

Advanced Smart Grid Technologies for Seamless Integration of Distributed Energy Resources in Urban Environments: Challenges, Opportunities and Future Directions

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Abstract

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Sustainable energy advancements in the global market increasingly depend on urban areas due to environmental needs and growing urban population. The research analyzes the mutual advantages between smart cities and smart grids to develop resilient sustainable urban energy systems. The article uses case studies of cities to show the transformative impacts achieved through smart grids together with energy-saving initiatives on sustainability and urban strength. The upcoming analysis explains how financial and legal and technical barriers prevent urban areas from implementing broad smart energy solutions across the board. The final section recommends different strategic solutions for the identified challenges through the development of stakeholder engagement procedures and digital infrastructure investments and innovative legislative frameworks. Research shows that smart urban areas need an interdisciplinary approach to fulfill their potential because this method allows cities to take charge of worldwide energy transition objectives. It has been concluded that The world experiences increasing cooling demands because of rising global temperature trends. Current space cooling equipment capacity of 850 GW is projected to achieve approximately double growth by 2030 and will subsequently double again by 2050. The increased need for cooling creates power grid operational problems that drives up electricity requirements thus impacting consumer access levels and increasing power costs. The prediction suggests that power consumption across ASEAN territories will increase from 10% to 30% throughout the period 2040 by metropolitan regions because of cooling demands. Studies indicate that an increase in world temperature levels up power demand by more than 4% during peak usage times.

INTRODUCTION

The current urban population stands at more than 50% of Earth's inhabitants yet forecasts indicate the number will reach about 70% by 2050. Cities have become responsible for roughly 70% of the global carbon dioxide (CO₂) emissions that appear worldwide. The combined impact of recovering cities from COVID-19 has created rapid increases in CO₂ emissions because the world is projected to experience its second-highest energy-related CO₂ emission levels during 2021. The majority of worldwide GDP originates from cities which stand as central economic centers that offer substantial potential to advance challenging climate targets. The world economy centers on cities because they serve as the main economic growth force (A. M. Minas *et al.*, 2024). Today nearly 8 billion people from about 56% of the global population inhabit metropolitan areas that generate more than 80% of global GDP. Between 2015 and 2020 the population living in cities worldwide reached about 400 million new residents. Urban growth during this period primarily happened in emerging market and developing economies where the highest percentage exceeded 90%. The majority of new urban residents settled in

Asian and African territories with Nigeria and China and India leading the numbers.

The enormous changes in urbanization patterns continue to transform societies as people and the population grow because of unprecedented global expansion. The world's population will double its urban residents from 2024 to over 70% by 2050 resulting in a population increase across cities of 1.8 billion people. The continental population of Africa is forecasted to increase four times while Asian population numbers will expand roughly one-third during this period. The population data shows historic and projected trends for urban regions worldwide from 1950 up to 2050 in Figure 1. Practically seventy percent of greenhouse gas emissions stem from urban areas while the population continues to increase and people move from rural to urban spaces starting from 2015. The rise in urban carbon dioxide emissions is projected to achieve its highest level ever at 29 billion tons by 2023 because of the transformation from rural to urban areas (C. G. Díaz, D. Zambrana, 2024).

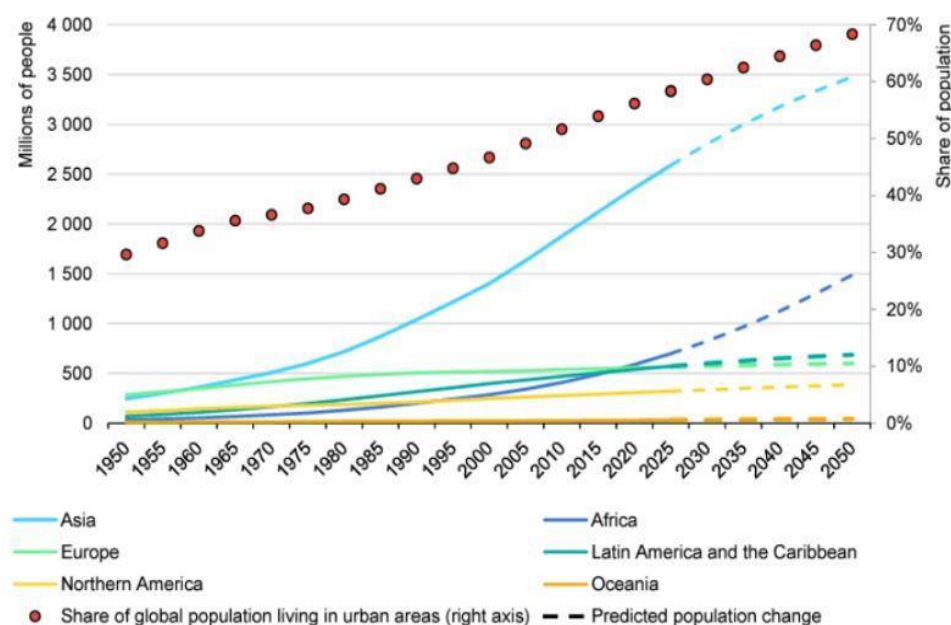


Figure 1. The historical and forecast urban population by area from 1950 to 2050.

Several urban areas have proven to be national climate plan leaders through their efforts to achieve net zero emissions within their established time boundaries. London works to achieve carbon neutrality before 2030 sets a challenging goal. The city improved its air pollution levels substantially after making the ultra-low emission zone cover all parts of Greater London during 2023. This approach builds active partnership while emphasizing people-oriented values while prioritizing equality between all citizens and social inclusion.

The community-funded solar projects established by Vienna enable its citizens to join together in investments for renewable energy generation. The important part cities play in developing net zero energy systems has received ongoing recognition from multilateral conferences. Cities play a crucial role in accelerating the shift towards renewable energy according to an official document released by G20 Energy and Climate Ministers at their 2021 Naples meeting. A historical statement emerged from the 2023 G7 Ministerial Meeting on Climate Energy and Environment in Sapporo Japan about organizing the first G7 Sub-National Climate Action Roundtable jointly with Urban7. Local actors play a

vital part in attaining the net zero transition according to the G7 Ministers statement that closed this meeting.

LITERATURE REVIEW

Smart grid systems handle several power-related problems experienced by growing cities thus earning their position as essential infrastructure in sustainable city building. Smart grid technology enables researchers to explore methods for building stronger urban spaces that enhance energy system sustainability alongside increased efficiency and reliability. The conventional smart grid design appears as shown in Figure 2. Smart grids implement modern technological solutions to improve power distribution along with transmission capabilities. Under the umbrella of general environmental and sustainable development principles this approach decreases energy losses while decreasing costs alongside greenhouse gas emissions. Cities with advanced infrastructure and heavy usage expose themselves to multiple power outages because of these factors (G. Hugo, "Patterns and trends of urbanization and urban growth in Asia, 2019).

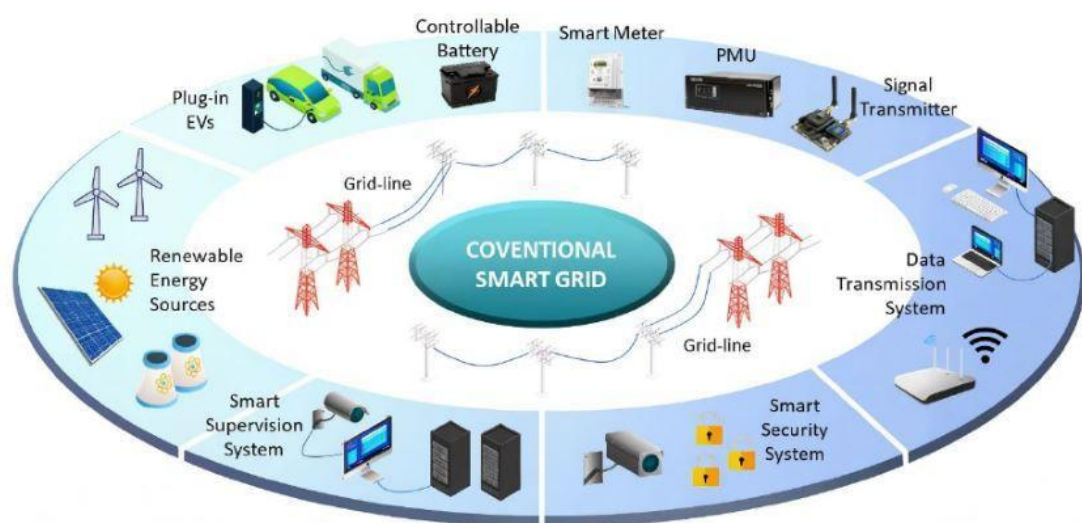


Figure 2. The diagram of a conventional smart grid.

The self-healing capabilities of smart grids detect and fix defects while automatically diagnosing

faults which results in shorter and less severe power outage duration. Smart grids simplify the integration

process of wind power and solar energy as part of urban energy distribution networks. The implementation of smart grid technology permits urban areas to develop climate-resilient regulation along with sustainable growth policies. Smart grids help municipalities access capital that enables the installation of electric vehicle charging stations while developing dynamic pricing systems and establishing regulations for carbon credits and energy transactions. Several researchers focus on analyzing smart grid applications for sustainable urban development. Most research explores how electric grids can boost three essential urban components: sustainability and dependability alongside energy efficiency (M. Khaleel, Z. Yusupov, 2023). The research focuses on studying modern metering systems as well as renewable energy integration along with distributed generation and demand response to reduce urban carbon emissions while improving city-wide energy oversight. Local researcher Dorji et al. argue that global energy efficiency and environmental management requires complete overhaul because climate change difficulties become more intricate alongside expanding energy requirements. A widespread disaster could happen because uncontrolled energy demand growth from new infrastructure development and national developments. The installation of modern bidirectional digital energy flow networks represents a viable solution to address the coming energy crisis. The system features advanced cybersecurity measures which protect against threats and also has autonomous recovery operations alongside connection abilities between systems and prediction systems for uncertain conditions. Smart grids make it possible to blend renewable solar, wind power and energy storage solutions directly into existing power grids (Y. F. Nassar *et al.*, 2024). Smart grid acceptance and performance are

determined by their conceptual definition along with academic and political support for their promotion.

METHODOLOGY

The researchers investigate how contemporary technologies including nanotechnology and smart grids contribute to minimizing carbon emissions in their report. Smart grid energy efficiency relies on specific characteristics and abilities which experts actively discuss. The paper includes details about secondary components and future benefits connected to these advancements. The data from this report confirms smart grids have established themselves as fundamental components in clean energy policies because of recent technological progress. The complete growth and operational enhancement of smart grids will depend heavily on nanotechnology during the next few years. The merging technologies show that sustainable energy systems need development alongside environmental impact reduction efforts.

A broad assessment of worldwide power grid operations exists in this research which analyzes in detail both the involved organizations and parties and the conceptual model as well as goals and grid design features and potential advantages and disadvantages. This article presents an extensive breakdown of energy and transmission difficulties through smart grids examination that explores the technical and infrastructure elements of their obstacles (G. Ben-Ishai, J. Dean, J. Manyika, R. Porat, 2024). The defense against climate change coupled with ensuring enduring global energy sustainability demands an immediate transition to sustainable low-carbon energy systems. Smart grid technology continues to show increasing significance as a means to drive these changes forward. The research investigates complex impacts of smart grid technology on electricity industries through an evaluation of legislative forces

influencing their development. This research evaluates smart grids for their ability to improve power efficiency and their potential to incorporate renewable resources besides maintaining grid stability under different legal frameworks which either support or challenge the advancement of these technologies. This study examines the regulatory factors that affect technology innovation for energy systems which enables strong sustainable power systems to develop. The authors introduce an MLP-ELM approach as their proposed method for predicting smart grid sustainability levels. To improve prediction capability of MLP-ELM models Principal component analysis (PCA) serves as an included method in this research (L. McCann, N. Hutchison, and A. Adair, 2023). This report describes the implementation outcomes pertaining to smart grid stability via empirical examination and comparison with other approaches. The MLP-ELM approach's advantage over conventional machine learning approaches is confirmed by simulation results. Specifically, the MLP-ELM model shows its efficacy in forecasting the sustainability and operational stability of smart grids with 95.8% accuracy, 90% precision, 88% recall, and 89% F-measure.

Definition of Smart Grid

A "grid" represents the power delivery system that provides user access while a "smart" element refers to characteristics that include intelligence and efficiency together with cleanliness and automation and order. There exists no universal definition of "smart grid" because experts have not yet reached consensus so the term gets interpreted differently. A basic description of smart grid technology involves power distribution that functions like a system with neurological capabilities. Modern electrical grids function with bidirectional energy movement through connected systems that utilize bidirectional

communication protocols according to NIST technical specifications. According to IEEE the smart grid presents itself as "A revolutionary effort with new communications and control capabilities, energy sources, generation models, and regulatory structures that comply with cross-jurisdictional regulations (J. Yang, 2023)."

The IEC describes the smart grid as a system that links users' connected actions through generators and consumers to develop a sustainable and secure energy supply at minimum cost. The U.S. Department of Energy defines the smart grid as "an intelligent grid that employs digital technologies to advance electric power system reliability together with safety levels and energy and economic efficiency throughout large-scale generation systems and utility networks up to electricity customers and expanding distributed generation and storage assets." The definition shows that the smart grid functions as a modern infrastructure that directs flows of information and energy in both forward and backward directions (G. Siokas and A. Tsakanikas, 2023). The system enables customers to take energy-based decisions while allowing utilities to execute efficient control of energy distribution and transmission. The real-time communication system built from information technology processes electricity demand and supply through smart grid management. The main technical difference between conventional grids and smart grids stems from their ability to establish two-way power exchanges and data transfer between power companies and end customers. The benefits of smart grids include robust antimicrobial security defenses combined with stronger electrical reliability features and economic vitality. A precise definition of smart grid describes it as an advanced digital communication system which secures electrical energy flow while possessing self-healing abilities

and predictive features and interoperability under unpredictable conditions (G. Hugo,2019).

FINDINGS

Impacts of a Changing Climate and Energy System

Multiple national power grids have been working at increasingly maximum levels throughout recent years while climate change further complicates the situation. The storms that exceeded power network parameters led to disruptions in electricity supply throughout United States Europe and Japan. High temperatures disrupt power operations across specific regions with sensitive energy needs because most areas get their heating and cooling through electricity supply. The number of power consumption peaks per community has increased from single to double according to recent observations. The process of decarbonizing heating technologies throughout cold regions will boost overall heating demands during winter months

which produces higher power consumption peaks during cold temperatures. The summer used to be the peak demand season in the United States but predicted winter peak demand is emerging in specific states across the country. The exceptional Texas winter storm of February 2021 illustrates this significant change in the power sector. The disastrous weather led to blackouts affecting more than 4.5 million homes while disrupting both public heating and water supply services. The catastrophic storm left a \$20 billion loss behind it becoming the costliest winter natural disaster ever. It affected 15 million people throughout the entire state. Serious heat waves result in sustained increases of cooling system usage directly proportional to ongoing global temperature rises. The climbing demand for cooling creates complicated situations for power grid operations especially among regions that require enhancements to their infrastructure systems to adapt to multiple peak usage conditions and connect renewable power networks.

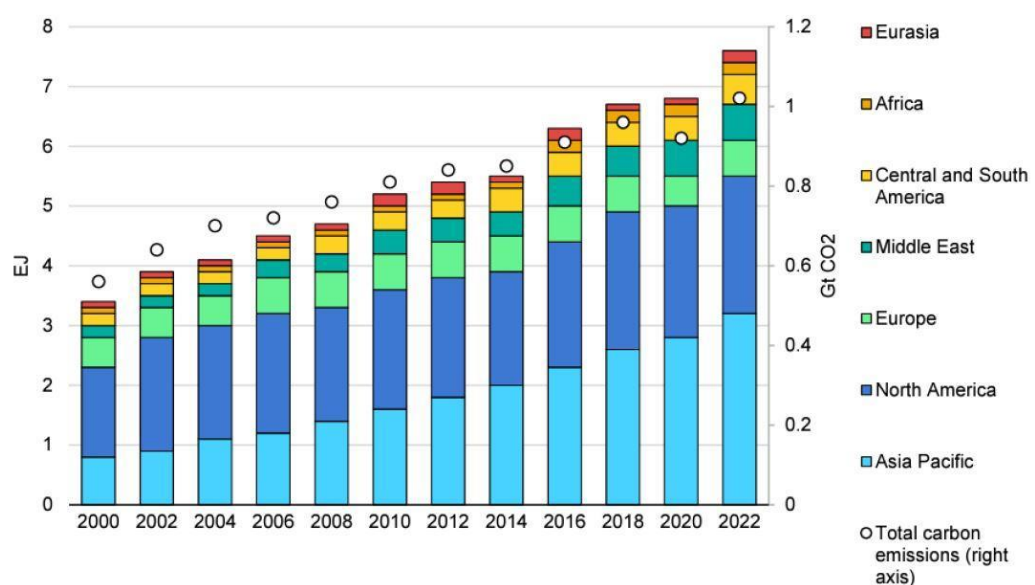


Figure 3. The final energy consumption and carbon emissions resulting from space cooling, categorized by region, for the years 2000 to 2022.

Between 2000 and 2022 the worldwide final energy consumption for space cooling increased by approximately 4% annually whereas water heating

usage grew half as much. The increasing demand for household air conditioners keeps growing rapidly as they have tripled since 2000 and analysts predict

they will reach more than 1.5 billion units by 2022. The dramatic increase in power consumption stems from extreme heat because it drives people to turn on their air conditioners in greater numbers. The electrical system needs to cope with a doubled power demand for electricity across heat-intensive

regions compared to other less hot regions because cooling systems dominate peak power usage at more than 70%. The penetration rates of air conditioners result in different impacts of temperature changes on power usage from one region to another.

Table 1. The major findings from recent studies on the effects of a shifting climate and energy system

Year	Key findings	Region
2024	▪ This study integrates a power system decision model within a computable general equilibrium (CGE) framework to thoroughly examine the low-carbon transition, environmental benefits, and economic costs associated with a combined carbon tax (CTax) and renewable energy investment (REI) policy. ▪ The findings indicate that a dynamic CTax, with carbon prices set at 290 RMB/ton CO₂ in 2035 and 590 RMB/ton CO₂ in 2050, can substantially reduce the proportion of coal-fired power from 65% in 2017 to 22% by 2050. This reduction corresponds to a decrease in coal consumption by 0.8 billion tons of standard coal equivalent (tce), resulting in a decline in coal's share of the energy system from 60% in 2017 to 29% in 2050. ▪ The article's investigation into the strategic design of a resilient, low-carbon energy system for Saudi Arabia, projected to be operational by 2050, elucidates numerous valuable insights and delineates a clear path for future research and policy development. ▪ The scenarios contemplated in the study, encompassing VRE (Variable Renewable Energy) penetrations of 40% and 70%, are exceedingly ambitious and fraught with uncertainties. Achieving such high levels of VRE penetration necessitates substantial technological advancements, robust policy interventions, and significant investments in grid infrastructure. ▪ The demand for hydrogen, which has experienced a more than threefold increase since 1975, continues its upward trajectory. Presently, the annual demand for pure hydrogen stands at approximately 70 million tonnes (MtH₂/yr). This hydrogen is predominantly derived from fossil fuels, with 6% of the world's natural gas and 2% of global coal dedicated to its production. ▪ Hydrogen production is responsible for approximately 830 million tonnes of carbon dioxide (CO₂) emissions per annum, a figure commensurate with the combined CO₂ emissions of Indonesia and the United Kingdom. In terms of energy, the global annual demand for hydrogen is estimated to be around 330 million tonnes of oil equivalent (Mtoe), surpassing the primary energy supply of Germany. ▪ The surge in renewable capacity is projected to increase the contribution of low-emission sources to electricity generation from 39% in 2022 to 71% in 2030, ultimately achieving a full transition to 100% by 2050. ▪ A factorial optimization-driven input-output model has been developed to rigorously investigate the socio-economic and environmental (SEE) impacts of greenhouse gas (GHG) emission reduction within Canada's electric power system, accounting for uncertainties and their interactions. ▪ The results elucidate the pivotal role of optimizing the structural composition of systems, such as energy or electric power systems, to facilitate comprehensive societal emission reductions in alignment with specific mitigation targets. ▪ The study identifies factors with significant interactive effects on sectoral total outputs. Specifically, increasing the proportion of clean energy sources—such as wind and solar power, small modular reactors, and coal-fired power with carbon capture and storage technology—proves instrumental in enhancing sectoral total outputs and achieving substantial GHG emission reductions by 2050.	China Saudia Arabia Germany Canada Africa
2024		
2024		
2024		
2024		

	▪ The article presents current trends in renewable energy (RE) development and access across various African nations, examining each country's capacity to lead the transition to sustainable RE for all.	
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Electricity consumption will increase from its current 2023 level of 20% to more than 50% by the year 2050. The modification of power systems becomes imperative to fulfill changing power requirements. The graphs in Figure 4 display the

electricity usage as a percentage of all industrial energy consumption starting from 2010 up to 2022 alongside predictions for the 2030 and 2050 NZE Scenarios.

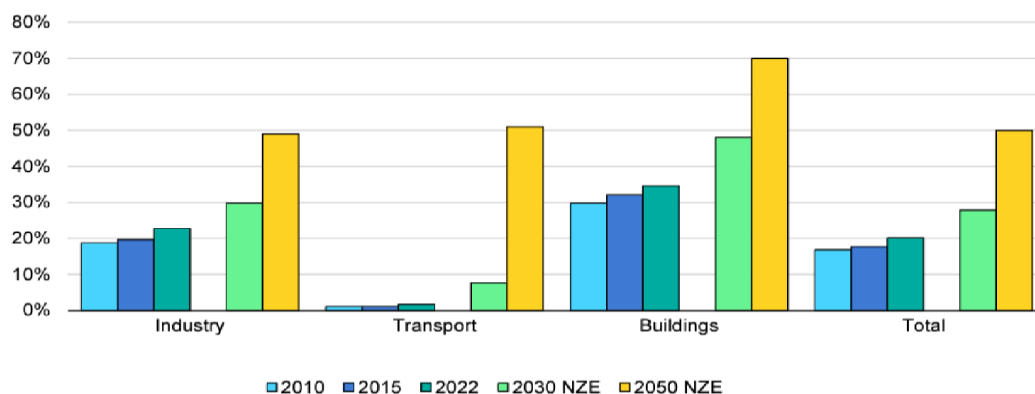


Figure 4. The proportion of electricity in the total consumption of energy for different sectors from 2010 to 2022, as well as in the NZE Scenario for 2030 and 2050.

The net zero transition shows clear signs of quick acceleration because many regions rapidly adopt efficient electric cars (EVs). Experts anticipate new EV sales to grow 35% during 2023 when compared to 2022. EV ownership will sustain its current trajectory while societies continue to install rooftop solar photovoltaic (PV) power systems and air conditioners together with heat pumps and distributed energy generation assets. The innovations mark a firm implementation of sustainable energy methods in urban areas and show indications of accelerating throughout upcoming years.

Opportunities for Sustainable Energy Transitions in Cities

The definition of urban sustainability strongly depends on the decisions of local government officials in policy making and urban planning activities. The nations build resilient communities

while working to reduce climate change effects through support for sustainable and intelligent energy options that include everybody. District-wide renewable energy installations together with low-emission mobility laws speed up the implementation of clean energy technology in urban environments (A. Alhajia and A. Lawal, 2017). The implementation of resilient power regulations and renewable energy solutions into regulatory frameworks becomes possible through city-based initiatives that support socially inclusive energy transitions. Several examples show how municipalities can combine human-centered strategies with environmental objective progress through national climate initiatives.

Future Grids Need New Sources of Flexibility

Two major renewable energy sources currently used for power systems consist of dispatchable thermal power plants along with pumped storage production

facilities. Power system flexibility refers to its speed in responding to changes that occur between electricity supply and demand. Thermal power plants face decreased significance in power generation due to environmental activism and greenhouse gas reduction regulations during the energy transition to low-carbon systems. More flexible power generation assets become crucial because thermal power plants are anticipated to produce reduced output (G. Deku *et al.*, 2024). The resolution of power grid instability requires joining demand response technologies alongside battery storage units and improved renewable power generation from wind and solar sources in order to establish energy storage systems. Improved connectivity and enhanced smart grid management systems combined with declining thermal power station roles will facilitate easier integration and control of various energy sources (D. da Fonseca-Soares, 2024). These interventions will sustain the stability as well as reliability of the grid system.

CONCLUSION

The world currently has eight billion people spread across 50% of urban landscapes because city populations continue to expand. New city residents numbered 400 million worldwide between 2015 and 2020 while EMDEs led the way with more than 90% of this population growth. The urban population segment is expected to grow from its current 56% to almost 70% by 2050 which will bring additional 1.8 billion people into urban settings. Urban land area research shows that by 2050 it will expand by 1 million square kilometers similar to combining Germany and Italy and Japan together.

The world experiences increasing cooling demands because of rising global temperature trends. Current space cooling equipment capacity of 850 GW is projected to achieve approximately double growth by 2030 and will subsequently double again by

2050. The increased need for cooling creates power grid operational problems that drives up electricity requirements thus impacting consumer access levels and increasing power costs. The prediction suggests that power consumption across ASEAN territories will increase from 10% to 30% throughout the period 2040 by metropolitan regions because of cooling demands. Studies indicate that an increase in world temperature levels up power demand by more than 4% during peak usage times.

The speed of large-scale initiatives must quicken because it is essential to achieve international renewable energy transition targets. Implementing renewable energy projects faced important delays in various locations due to complications within the planning phase. Many renewable energy projects totaling 3,000 GW need grid connection at present while energy saving initiatives remain inactive according to projections. An analysis shows that 200 GW of new solar power projects have been planned which exceeds the predicted capacities of national grid planning because several European nations have outdated grid infrastructure. The expected infrastructure spending deficit will reach at least €5 billion because of this situation.

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