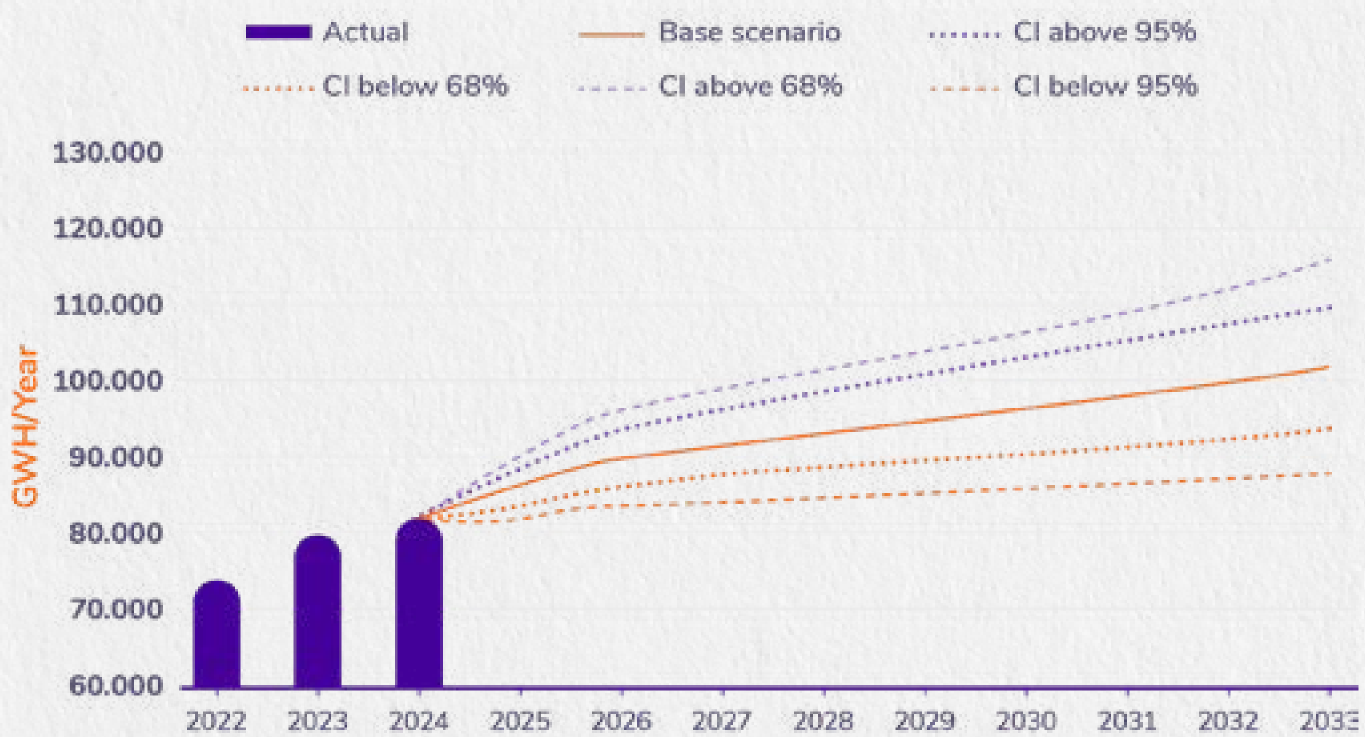


Figure 1. *Actual and forecast electricity demand in the SIN, including large commercial users, WEM, and distributed generation reported to the UPME (GWh/year). Source: Sinergox - UPME. Own work. **CI:** confidence interval.*

To meet the expected growth in demand, the installed capacity of the SIN is projected to increase from 21.5 GW to 37.7 GW by 2033, in line with the connection point allocation procedure established by the Energy and Gas Regulatory Commission (CREG) in Resolution 075 of 2021. Nearly 87% of the capacity to be integrated into the system between 2025 and 2033 will come from solar and wind plants *(see **Figure 2**)*.

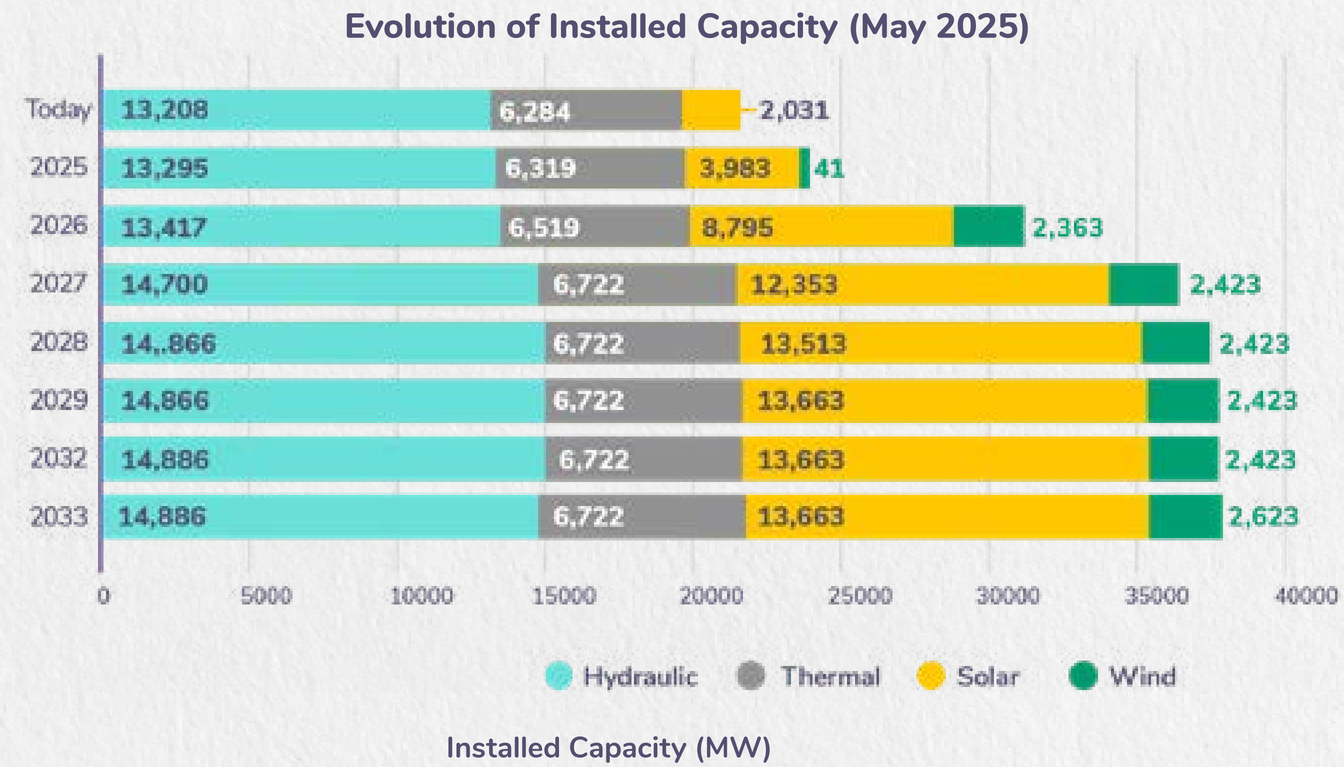


Figure 2. *Evolution of SIN's installed capacity. Source: Own work based on UPME transmission capability allocations (CREG Resolution 075 of 2021).*

Non-conventional renewable energy projects account for 87% of the new generation projects expected to be integrated into the system. Of these, 58% will be installed in Colombia's Caribbean Region, particularly in Alta Guajira, which offers favorable climatic and geographical conditions—high solar radiation and strong winds.

To transport energy from the current generation fleet, the National Transmission System (STN) uses 111 substations operating at a nominal voltage of 220 kV and 19 substations at an extra-high voltage of 500 kV. The system includes 3,833 km of 500-kV lines and 13,825 km of 230/220-kV lines extending throughout the country *(see **Figure 3**)*.

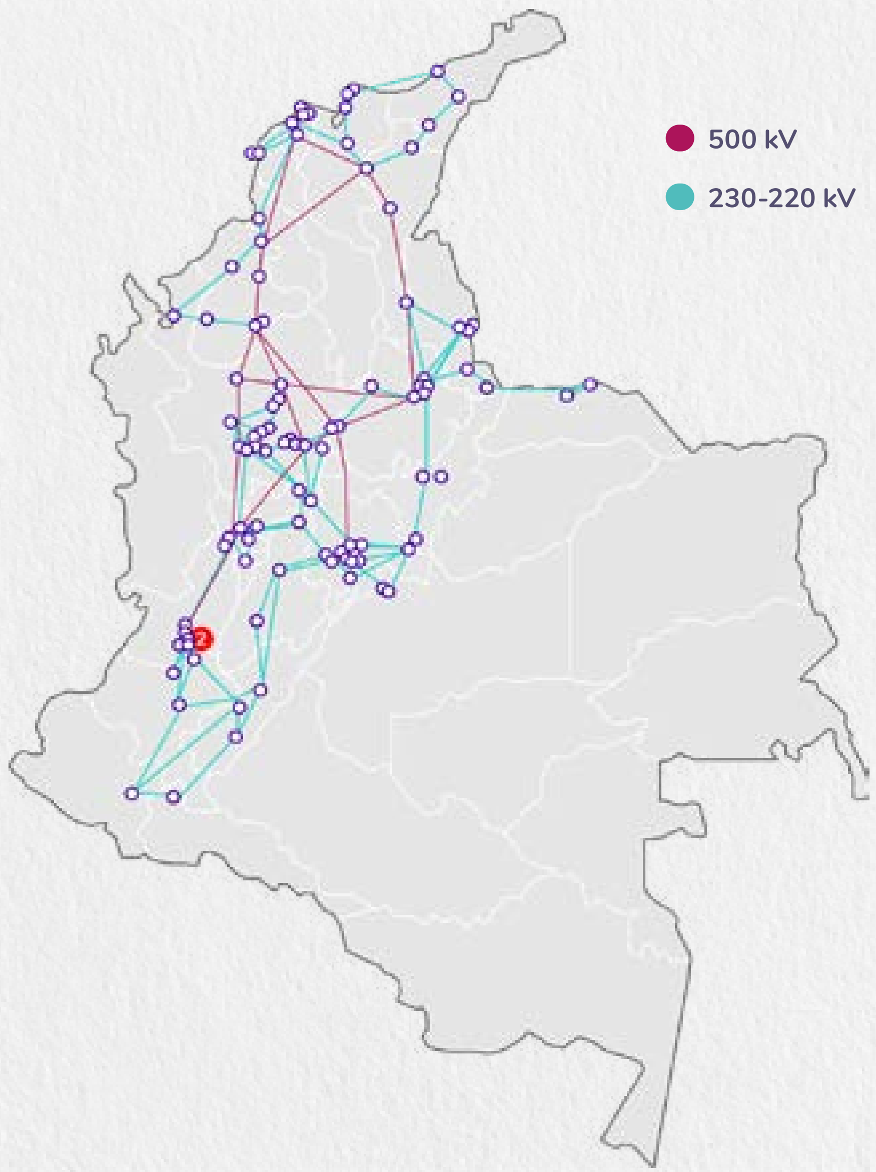


Figure 3. *National Transmission System (STN)*

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To provide greater security in the system, the UPME has defined new electricity transmission infrastructure projects in various expansion plans under its responsibility, with the aim of positioning the STN as the key enabler of the energy transition. Currently, 36 STN projects are under development, and in the subtransmission system (57.5 kV to 115 kV), 87 expansion projects have been identified to relieve network congestion, meet growing demand, integrate new generation sources, and enhance operational flexibility.

Given the concentration of power generation projects in northern Colombia, the UPME is evaluating the development of a high-voltage direct current (HVDC) transmission ring spanning approximately 1,500 km—from La Guajira to the center of the country. This would be Colombia's first HVDC project and is seen as an efficient solution for long-distance energy transport, bringing power generation closer to large consumption centers. Its development will require unprecedented institutional coordination.

At the same time, the current growth of the WEM is particularly relevant, and it is expected to continue increasing as new players enter the system.

Over the past five years:

- The number of registered metering points has increased from 20,000 to over 50,000—a growth marked by regulated demand (users who consume less than 55,000 kWh per month or 100 kW of power, such as households and small businesses).
- The number of registered market participants has risen from 237 to around 330, and with the issuance of CREG Resolution 075 of 2021, the number of promoters increased from 65 to approximately 400. This trend is expected to continue as more renewable energy projects are developed, such as wind and solar power generation, as well as transmission infrastructure projects, connecting the new generation.
- The number of resources authorized to submit bids into the energy dispatch system has also increased from 53 to more than 80.
- These increases mean that the energy market settles approximately 1.5 trillion Colombian pesos per month through transactions on the energy exchange and 2.5 trillion Colombian pesos through bilateral contracts. In addition, the energy market manages more than 450 guarantees to support the entry of projects, amounting to approximately 3.28 trillion Colombian pesos.

3. Enablers of Transition in Colombia

Colombia's electricity sector is evolving rapidly, driven by the need to reduce CO2 emissions—as a strategy to mitigate the risks of climate change—and by the growth in demand due to the country's social and economic development and emergence of new consumers.

Through Law 1844 of 2017, Colombia ratified the Paris Agreement on Climate Change, committing to mitigate the global temperature increase to 2 °C. In line with this objective, the country has taken on the challenge of progressively reducing its dependence on fossil fuels in the residential, transportation, and industrial sectors, which are shifting toward electrification. At the same time, the rise of electricity-intensive industries—such as data centers and hydrogen production—will significantly increase energy demand, requiring a more secure, reliable, and sustainable supply.

In this context, the energy transition requires a timely and efficient evolution of the electricity system—one of the most complex infrastructures ever developed by humankind. Maintaining continuous service while upholding the high standards of quality, security, and reliability achieved represents one of the most critical challenges for XM and the electricity sector as a whole.

The simultaneous growth in demand and generation sources will require unprecedented development across all transmission networks—the STN, the Regional Transmission System (STR), and the Local Distribution System (SDL). These upgrades are essential to efficiently connect generation and consumption centers, absorbing the variability of the new matrix without compromising supply continuity. To achieve this, the electricity system should be equipped with elements that reinforce its flexibility and resilience, which are essential attributes for maintaining secure, reliable, and cost-effective demand coverage.

Globally, the sustained increase in electricity demand, the inadequacy of existing infrastructure, and the lack of preparedness of networks to integrate inverter-based resources (IBRs) are affecting the reliability of supply. In Colombia, these challenges are evident in delays to the development of transmission and generation infrastructure, as well as in the rapid depletion of transmission capability, which affects demand and limits production before new expansion projects are designed and implemented.

In this scenario, distributed energy resources (DERs) and energy communities are taking on a central role in the evolution of Colombia's electricity system. Their effective integration requires overcoming significant challenges related to the observability and controllability of these resources, the definition and compliance with technical requirements, and the modernization of protection systems such as the automatic load shedding scheme (ALSS). It is also necessary to update regulatory frameworks and promote advanced technologies that support the participation of DERs in electricity markets—not only as generators but also as providers of essential ancillary services for grid balancing.

Moreover, electricity markets should evolve to facilitate the integration of renewable sources, the expansion of transmission infrastructure, and the incorporation of new elements and operational standards in a way that is economically attractive. This involves implementing additional mechanisms in the spot market to allow for real-time adjustments in operating conditions and the negotiation of energy surpluses or shortages, with active demand-side participation and adequate price signals.

Addressing these challenges requires XM and the electricity sector to act with foresight, through comprehensive strategic planning, effective coordination between the different stakeholders in the sector, and a long-term vision capable of accurately identifying of current and future threats and responding proactively to changes in the energy landscape.

In this regard, XM has identified six key enablers for the secure, reliable, resilient, and sustainable evolution of the electricity system. Each enabler represents a critical factor that should be addressed through strategic actions, institutional coordination, and the adoption of new technologies to ensure that the energy transition effectively contributes to Colombia's economic, social, and environmental development.

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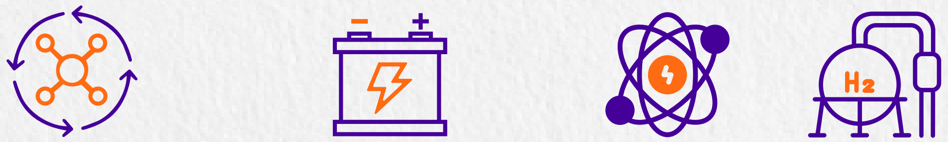
Closing the existing gaps, developing appropriate solutions, and implementing them without delay—supported by strong institutions responsible for regulation, planning, and operation—will be essential. Coordinated action among stakeholders will be key to unlocking new opportunities, improving the quality of life for Colombians, and fostering sustainable and dependable economic growth, all within the framework of an energy transition that is already underway.

The challenge lies in developing integrated expansion plans that anticipate growth in electricity demand while promoting an energy matrix that is resilient to climate change. This includes incorporating flexible energy sources and deploying technologies such as:



Synchronous Condensers | Battery Storage Systems | Hydrogen | Nuclear Energy

And the development of transport infrastructure through the modernization and expansion of the network to ensure a reliable supply.

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Enablers

1. A flexible, complementary, and resilient electricity grid.
2. Implementing expansion plans and developing new infrastructure projects.
3. Modernizing the transmission network and integrating the technologies, processes, and studies required to operate a system with greater participation of renewable generation.
4. Modernizing the market by integrating new products and services that efficiently adapt to new supply and demand conditions.
5. Expanding and enhancing the technological infrastructure, maintaining high levels of cybersecurity and resilience.
6. Developing and maintaining the human talent required for the energy transition.

Enabler 1: A Flexible, Complementary, and Resilient Electricity Grid

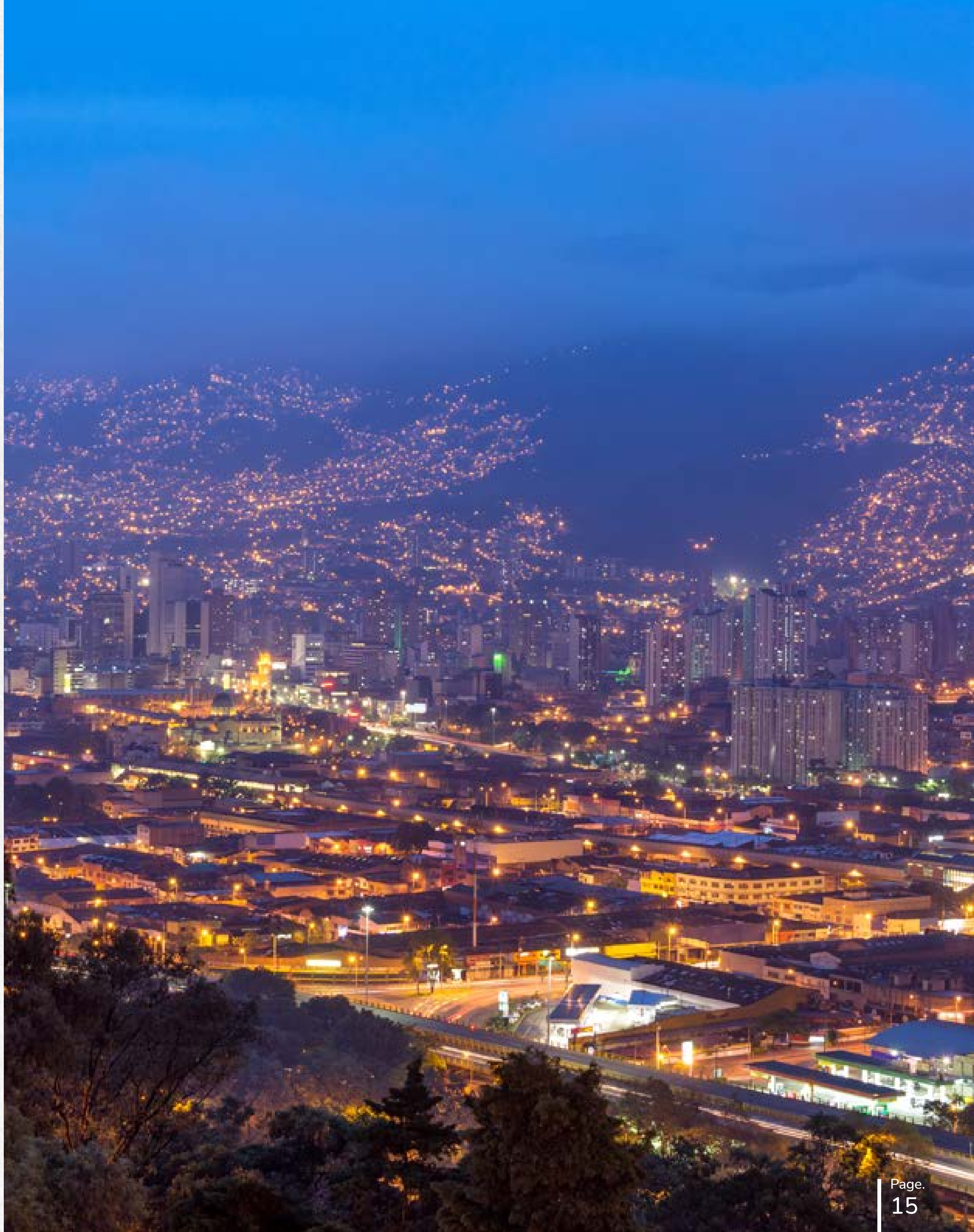
A flexible, complementary, and resilient electricity grid is crucial for a system historically impacted by water shortages. Thus, the grid is expected to transition toward greater integration of solar and wind generation sources.

In recent reliability charge auctions in Colombia, 98% of newly awarded capacity was associated with solar technology.

Colombia mirrors the global trend of installing solar farms, driven by the low costs of the technology. However, it should be noted that solar energy alone cannot meet the system's peak demand, which occurs between 6:00 p.m. and 9:00 p.m. Additionally, under adverse weather conditions, such as high cloud cover—common during Colombia's rainy seasons—solar energy production can be drastically reduced throughout the country. Given these conditions, analyses carried out by XM based on the historical and operational evaluation of the country's irradiation indicate that the availability values of this technology could reach a maximum of 25% of its installed capacity.

Therefore, different efforts are required to diversify energy supply sources to ensure a system that is **flexible,** to respond quickly to fluctuations; **complementary,** to maintain continuous, efficient, and reliable service; and **resilient,** to withstand adverse events.

[2] *The reliability charge is a mechanism designed to ensure sufficient firm energy is available to meet the country's demand under critical conditions.*



Taking the above into account, XM has identified the following actions:

Increasing Complementarity in the Generation Mix

The impact of climatic conditions—such as droughts or intense rainfall—on the production capability of water sources and solar and wind generation accentuates the vulnerability of the generation mix to climate variability, where more frequent and severe weather events are anticipated. Therefore, it is imperative to implement policies that guarantee an expansion of generation capability with the required complementarity, encouraging the deployment of technologies that guarantee reliability and can be used as backup during adverse conditions that compromise the country's energy security. Alternatives can be adopted in new expansion planning policies, which include modern nuclear energy through the deployment of small modular reactors and hydrogen production.

With regard to existing plants, it is crucial to maintain the flexibility of the hydroelectric generation fleet with storage capacity and to keep the thermal fleet available, ensuring the transport and availability of the primary resource for supply. This is necessary until the system has a resilient and sustainable energy mix that replaces the energy provided by these resources, especially in periods of low water supply.

Incorporating Energy Storage

The growing share of solar and wind resources will inevitably add uncertainty and variability to the operation of the system. As NCRES projects expand, the system could have daytime periods in which generation must be limited due to excess production, and nighttime periods in which the traditional fleet may be pushed to its limits, especially during periods of peak demand on the system.

To address this, it is necessary to promote the development of solar generation projects with storage capacity so that the energy available during periods of high sunlight levels can be transferred to periods when there are fewer primary resources available.

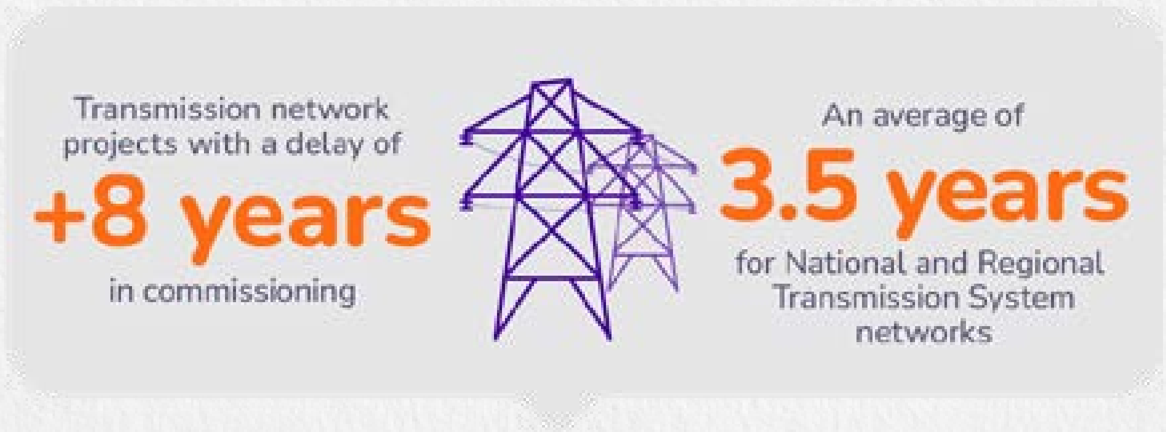
Enhancing Weather Forecasting Capabilities

Improving the ability to respond to the uncertainty of renewable resources in the long, medium, short, and very short term will be essential for the operation of the electricity system. This requires improving institutional capability for the measurement, characterization, and forecasting of meteorological variables—such as temperature, humidity, irradiation, wind speed and direction, and flow—that are relevant to the electricity sector. These improvements should aim for lower spatial and temporal resolution while deploying field measurement stations as part of open-access solar and wind initiatives, which will support the calibration of assimilation and prediction models at scale.

Enabler 2: Implementing Expansion Plans and Developing New Infrastructure Projects

Abundant electricity supply and efficient and flexible transmission networks are essential to meet growing demand and bring energy to consumption centers.

However, consistent delays have been identified at initial operational stages of transmission projects defined in the expansion plans. According to project promoters and implementers, these delays are caused by different factors mainly related to contract awarding, prior consultations, environmental licensing, and technical developments. Similarly, in generation projects, the recent incorporation of new megawatts into the SIN has not resulted as expected.



Obstacles should be overcome and ongoing expansion plans should be implemented, capitalizing on lessons learned by implementing **methodological changes that improve the timing of expansion planning.**

This includes adapting the planning process to current realities so that awarded projects anticipate the risk conditions they are intended to mitigate. Achieving this would involve broadening planning horizons, creating spaces and working groups to coordinate efforts for project development, and working to avoid delays in the commissioning of expansion works—especially those related to environmental licensing and prior consultations with communities.

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Taking the above into account, the following actions are identified:

Materializing the Entry into Operation of Projects

If generation expansion plans fail to materialize in the coming years, the system's installed capacity relative to demand may fall to levels that would jeopardize secure, reliable, and cost-effective energy supply. This would increase the use of available resources to meet periods of peak demand or periods of water shortages.

In this regard, prompt development of the network infrastructure already defined in UPME's expansion plans is required to minimize the electrical and operational constraints of the system. Deficient articulation between the system and the growing generation, demand, and transmission network may increase such constraints. Transmission is a determining factor in the energy transition, particularly the development of a network that eliminates network bottlenecks.

Therefore, adequate inter-institutional coordination is required to ensure the entry into operation of generation and transmission projects that meet demand growth with the expected levels of quality, reliability, and cost-efficiency.

Promoting Financing and Contracting Mechanisms

For effective integration of new generation projects, financing and banking mechanisms are essential, especially considering technological diversity. In this regard, it is key to promote mechanisms such as auctions for the allocation of new capability, which offer clear and stable signals to the market. Likewise, it is necessary to strengthen contracting frameworks, promoting the use of standardized products and the participation of counterparties that provide financial security. This will contribute to reducing the risk perceived by investors and boosting the development of energy infrastructure in the country.

Developing Urgent Transmission Works

National and international experience indicates that urgent developments not foreseen in long-term grid expansion plans will be necessary to mitigate or eliminate risk conditions affecting secure, reliable, and cost-effective demand coverage. These needs will arise as operating conditions change and the system evolves into a grid that integrates more renewable energy sources while demand continues to grow at high rates. In this regard, it is essential to strengthen the rapid execution of mitigation works that compensate for delays in the execution and/or definition of projects. The main challenge lies in guaranteeing the necessary investments and appropriate incentives for the execution of these works. Thus, extensive institutional coordination is required to enable the rapid and timely development of this type of infrastructure.

Improving the Capacity for Electricity Exchange between Northern and Central Colombia

The Caribbean Region has a significant thermal generation base. Added to this is the expected growing availability of solar and wind power generation in the region. Therefore, the expected generation potential of the area could reach 12 GW (8 GW additional to the current capacity).

In light of this, the development of the national transmission infrastructure is required to enable the flow of energy blocks to other areas of the system. With the current infrastructure—and even with the planned additions expected to enter into operation—it would not be possible to evacuate the region's available energy potential. This limitation poses risks to supply and could lead to production outages due to insufficient transmission capability.

Increasing the Short-Circuit Capacity of the Infrastructure

Transmission substations that have reached their maximum short-circuit design values are identified in the SIN. Infrastructure that has reached its short-circuit capacity limits the deployment of new generation resources, restricts the possibilities for expanding the system's transmission capability, and creates operational constraints.

It is paramount to upgrade the infrastructure or define projects for the redirection or mitigation of short-circuit flows to reduce the risk associated with damage or malfunction of the infrastructure due to exceeding design capacity levels.

Integrating Resilience and Reliability Criteria into System Expansion

In the context of the energy transition, integrated, holistic expansion plans that anticipate growing electricity demand and new consumers need to be designed and implemented. These plans should guide the development of energy sources that contribute to a complementary and resilient energy mix. They should also incorporate flexible resources and emerging technologies that mitigate the risks associated with the variability and uncertainty of renewable sources across all time horizons. Additionally, these expansion plans should ensure the timely development of the required transportation infrastructure through the modernization of the existing network, the introduction of new technologies, and the development of new projects for a secure and reliable supply under a new production and consumption environment.

Incentives should be created to ensure that STN and STR expansion plans comprehensively address reliability and resilience criteria for a continuous and secure electricity supply. These criteria should include provisions for transport network maintenance, limits on the impact of failures at critical nodes, cyberattack mitigation, and resilience to extreme natural events.

Enabler 3: Modernizing the Transmission Network and Integrating the Technologies, Processes, and Studies Required to Operate a System with Greater Participation of Renewable Generation

It is essential to enhance the reliability and resilience of the transmission infrastructure. The deployment of equipment and technologies is also necessary to provide the network support services and strength required for stable operation, such as inertia and short-circuit capacity. Repowering existing infrastructure, updating protection and control systems, and efficiently using the available transmission network are equally important efforts. In addition, it is critical to manage the variability, uncertainty, and vulnerability of current and future generation resources. All of these actions are vital in the new operating scenario defined by the energy transition.

The modernization of existing infrastructure—as a complement to the structural expansion of the network—poses a significant technical and economic challenge for the sector, due to the need to replace infrastructure that has exhausted its capacity. Other solutions aimed at optimizing the use of infrastructure are desirable and can generate lower social and environmental impacts. These include installing double circuits on single-circuit infrastructure, increasing the transmission voltage of the grids, and repowering transmission circuits by implementing new cable technologies such as superconductors and flexible alternating current transmission systems (FACTS).

Importantly, the high penetration of solar and wind sources in the electricity system, along with the increase in loads sensitive to voltage deviations, creates a need for urgent action. In particular, the protection systems in the STR and

SDL networks should be modernized to ensure timely fault clearance and prevent large-scale generation and demand disconnections.

Moreover, international experience indicates that, in a scenario of accelerated energy transition, it is essential that new equipment connected to the grid provides grid support services (inertia, short circuit, fast and continuous frequency response, among others). Likewise, a flexible generation fleet is necessary in terms of technical minimums, start-up and shutdown times, and ramp speeds so as to minimize the possibility of low-cost generation being restricted.

It is necessary to modernize the transmission and distribution network by replacing and installing equipment that increases capacity and short-circuit withstand levels.

Increases in the magnitude and duration of net demand ramps, intra-hour imbalances, deviations, regulation reserve requirements, and the number of market participants involved in real-time operational coordination are creating new challenges. To address these, new regulatory, technological, and market mechanisms are needed to ensure timely supervision and control of frequency, voltage, and operational and electrical constraints in the SIN. The recommendations for the sector in this respect are the following:

Encouraging Flexibility in the Technical Characteristics of the Generation Fleet

A flexible system can integrate variable generation without causing inefficient production outages due to grid congestion, high inflexible generation at the base of production, or stability conditions, while maintaining the controllability necessary to achieve stable system operation. Market mechanisms need to be developed to encourage flexibility in thermal and hydroelectric power plants, reducing technical minimums, online and offline time, notice times, among others. One recommendation is to encourage options that allow synchronous power plants to operate as rotating synchronous condensers, maintaining the production infrastructure intact and providing essential services to the system (voltage control, inertia contribution, and short-circuit contribution).

Deploying Inertia and Grid Strength Solutions

Solar and wind technologies are integrated into the system in a different way than synchronous generators. Since these plants are synchronized via control interfaces, they are not electromechanically coupled to the system. As a result, they cannot respond instantly to disturbances in voltage (grid strength) and frequency (inertia) under the exact same conditions as traditional synchronous plants. The future operation of the system will be characterized by service requirements associated with the containment of voltage and frequency disturbances.

Anticipation is necessary to define coordinated inter-institutional plans for implementing the measures and equipment required to successfully incorporate new generation sources. Studies conducted by XM show a decrease in the system's strength and inertia levels, with possible impacts on its ability to maintain quality and reliability in demand coverage. In this regard, it is necessary to define in the early stages of the transition the required services and quickly deploy the equipment to provide them (synchronous condensers and eventually grid-forming batteries).

Developing Tools for Measuring Inertia and Grid Strength

Planning and monitoring the levels of inertia and grid strength required during actual system operation demands a dynamic and behavioral characterization of the load and the various elements that make up the network. Therefore, detailed models of all the elements that comprise the system (generation, transmission network, and load) should be available. In turn, and considering the uncertainty in the variables that define these attributes, it is necessary to deploy advanced and innovative technology for real-time measurement through passive or active methods. Passive methods are based on the large-scale deployment of phasor measurement units, and active methods are based on the injection and precise measurement of high-frequency disturbances induced by batteries deployed for this purpose.

Technological solutions should be deployed to accurately measure inertia and grid strength during actual system operation. Similarly, decreases in these services should be addressed so as not to compromise the secure and reliable operation of the SIN.

- Deploying solutions for real-time measurement of grid strength.
- Deploying solutions for real-time measurement of inertia.

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Developing New Mechanisms for Operational Coordination

In the short term, new regulatory and technological elements of operational coordination are required to maintain the balance between load and generation. The following actions are recommended:

- Enabling **redispatches of variable generation and demand near real-time system operation,** supported by market mechanisms that encourage the provision of the best information available.
- Including lower-resolution operational adjustments, which are **nearer to system operation** (five-minute operational dispatch).
- Establishing the integration of all the centrally dispatched plants into the **automatic generation control (AGC) of the National Dispatch Center (CND) so that they receive digital power commands** for on-site implementation.

Deploying Battery Energy Storage Systems

Battery energy storage systems (BESSs) have become fundamental to the energy transition. Although Colombia was a regional pioneer in establishing a regulatory framework of this technology—through CREG Resolution 098 of 2019—it is essential to update this regulation and incorporate definitions for new services that are already technologically viable such as grid-forming batteries. Additionally, considering that specific needs for the deployment of this technology have been identified under the existing framework, a significant volume of BESS equipment has been included in the Master Modernization Plan published by the UPME.

Likewise, new applications for the use of batteries need to be explored and regulated after reviewing CREG Resolution 098 of 2018 and adapting it to the definition of services and incentives for the integration of storage solutions. These should address specific grid challenges and new system requirements, such as short-circuit current and inertia contributions through grid-forming batteries.

Electrical and operational congestions:

Signs of expansion linked to costs associated with electrical and operational congestions on the system.

Other battery applications:

Exploration and regulation of new applications for the use of batteries in the system.

Improving System Observability

The variability and uncertainty of renewable primary resources and demand pose challenges for efficiently managing deviations and forecasting the system's production requirements—especially with the growing integration of behind-the-meter generation and the need to serve it when internal primary resources are unavailable. In this context, maintaining network observability is essential to ensure proper decision-making by system operators and to enable intelligent operational support tools to be deployed with the required levels of reliability and accuracy. These tools include consumption and generation forecasting systems, production optimization and ancillary service management tools, and automatic voltage control (AVC) systems. Regulatory incentives are needed to enhance observability across consumption, generation, and transmission infrastructure. These should be supported by quality and availability indicators for analog and digital measurements, as well as by robust communications redundancy to ensure the resilience of the monitoring infrastructure in the event of system failures.

Integrating and Operating Distributed Energy Resources

An important feature of the energy transition is the possibility of installing DERs connected at the SDL level. The widespread use of generation in distribution systems requires improvements in the capability of network operators (NOs) to manage the high volumes of generation that will be integrated. This is essential not only to ensure the security of their networks, but also to enable the management of services these systems can provide—either to today's spot market or to future markets that may emerge through aggregation strategies. Advancing in the definition of roles and services for NOs—particularly through the development of distribution system operator models—is therefore a key priority.

Increasing Participation in Central Dispatch

Market operating rules allow small-capability plants to connect to the system and supply energy without being centrally dispatched. These plants are not required to comply with the requirements for effective operational coordination that enable generation adjustments in line with the system's needs. Considering the ongoing generation expansion plans, a significant increase in installed capacity is expected within this segment. Coupled with the growing interaction of DERs, this could affect system reliability and hinder the ability to maintain balance between generation and demand.

To address this, it is essential to establish testing protocols for these types of plants to validate the parameters and models used for planning Colombia's electricity system.

Lowering the threshold for central dispatch participation to 5 MW would be a key measure for maintaining reliable and stable system operation, as well as strengthening the coordination and operational control mechanisms for these resources.

Encouraging Improvements in Demand and Generation Forecasts

Accurate demand and generation forecasts enable system operators to anticipate supply needs and properly plan production, consumption, and transmission system usage. This minimizes operational risks and optimizes the use of available resources.

To reduce the uncertainty of these forecasts in a scenario of high variability and climate uncertainty, **it is vital to develop models that integrate accurate meteorological data.** These models can improve the accuracy of renewable energy generation and electricity demand forecasts, thereby enabling dynamic and flexible management of the electricity system.

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The frequency of information flows between market participants and the system operator should be increased. In addition, the necessary regulatory and market incentives should be developed to ensure that the generation and demand forecasts presented by market participants use the best available technology, are updated in a timely manner, and maintain the levels of accuracy required for the secure and reliable operation of the system.

Improving Protection Systems

The widespread integration of inverter-based generation presents unique challenges for protection systems. Due to the specific characteristics of these technologies, both primary and backup protection systems must be capable of clearing faults within the minimum operating time of protection relays. This reduces voltage sags caused during faults and minimizes the potential impact on demand and generation. **To achieve this, selective, redundant, and fast-acting protection devices are required across the STN and STR to detect and clear faults in a timely manner.**

In this context, it is necessary to regulate aspects related to maximum allowable times for clearing faults in the system, mandatory equipment and redundancies, and standardized procedures for addressing loss of effectiveness due to component unavailability.

Furthermore, current protection technologies should be updated and replaced with more advanced solutions that offer greater selectivity and faster fault-clearing capabilities. This is especially relevant in SDL and STR networks, where protection systems must operate reliably and selectively under conditions of bidirectional power flows and low short-circuit contribution levels. Ensuring rapid and accurate fault clearance in these networks is critical to mitigating the impacts of delayed fault resolution on both demand and generation.


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Improving Dynamic Network Models

Validating the dynamic and transient performance of the system during the assignment of new connection points and during the operational planning of the electricity system will be decisive for identifying early mitigation actions to ensure stable system operation. This process is particularly important for determining whether new generation projects must be supported by system-strengthening solutions or incorporated into STN and STR expansion plans. **To support these goals, the following measures are proposed:**

- Incorporating criteria for transient and dynamic system stability into the assignment of connection points, using root mean square (RMS) and electromagnetic transient (EMT) simulations.
- Requesting developers to submit RMS and EMT dynamic simulations as part of connection studies, accounting for expected operating conditions of the connection point and possible interactions with other IBRs in the system and demonstrating that the developments are appropriately equipped to operate under low-inertia and low short-circuit conditions.
- Performing comprehensive RMS and EMT analyses across the STN and STR network, considering all previously approved generation projects, to define whether new projects are needed or whether new points should be limited.
- Regulating cases in which, due to grid strength deficits or other performance characteristics, additional equipment—such as synchronous condensers and/or batteries—are necessary to meet technical requirements, ensure stable operation of integrated fleets, and maintain the system's short-circuit and inertia levels.
- Regulating the submission and validation of EMT models for all the equipment integrated into the system, defining timelines and characteristics. Likewise, minimum quality criteria should be defined for the RMS and EMT models used to represent the different elements connected to the SIN. This should apply to loads, synchronous generators, compensation systems, lines, transformers, FACTS, BESS, and new technologies within the system.

Deploying Frequency Support Services

As renewable generation increases its share of demand coverage and synchronous resources are displaced, XM's analyses show a decrease in the system's inertia levels, which increases the risk of frequency excursions outside the defined quality and withstand values.

In the absence of mitigation measures, it may be necessary to limit the operation of solar and wind power plants to have the levels of inertia that guarantee adequate frequency containment, since these technologies are not currently required to provide inertia or frequency support.

To address these challenges, the following actions are recommended:

1 Given that CREG Resolution 060 of 2019 temporarily exempts photovoltaic and wind power plants connected to the STN and STR from providing primary response services for underfrequency events, **it is recommended to enable the primary frequency regulation service either by providing the required capacity or by installing batteries** that expand the capacity of this type of resource.

2 Updating the criteria for the design of the ALSS to consider the technological upgrades necessary for the incorporation of generation at the SDL level, and the withstand criteria regarding the rate of change of frequency (ROCOF) and nadir for the equipment integrated into the system (generation and demand).

3 Establishing incentives to meet the primary regulation requirements across technologies, including mechanisms for enabling, monitoring, and withdrawing generation plants that provide the service.

4 Evaluating the need to deploy the continuous response service (also called fast frequency response), with an activation time of less than one second and continuous frequency regulation

5 Evaluating the need to deploy the rapid load shedding service **as a containment measure prior to ALSS action.**

Developing Automatic Voltage Control

Voltage control is essential to maintain a stable power system and enable the transfer of active power to the STN and STR. The power system has become more complex as the number of control elements and the demand grow. With the large-scale introduction of non-synchronous sources, international experience indicates that the operational requirements for maintaining adequate voltage profiles throughout the electrical grid are increasing. In response, **the implementation of an AVC strategy is proposed, as defined by CREG Resolution 080 of 1999.**

For the implementation of this framework, it is necessary to define the regulatory requirements for the implementation of this technology in the SIN, for which the following actions are recommended:

1 All STN and STR substations equipped with voltage control equipment (generation units, transformers with on-load tap changers, compensators, reactors) should have a VQC-type automatic local control. The operating zones, the classification of day types, the adjustment of control bands for different times of day, and the on–off status of these mechanisms may be updated from the CND to manage actual system operating conditions and address telecommunications or AVC system failures.

2 Local VQC systems should automatically receive connection and/or disconnection commands from the CND, either directly or through the NOs' control centers.

3 All static var compensators, static synchronous compensators, synchronous condensers, battery banks, and/or any other device equipped with an automatic voltage regulator should automatically receive voltage, reactive power, or operating mode commands from the CND, either directly or through the NOs' control centers.

4 All operating generation resources connected to the STN or STR should automatically receive voltage, reactive power, or operating mode commands from the CND, either directly or through the generation operators' control centers, if available.

5 All STN transformers and STR–STN connection transformers with automatic on-load tap changers should automatically receive commands to increase or decrease tap positions or block automatic control from the CND, either directly or through the NOs' control centers.

6 All market participants should be responsible for reporting to the CND in real time, using the technology available to the CND for this purpose, the availability of their equipment to participate in the AVC mechanism. If any equipment is unavailable to participate in the AVC, this condition will affect the quality indices established in the applicable regulation.

Improving the Information Required for System Performance Evaluation

To efficiently monitor the performance of the electricity system in a context of increasing integration of renewable energies, it is necessary to implement advanced analyses and evaluations of critical variables. Operating conditions should be analyzed to identify recurring patterns and possible solutions, ensuring timely detection and resolution of problems.

The integration of high-resolution measurements, combined with advanced analytics and periodic assessments, will optimize the stability, efficiency, and reliability of the electricity system, supporting its long-term sustainability through the evaluation of new services and technologies.

This requires adjusting monitoring platforms to capture rapid and distributed phenomena, such as high-frequency oscillations and sub-synchronous interaction problems. In turn, this implies expanding the use of phasor measurement technologies and adopting new tools and regulatory incentives to obtain the required data quality and availability.

In conclusion, given the system's reduced ability to respond effectively to frequent events (decrease in system inertia) and its reduction in short-circuit levels (weak grid operation), its operation requires the following actions:

- Updating the regulatory framework associated with the design of the ALSS, considering the high incorporation of DERs and equipment withstand criteria.
- Enabling the mandatory provision of primary regulation services for underfrequency events in non-conventional renewable solar and wind sources.
- Establishing short-circuit and inertia contribution services, as well as minimum grid strength levels and criteria to limit the propagation of voltage sags.

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- Creating incentives to increase the flexibility of the synchronous generation fleet (reducing technical minimums, increasing operating ranges, and increasing load ramp rates).
- Deploying synchronous compensators or other technologies with the capacity to provide inertia and short-circuit protection from the expansion planning stage.
- Evaluating the need for continuous frequency response services and rapid load disconnection services as a containment measure prior to ALSS action.
- Adjusting the grid code to incorporate aspects associated with maximum allowable times for timely fault clearance at the STN and STR levels, as well as the redundancy and equipment necessary for their operation.
- Establishing new regulatory connection requirements for the secure incorporation of inverter-based generation in weak grid conditions:

RMS and EMT analyses in the connection studies

RMS and EMT models validated before the commissioning of projects

Withstand curves during temporary over-voltages

Rapid contribution of negative sequence current during faults

Maximization of current contribution during faults

Uninterrupted delivery of active power

- Establishing mandatory reporting of dynamic load models.
- Advancing regional interconnection with other systems as a measure to strengthen the system's response.

Enabler 4: Modernizing the Market by Integrating New Products and Services that Efficiently Adapt to New Supply and Demand Conditions

Colombia's electricity market, which began three decades ago, has a design based mainly on conventional generation, which was predominant at the time (hydraulic and thermal generation). Although this market model has supplied demand and efficiencies in the different links of the electricity value chain, it should be reviewed and adjusted in an energy transition scenario.

This is necessary to ensure that it responds to the increasing integration of variable non-conventional sources, demand-side participation, and the incorporation of new stakeholders in the value chain. It should also provide the appropriate signals and necessary incentives for ancillary services and the flexibility required for the secure, flexible, and reliable operation of the Colombian system.

As things stand, the current market design requires adjustments to efficiently integrate variable resources. The main adjustments should be made in the spot market and ancillary services. Currently, Colombia only has secondary frequency regulation as an ancillary service through AGC. Likewise, it is necessary to implement demand response and storage programs, harmonize the new schemes with regional interconnections such as the Andean Regional Electric Spot Market (MAERCP), adjust the reliability charge and market coverage mechanisms, among others. These actions would efficiently and reliably manage the variability of the primary resource, as well as incorporate criteria for flexibility and resilience into the system, benefiting the country's demand.

This condition is not unique to Colombia. The most advanced electricity markets worldwide have integrated additional instances into their spot markets to negotiate electricity surpluses or shortages at intervals close to the time of demand coverage. They are also implementing mechanisms that seek efficient price formation under a design that facilitates the incorporation of generation from non-conventional renewable resources, which poses additional challenges for both operation and the market.

Colombia's electricity sector has been making progress in the design and implementation of a comprehensive market, including efficient and sustainable instances for the entire energy trading horizon, ranging from long-term (15 to 20 years) to spot markets.

This market approach involves efficient coordination between long-term investment decisions and daily operations, thus facilitating the optimal management of energy resources in a changing environment. It also ensures market sustainability by providing physical and financial mechanisms that allow all participants to manage their risks and generate benefits for demand.

Financing Network Replacement and Expansion Projects

The regulatory framework should be updated and harmonized to encourage the implementation of transmission expansion and equipment replacement projects. It is important that the system's electrical and operational constraints send economic signals that promote efficient and effective investments in infrastructure and establish mechanisms that reflect the costs associated with their mitigation.

Developing Comprehensive Markets

Based on operational needs, the following market strategies are proposed for responding to energy adequacy, sustainability, and system efficiency:

1 Development of Long-Term and Spot Markets

Creating and adjusting the market and contracting mechanisms required by the system to ensure financial sustainability in the short and long term.

2 New Ancillary Services

Introducing and adjusting services that complement the electricity supply and improve system stability as renewable sources are incorporated.

Some services to consider:

- **Inertia and Short Circuit**

  Mechanisms to make these services available to meet demand, in line with system reliability needs.

- **Fast Frequency Response**

  Mechanisms that incentivize this service to maintain frequency stability.

- **Low-Frequency Demand Disconnection**

  Market products to quickly disconnect load in response to critical events.

- **Storage**

  Implementation and evaluation of different services provided by storage technologies to manage generation and demand variability.

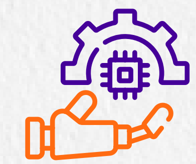
3 Mechanisms for Demand-Side participation

Defining alternatives and mechanisms that promote demand-side participation in the energy market through demand response programs, using schemes such as time-of-use rates, load interruption, and market offers. These mechanisms would improve system efficiency, alleviate congestion, and provide economic benefits to end users, among others.

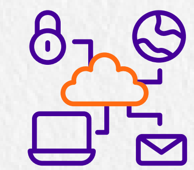
Likewise, it would be possible to evaluate the possibility of establishing mechanisms for demand-side participation in the daily market, auctions for system reliability, for the ancillary services market, in emergency situations or critical conditions.

Enabler 5: Expanding and Enhancing the Technological Infrastructure, Maintaining High Levels of Cybersecurity and Resilience

The technological challenges of the energy transition include, among others, the integration of the following technology:



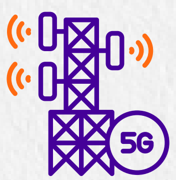
TO
(Operational Technology)



TI
(Information Technology)

Strengthening communications infrastructure and improving cybersecurity and interoperability should be focused on increasing the reliability, efficiency, and resilience of the electricity system. In this context, it is essential to develop integrated platforms that enable fluid communication between OT and IT and manage real-time data securely and efficiently. From an operational and transactional perspective, the energy transition will increase data and information granularity and spatiality thanks to advanced sensors and automation that respond to demand variability, distributed generation, and faster and more complex phenomena. This is leveraged by the need for greater observability and control of the network and a greater number of products and participants in market transactions.

In this regard, there is a need for an information governance model that adapts to the needs of the energy transition, including data quality and advanced analytics as key drivers. This will provide definitions, responsibilities, and data flow, as well as continuous monitoring of information quality through indicators that measure completeness, consistency, and validity. It will also support advanced analytics models that enable system behavior to be anticipated, resources to be optimized, risks to be managed in real time, and market strategies to be designed.



Another technological challenge is to expand the capacity of communication systems and **implement robust and secure communication networks, such as 5G or fiber optics,** that support massive, real-time communication between components—particularly for managing distributed renewable energy. In line with this growth in information, it is necessary to develop big data platforms and conduct predictive analysis to process large volumes of data and provide critical information for decision-making and optimizing the market and network operation.

At XM, we have an information security strategy that integrates technology implementation, people, business processes, and infrastructure. **This strategy includes a roadmap designed to protect our computer systems and networks against cyberattacks.**

Our approach places a strong emphasis on strengthening the culture of information security among our employees and incorporating best practices into business processes with a structured approach. This includes identification, protection, detection, response, and recovery from security incidents, ensuring secure information and infrastructure, business continuity, and resilience against cyber threats.

Other Technological Actions

- Modernizing IT tools with support in force, thus closing cybersecurity vulnerability gaps. Achieving operational resilience is key to responding quickly and securely to the demands of an increasingly digitized, interconnected, and sustainability-oriented electricity market.
- Observing and incorporating new IT tools is essential to accelerate the energy transition in Colombia. Integrating Fourth Industrial Revolution tools into the electricity sector's business processes enables automated operations, improved operational efficiency, and a more agile response to market dynamics and user needs.

The energy transition in Colombia faces significant technological challenges, especially in the IT and OT field. Digitization is transforming the energy sector, enabling new value propositions in terms of resource availability, orchestration, and management (see ***Figure 4***). The integration of DERs, such as solar panels and energy storage systems, controlled by software and optimized through smart assets, is crucial to improving the efficiency and reliability of the electricity grid.

Figure 4. ***Gartner, Inc. (2024). Predicts 2025:*** *Navigating the Digital Nexus in Power and Utilities. Gartner. (p. 4)*

In Colombia's energy transition, digitization allows companies in the electricity sector to connect, communicate, and control resources more efficiently. The integration of advanced technologies, such as artificial intelligence (AI) and real-time data analysis, is essential for optimizing energy distribution and meeting diverse demands.

The implementation of robust data infrastructure and advanced analytical capabilities is critical to managing the variability of renewable generation and improving operational decision-making. In addition, adopting cloud-based services and preparing the operationalization of AI in control rooms are key actions for companies in the electricity sector to thrive in this new era of innovation and competition. All of this should be supported by robust information governance and data quality, which enable reliable, accurate decisions aligned with the challenges of the energy transition.

To ensure control and value creation through technology, **the following aspects should be considered:**

Stable, Scalable, and High-Performance Technology	Adaptation to the growing demands of the sector and the evolution of technologies.
Agile Generation and Evolution of Solutions	Timely implementation of sustainable solutions with adequate functional coverage.
Greater Interoperability	Interconnection of different systems and technologies, ensuring compatibility between different technology platforms.
Big Data Management	Efficient handling and processing of large amounts of data.
Real-Time Data Analysis	Operation optimization, demand forecasting, and management of renewable generation volatility.
Cybersecurity and Resilience	Protection against cyber threats and guarantee of continuing critical systems.
Information Management	Efficient, secure, and structured information management for smooth decision-making.

The trend surrounding new business models **encourages work on aspects such as the following:**

I Integrated Customer Experience Program

Customer satisfaction is a key factor in the energy sector. Companies such as Origin Energy and MVV Enamic have demonstrated that digitization and personalization can significantly improve customer experience.

Necessary Actions

- **Process Digitization.** Implementing customer relationship management systems to enhance interaction and satisfaction.
- **Smart Metering.** Using IoT-enabled meters to reduce resource waste and provide real-time data to customers.
- **Service Personalization.** Offering personalized services based on data analysis to increase customer loyalty and retention.

II AI-Powered Energy Forecasting

The integration of AI-enhanced energy forecasting can increase the accuracy, efficiency, and sustainability of the energy system.

Necessary Actions

- **Resources and Support.** Providing the necessary resources to ensure the successful implementation of the AI-powered forecasting system.
- **Process Optimization.** Unifying forecasting approaches across all business divisions to improve network management and decision-making.

III Alignment of Operational Technology and Information Technology

The growing demand to integrate IT and OT systems is essential to optimize operations as DERs and smart sensors are implemented.

Necessary Actions

- **Team Collaboration.** Encouraging collaboration between IT and OT teams to ensure seamless integration and alignment.
- **Investment in Initiatives.** Supporting investment in alignment initiatives to improve operational efficiency and resilience against disruptions.
- **Cybersecurity.** Implementing robust cybersecurity measures to protect critical infrastructure from attacks.

IV Resource and Cost Optimization

Resource and cost optimization is essential to improving the profitability and operational efficiency of the energy sector.

Necessary Actions

- **Resource Utilization Maximization.** Implementing technologies that enable better use of available resources.
- **Reduction of Operating Costs.** Adopting technological solutions that reduce operating costs and improve efficiency.
- **Network Management.** Using accurate, real-time data to improve network management and strategic decision-making.

In summary, digitization and the incorporation of advanced technologies are fundamental pillars for addressing the technological challenges of the energy transition in Colombia.

Smart operation—based on the adoption of emerging and advanced technologies—will enable companies in the electricity sector to optimize their operations, improve the efficiency and reliability of the grid, and meet the demands of a constantly evolving sector.

Enabler 6: Developing and Maintaining the Human Talent Required for the Energy Transition

The energy transition is a complex and multidimensional process that requires efficient knowledge management to achieve an effective shift toward more sustainable energy sources. In this context, knowledge management involves identifying, sharing, and applying the expertise necessary to support this transformation. **This fundamental pillar of the energy transition demands a comprehensive approach that encompasses not only knowledge management but also the promotion of a culture of innovation and continuous improvement.**

In this sense, companies, universities, and research centers have a great responsibility to contribute and generate new knowledge around new technologies. They should also commit to train professionals with competencies and skills, capable of leading the energy transition process. The training and enhancement of human talent is essential to move towards a flexible and resilient system, ensuring that personnel are prepared to face the challenges and take advantage of the opportunities presented by the integration of renewable sources.

For approximately eight years, XM has been constantly preparing talent and its processes for the current and future system. This includes certifications, exchanges, advice, and the adoption of global best practices in the planning and operation of systems with increased NCRES integration. To this end, XM has led strategic alliances with various stakeholders, including research centers, global operators, universities, and government entities. These collaborations have generated key studies and proposals to implement the necessary changes in regulatory frameworks, infrastructure, and the market, allowing for the efficient integration of new technologies into the electricity system.

Furthermore, the inclusion of the gender perspective in the energy transition has been fundamental. **Women contribute valuable knowledge and practical experiences to social resilience.** In addition, since men and women have different levels of access to energy, as well as distinct needs and usage patterns, integration is crucial to guarantee that no segment of the population is left behind.

To address this need, **we have implemented a series of strategies and actions that ensure our team is prepared to face the challenges and take advantage of the opportunities presented by the energy transition.**

An analysis is needed to identify medium- and long-term technical talent needs, including an assessment of the competencies and skills required to operate and manage a more diversified and sustainable system, with emerging trends in the energy sector.

Based on the identification of needs and trends, specific proposals should be designed to attract, train, and retain technical talent, focusing on the skills and competencies necessary for the energy transition. This should include training and continuing education programs, **strategic alliances with educational institutions and research centers, and the implementation of professional development initiatives.** A culture of innovation and continuous improvement is also fostered. Similarly, a monitoring and evaluation system has been established to tailor strategies and ensure that the company is prepared for the challenges of this transition.

4. Call to Action

The electricity system as we know it is evolving faster than ever. The rapid advancement of new technologies, market structures, electrification trends, and consumption patterns is outpacing institutional capability to develop the infrastructure and regulatory frameworks needed to support the emerging operational and market paradigms. This underscores the urgent need to identify key risks and implement coordinated action plans across public policy, regulation, expansion, and operations to ensure a secure, reliable, and resilient electricity system in the face of increasing complexity, variability, and uncertainty. Risk identification—particularly in relation to the integration of variable sources—helps gauge the magnitude of the challenges facing the system. It also serves as a basis for prioritizing the deployment of enabling actions throughout the technology integration process.

Analyses conducted by XM have identified 25 qualitative and quantitative risk indicators that are key for aligning sectoral efforts and addressing the challenges of the energy transition. These risks are categorized under four characteristics of a flexible and resilient system: energy adequacy and sustainability; power flexibility; system quality, security, and reliability; and energy transmission capability (see ***Figure 5***). Based on this framework, the following actions should be prioritized and implemented in advance to enable the integration of 4 GW to 8 GW of inverter-based generation.

- A flexible, complementary, and resilient electricity grid.
- Implementing expansion plans and developing new infrastructure projects.
- Modernizing the transmission network and integrating the technologies, processes, and studies required to operate a system with greater participation of renewable generation.
- Modernizing the market by integrating new products and services that efficiently adapt to new supply and demand conditions.
- Expanding and enhancing the technological infrastructure, maintaining high levels of cybersecurity and resilience.
- Developing and maintaining the human talent required for the energy transition.

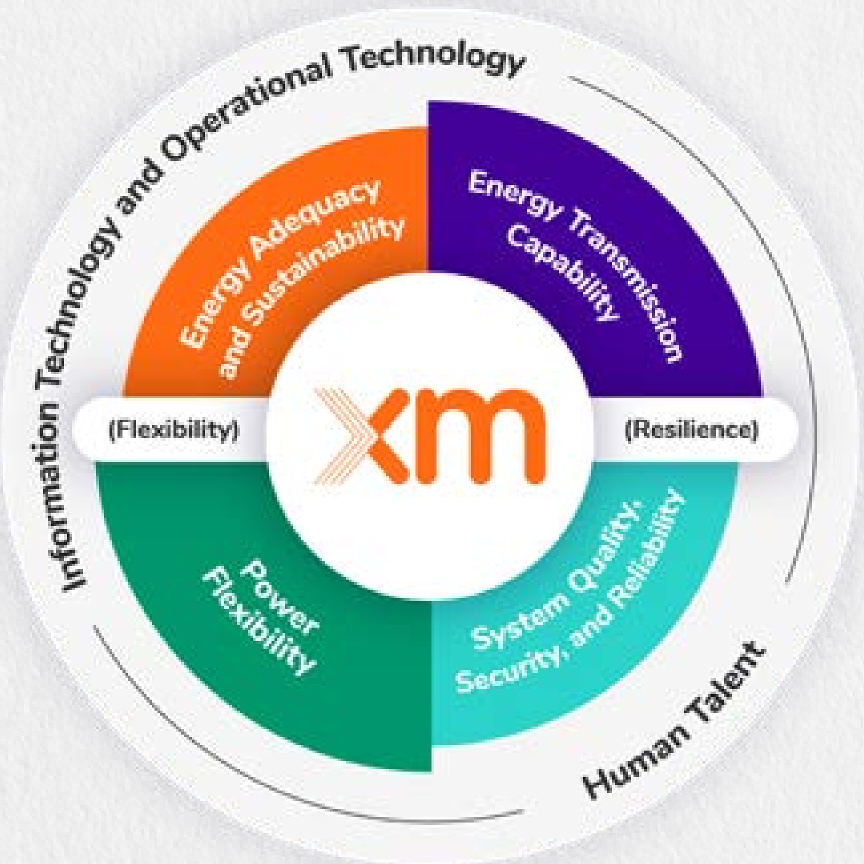


Figure 5. *Articulation based on four characteristics of a flexible and resilient system.*

From the flexibility and resilience perspectives, challenges are articulated and prioritized to achieve a flexible system that is adaptable to changing conditions and resilient by being better prepared to respond to infrastructure events.

Security Categories	#	Flexibility Study Indicators	Generation Connected Via Inverters: 2 GW	4.4 GW	8.2 GW	11 GW	16.2 GW
Energy Adequacy	1	Demand Coverage	No Risks	No Risks	No Risks	No Risks	Partial Risks
	2	Complementarity	No Risks	No Risks	Partial Risks	Partial Risks	Identified Risks
Power Flexibility	3	Net Demand (downward reserve deficit)	No Risks	No Risks	Partial Risks	Identified Risks	Identified Risks
	4	Generation Ramp Coordination Capability	No Risks	Partial Risks	Identified Risks	Identified Risks	Identified Risks
	5	Hourly Ramps	Partial Risks	Partial Risks	Identified Risks	Identified Risks	Identified Risks
	6	Five-Minute Ramps	No Risks	No Risks	No Risks	Partial Risks	Identified Risks
	7	Intra-Hour Imbalances	Partial Risks	Partial Risks	Identified Risks	Identified Risks	Identified Risks
	8	Deviations	Partial Risks	Partial Risks	Identified Risks	Identified Risks	Identified Risks
	9	Hot and Cold Reserve	No Risks	No Risks	Partial Risks	Partial Risks	Identified Risks
	10	AGC Reserves (hourly)	No Risks	Partial Risks	Partial Risks	Identified Risks	Identified Risks
Transmission Capability	11	Congestions	Partial Risks	Partial Risks	Partial Risks	Partial Risks	Identified Risks
	12	Curtailments due to Network Constraints (trapping)	No Risks	No Risks	Partial Risks	Partial Risks	Identified Risks
	13	Impact of Deviations on Security Limits	No Risks	No Risks	Partial Risks	Identified Risks	Identified Risks
Security	14	Inertia	No Risks	Partial Risks	Partial Risks	Identified Risks	Identified Risks
	15	Primary Regulation	No Risks	No Risks	Partial Risks	Identified Risks	Identified Risks
	16	Maximum Short-Circuit Level	No Risks	Identified Risks	Identified Risks	Identified Risks	Identified Risks
	17	Grid Strength	No Risks	Partial Risks	Identified Risks	Identified Risks	Identified Risks
	18	Frequency Nadir Withstand Capability	No Risks	Partial Risks	Identified Risks	Identified Risks	Identified Risks
	19	ROCOF Withstand Capability	No Risks	Partial Risks	Identified Risks	Identified Risks	Identified Risks
	20	ALSS Adequacy	No Risks	Partial Risks	Partial Risks	Identified Risks	Identified Risks
	21	Oscillations	No Risks	Partial Risks	Identified Risks	Identified Risks	Identified Risks
	22	Voltage Sag Propagation	No Risks	Partial Risks	Partial Risks	Identified Risks	Identified Risks
	23	Slow Recovery Following Faults (frequency and voltage)	Identified Risks	Identified Risks	Identified Risks	Identified Risks	Identified Risks
	24	Transient Stability	No Risks	No Risks	No Risks	Partial Risks	Identified Risks
	25	Protections	No Risks	Partial Risks	Partial Risks	Identified Risks	Identified Risks

No Risks | Partial Risks | Identified Risks

The following are the prioritized actions. However, for each level of renewable energy integration, it is necessary to work across all indicators in the following pages:

Energy Adequacy and Sustainability

1. Institutional articulation to implement generation projects.
2. Preservation and expansion of a flexible natural gas infrastructure as operational backup.
3. Improvement of institutional capability for measuring and characterizing meteorological variables.
4. Incentives for the installation of solar and wind generation resources with storage capacity.
5. Improvement of daily and seasonal storage capacities (batteries, pumps, hydrogen, nuclear power).

Flexibility

1. Incentives for better forecasts (demand and generation).
2. Deployment of hourly and intra-hourly adjustment mechanisms (dispatches with lower granularity).
3. Deployment of new ancillary services (flattening of the solar production curve, ramps, arbitrage, and others).
4. Improvement of the capacity of NOs to manage the operation of SDLs (observability, controllability, ancillary services).
5. Deployment of near real-time markets with demand-side and nuclear generation participation.

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Energy Transmission

1. Institutional articulation to implement ongoing transmission projects.
2. Emergency plan for the modernization and repowering of transmission infrastructure (STN and STR infrastructure, protection systems).
3. Technical framework for the deployment of grid-forming batteries for congestion management and deployment of solutions.
4. N-1-1 resilience and reliability criteria in network expansion plans.
5. Deployment of solutions for network optimization.

Quality, Security, and Reliability

1. Activation of primary regulation in all technologies.
2. Regulatory framework and updating of the ALSS.
3. Updating of IBR technical requirements.
4. Implementation of enhanced protection systems in the STN, STR, and SDL.
5. New network code (reliability, resilience, and flexibility).
6. Regulatory framework and deployment of synchronous condensers and grid-forming batteries.
7. New ancillary services: grid strength, inertia, fast frequency response, and frequency containment via demand response.
8. EMT model (digital twin) requirements for the Colombian system.
9. Inertia contribution and short circuit in NCRESs.

With the aim of comprehensively addressing the energy transition and capitalizing on its opportunities, **XM has designed a set of specific actions.** These actions are implemented based on the level of integration of renewable energies into the SIN planned for each year, and they are organized according to previously defined strategic themes.

Energy Adequacy and Sustainability

- Institutional articulation to develop generation infrastructure when needed.
- Institutional capability for meteorological measurement and forecasting.
- Characterization of meteorological monitoring and alarms.

- Preservation and expansion of the natural gas infrastructure.
- Backup capacity and flexibility for gas plants (storage).

Flexibility

- Reduction to 5 MW in the participation threshold for central dispatch.
- Hourly and intra-hourly adjustment mechanisms.
- Dispatches with lower granularity.
- Incentives for better forecasts (demand and generation).
- **Analysis of operational needs for ancillary services.**

- **Analysis of operational needs for ancillary services.**
- AGC.
- Improvement of consumption and generation observability.
- Availability of batteries in solar and wind plants.
- Improvement of the capacity of NOs to manage generation in SDLs.

- Flexibilization of the thermal and hydraulic generation fleet.
- Emergency services in DERs.
- Definition of the distribution system operator and its coordination and control functions.
- Analysis of new ancillary services (ramps).

Quality, Security, and Reliability

- Incentives for compliance with primary regulation in all technologies.
- Activation of the primary regulation service in NCRESs.
- Regulation of short-circuit and inertia contribution services.
- Institutional articulation (CREG, UPME, Ministry of Mines and Energy, market participants, academia).
- Demand-side participation mechanisms.
- **Proposed regulatory update regarding spot market mechanisms.**
- **Proposed spot market update with binding dispatch and demand-side participation.**

- Development of the new network code.
- **Establishment of criteria for operation with low levels of inertia.**
- **Implementation of grid strength limits.**
- Regulation of maximum times for fault clearance.
- Deployment of synchronous condensers.
- Improvement of protection systems in the STN and STR.
- New roles for ancillary services.
- Storage systems.

- Connection studies providing RMS and EMT simulations.
- Development of long-term and spot inertia and short-circuit markets.
- Incorporation of IEEE 2800 and IEEE 1547 standards.
- Implementation of EMT requirements.
- Provision of fast frequency response services.
- Implementation of ancillary service mechanisms for the intraday market*.
- Energy communities.
- **Diagnosis of information symmetry and transparency of the systemic risk model.**
- **Validation of proposals for new market elements for systemic risk.**

Energy Transmission

- Network infrastructure required to minimize electrical and operational constraints on the system.
- Inclusion of N-1-1 planning in the expansion.
- Plan to upgrade the transmission infrastructure (short circuit).

- Availability of batteries in solar and wind plants to mitigate infrastructure problems.
- Promotion of preventive maintenance and hot work and discouragement of opportunistic work.
- Network expansion plans considering comprehensive analyses of the STN and STR.
- Development of urgent projects.

- High-temperature conductors (superconductors) and other alloys.
- Reinforcement of SDLs.
- Repowering of infrastructure.

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	2028	2030	
Energy Adequacy and Sustainability	• Institutional articulation to develop generation infrastructure when needed. • Institutional capability for meteorological measurement and forecasting. • Characterization of meteorological monitoring and alarms.	• Daily and seasonal storage. • Large-scale storage. • Nuclear energy, hydrogen, P2X.	
Flexibility	• Real-time markets, demand-side participation, and generation. • Aggregators and DER participation in the market.	• Ancillary DER services. • DER automation and controllability.	
Quality, Security, and Reliability	• Rapid demand disconnection services. • Grid-forming batteries. • Resilience criteria in expansion plans.	• Conversion to clean fuels or synchronous condensers. • Modernization of the ALSS (DER). • Ancillary DER services market. • Participation in the large-scale storage market. • **Incorporation of DER automation and controllability.** • **Structural organizational definition for systemic risk (application of process reengineering methodologies).** • Integration of regional markets with spot markets and ancillary services in Colombia (MAERCP and SINEA).	• Implementation of a standardized systemic risk reporting process for authorities. • Reinforcement of the reliability charge mechanism to ensure physical delivery of energy. • Proposal for strengthening financial sustainability mechanisms for the energy market. • **Identification of elements of the mechanism in Colombia to be adjusted.** • **Revision of the estimate of firm energy from technologies.**
Energy Transmission	• HVDC. • Network optimization (repowering-SSSC-DLR). • Black start services, grid-forming batteries.	• HVDC - Multiport. • EMT digital twin of the system.	

The highlighted text corresponds to XM's actions.

XM plays a vital role in ensuring that Colombia's energy transition progresses in an orderly manner, enabling the country to continue delivering the high-quality energy to its citizens.

In this context, the roadmap presented here provides a detailed overview of the challenges and opportunities that, from XM's perspective, should be addressed to advance the energy transition and therefore the transformation of the country's electricity sector. These insights are grounded in analyses of the system needs and the technical and market requirements associated with the integration of variable and distributed energy sources.

Inter-institutional coordination, alignment, and shared accountability are imperative in fulfilling this national commitment, both today and in the years to come.

5. Glossary

AGC: automatic generation control

BIAS: automatic load shedding scheme

AVC: automatic voltage control

BESS: battery energy storage system

CND: Colombia's National Dispatch Center

CREG: Colombia's Energy and Gas Regulatory Commission

DER: distributed energy resource

EMT: electromagnetic transient

FACTS: flexible alternating current transmission system

GWh: gigawatt hour

HVDC: high-voltage direct current

IBR: inverter-based resource

MAERCP: Andean Regional Electric Spot Market

MW: megawatt

MWh: megawatt hour

NCRES: non-conventional renewable energy source

NO: network operator

RMS: root mean square

ROCOF: rate of change of frequency

SDL: Colombia's Local Distribution System

SIN: Colombia's National Interconnected System

STN: Colombia's National Transmission System

STR: Colombia's Regional Transmission System

UPME: Colombia's Mining and Energy Planning Unit

WEM: wholesale energy market


20 years
Made by Colombia