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Research Article

Impact of Smart Grid Technologies on Sustainable Urban Development

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Abstract: Urban areas are increasingly pivotal in the global transition towards sustainable energy, driven by rapid urbanization and environmental imperatives. This paper explores the synergistic role of smart cities and smart grids in fostering resilient, efficient, and sustainable urban energy systems. The paper presents case studies from cities that have successfully implemented smart grids and energy-efficient practices, illustrating the transformative effects on energy sustainability and urban resilience. Further discussion focuses on the challenges urban centers face, including technological, regulatory, and financial barriers that can impede the adoption of smart energy solutions. Finally, the paper proposes strategic approaches for overcoming these challenges, such as policy frameworks that encourage innovation, investment in digital infrastructure, and stakeholder engagement processes that include local communities in planning and implementation phases. The conclusion underscores the critical need for interdisciplinary approaches in realizing the potential of smart cities and smart grids, thereby empowering urban areas to lead the charge in achieving global energy transition goals.

Keywords: Smart grid, Urban, Energy consumption, Carbon Emissions, Opportunities, Future grids.

1. Introduction

More than 50% of the world's population currently resides in urban areas, a figure projected to rise to nearly 70% by 2050. Cities are responsible for approximately 70% of global carbon dioxide (CO2) emissions [1-3]. As societies recover from the COVID-19 pandemic, CO2 emissions are rebounding swiftly, with the increase in global energy-related CO2 emissions in 2021 anticipated to be the second-largest in recorded history. Cities, as global economic engines generating 80% of global GDP, present a significant opportunity to accelerate progress towards ambitious climate goals [4-6].

Cities function as pivotal hubs for global economies, serving as the primary catalysts for economic expansion. As urban centers, they accommodate approximately 56% of the global population, which now totals 8 billion individuals, and are responsible for contributing over 80% of the worldwide GDP. The period between 2015 and 2020 witnessed a dramatic surge in the urban demographic, increasing by nearly 400 million globally. Significantly, over 90% of this urban expansion has transpired in Emerging Markets and Developing Economies (EMDEs), predominantly within the regions of Asia and Africa, with the most pronounced growth observed in India, China, and Nigeria [7-11].

The dynamics of urbanization, coupled with the rising global populace, are rapidly reshaping societal structures at an unprecedented rate. By 2024, more than half of the world's population resides in urban locales, a proportion anticipated to escalate to approximately 70% by 2050, representing an augmentation of about 1.8 billion individuals. In Asia, the total population is projected to augment by approximately one-third, whereas in Africa, the continental population is expected to double within the same timeframe [12,15]. Figure 1 displays the historical and forecast urban population by area from 1950 to 2050. Concomitant with the general escalation in population and the ongoing transition from rural to urban environments, the proportion of greenhouse gas (GHG) emissions emanating from urban areas has risen from approximately 62% in 2015 to around 70% in the present day. This shift has propelled urban-related emissions to an unprecedented peak, reaching nearly 29 billion tonnes of CO2 in 2023 [16-21].

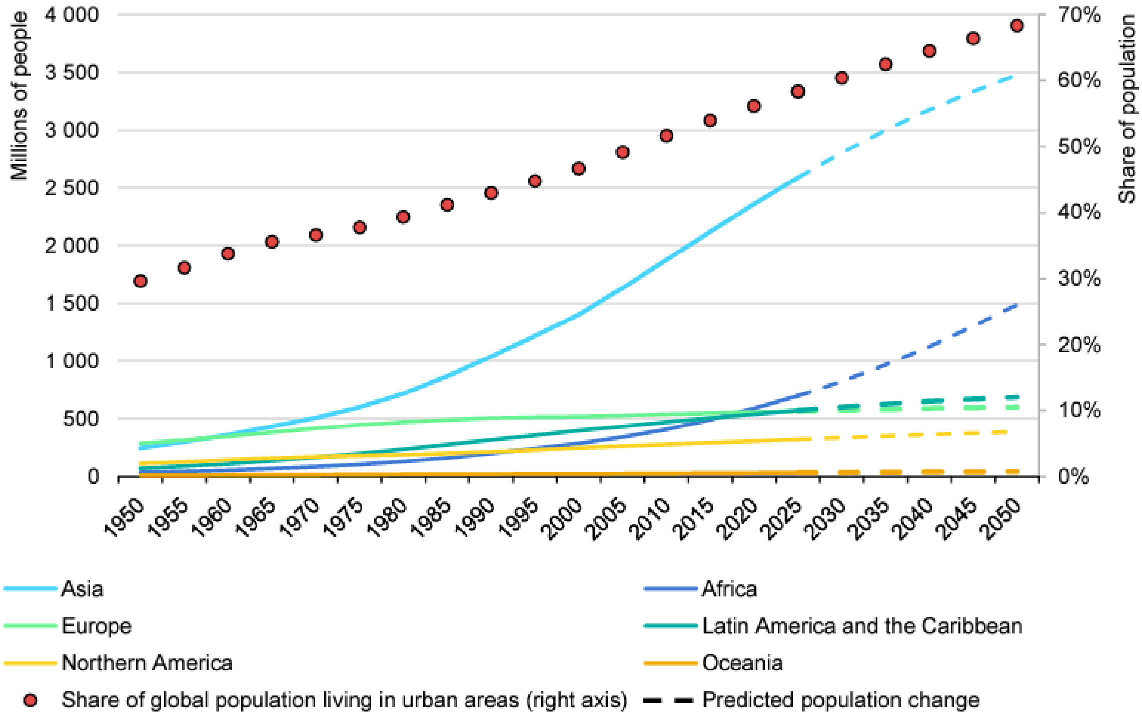

Figure 1. The historical and forecast urban population by area from 1950 to 2050.

Numerous cities have emerged as vanguards in their national climate strategies, spearheading efforts to attain net-zero emissions prior to the timelines established by nationally determined contributions. For instance, London has set an ambitious objective to achieve carbon neutrality by 2030. In 2023, the city expanded its ultra-low emission zone to encompass the entire Greater London area, significantly contributing to the reduction of air pollution. Similarly, Vienna has unveiled a revised smart city strategy aiming for climate neutrality by 2040, with intermediate targets that include reducing per-capita energy consumption, greenhouse gas emissions, and the material footprint. This strategy prioritizes human-centric values, emphasizing inclusion and equality, and fostering participation and active engagement [22-24].

Moreover, Vienna has facilitated avenues for its residents to collectively invest in renewable energy through community-funded solar energy projects. In this direction, multilateral forums persistently acknowledge the critical role that cities play in the advancement of net zero energy systems. The 2021 G20 Energy-Climate Ministerial Communiqué, held in Naples, Italy, underscored the significance of urban areas in expediting the transition to clean energy. Additionally, the 2023 G7 Ministers' Meeting on Climate, Energy, and Environment, which took place in Sapporo, Japan, concluded with a groundbreaking announcement: the inaugural G7 Roundtable on Subnational Climate Actions, developed in collaboration with Urban7. The communiqué issued by the G7 Ministers at the conclusion of this meeting emphasized "the vital role of subnational actors in realizing the transformation toward net zero," highlighting their indispensable contribution to global climate objectives [25-27].

Smart grid technologies are essential components of sustainable urban development, offering solutions to many of the energy challenges faced by growing urban populations. This contribution explores how smart grid technologies can enhance the efficiency, reliability, and sustainability of urban energy systems, thereby facilitating more resilient and adaptable urban environments [28-31]. Figure 2 illustrates the diagram of a conventional smart grid. Smart grids incorporate advanced technologies that allow for more efficient transmission and distribution of electricity. This reduces energy waste, lowers costs, and decreases greenhouse gas emissions, aligning with broader environmental and sustainability goals. Urban areas are particularly vulnerable to power outages due to high demand and complex infrastructure systems.

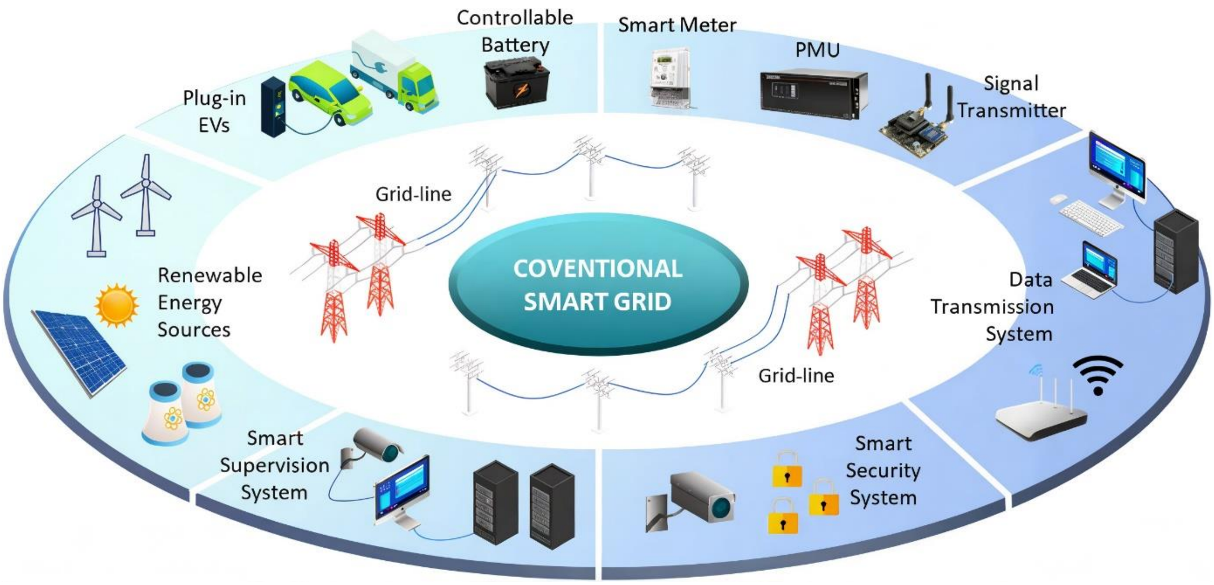

Figure 2. The diagram of a conventional smart grid.

Smart grids enhance reliability through self-healing technologies that can detect, diagnose, and respond to faults automatically, minimizing outage times and impacts. Smart grids facilitate the integration of renewable energy sources, such as solar and wind, into the urban energy mix. Smart grid technologies support urban policies aimed at sustainability and climate resilience. They provide cities with the tools to implement dynamic pricing, manage electric vehicle charging networks, and develop new regulatory frameworks for energy trading and carbon credit systems.

There are numerous studies focusing on the integration of Smart Grid technologies within the framework of sustainable urban development. These studies typically examine how Smart Grids can enhance energy efficiency, reliability, and sustainability in urban settings. They explore the deployment of advanced metering infrastructure, demand response, distributed generation, and renewable energy integration, all crucial for reducing urban carbon footprints and improving city-wide energy management. According to Dorji et al., [32] the multifaceted dimensions of climate change coupled with escalating energy requirements necessitate a paradigm shift towards energy efficiency and environmental stewardship on a global scale. Unchecked, the burgeoning demand for energy spurred by technological advancements in urban and national infrastructures will likely spiral into a crisis. A potential resolution to this impending energy dilemma is the deployment of an advanced, bidirectional digital power flow system. This system, characterized by its self-healing capabilities, interoperability, and capacity to anticipate variable conditions amidst uncertainties, is also fortified with robust cyber defences to thwart malicious intrusions. The smart grid facilitates seamless integration of renewable energy sources—such as solar, wind, and energy storage solutions—into the existing grid framework. Consequently, the conceptualization of the smart grid and the significance attributed to it by researchers and policy makers is critical for its adoption and effectiveness.

In this paper [33], the researchers explore the potential impacts of emerging technologies, including Smart Grids and nanotechnology, on reducing carbon emissions. The discussion centers on the essential characteristics and capabilities required for Smart Grids to enhance energy efficiency. Additionally, the enabling technologies and anticipated advantages these innovations offer are examined. The evidence presented in this review indicates that recent advancements position the Smart Grid as a crucial component of future clean energy strategies. Concurrently, nanotechnology is projected to become essential for the full maturation and operational optimization of the Smart Grid in the near term. This convergence of technologies underscores their pivotal role in shaping sustainable energy systems and mitigating environmental impacts.

In [34], the authors address the challenges associated with the scarcity of alternative fuels in developed regions and explore how new smart grids can evaluate their environmental impact. The analysis demonstrates that integrating both non-renewable and renewable energy sources through smart grid technology can significantly mitigate environmental hazards and reduce production costs. The smart grids are designed to provide reliable, secure, and cost-effective power grid functions by efficiently coordinating power sharing among various renewable energy sources, which are both freely accessible and economically viable. This article offers a thorough review of the conceptual model, objectives, architecture, potential benefits, and challenges of power grids with a comprehensive understanding of the various stakeholders and entities involved in the global scenario. Additionally, the article provides an extensive examination of energy and transmission issues, focusing on smart grids and the obstacles they face, offering insights into both the technological and infrastructural dimensions.

The shift towards a low-carbon and sustainable energy framework is critical for addressing climate change and securing the future sustainability of the global energy sector. Smart grid technologies are increasingly recognized as pivotal in driving this transformation. This research [35] delves into the complex effects of smart grid technologies on the evolving energy industry and assesses how various policies and regulations are guiding its progress. The study highlights the role of smart grids in enhancing energy efficiency, enabling renewable integration, and ensuring reliable energy supply, while also considering the regulatory landscape that supports or hinders these technological advancements. The analysis provides insights into the interplay between technological innovation and policy frameworks, crucial for fostering a resilient and sustainable energy system.

The principal contribution of this research [36] is the provision of a novel methodology for developing future-oriented models of sustainable urban growth, along with actionable insights for crafting strategic planning processes that foster transformative change towards sustainability through integrated approaches. The model proposed in this study aims to expedite progress towards the long-term sustainability objectives for cities that are either branding or rejuvenating themselves as eco-cities, or are explicitly planning to evolve into smart eco-cities in the age of big data. This comprehensive model not only guides urban development but also aligns with the evolving dynamics of urban sustainability in a data-rich world.

This paper [37] presents the multi-layer perceptron-Extreme Learning Machine (MLP-ELM) methodology designed to forecast the sustainability of smart grids. The study also employs principal component analysis (PCA) to extract relevant features, enhancing the predictive capabilities of the MLP-ELM model. Through empirical evaluation and comparative analysis with other methods, this research delineates the implementation outcomes pertaining to smart grid stability. The simulation results validate the superiority of the MLP-ELM approach over conventional machine learning techniques. Notably, the MLP-ELM model achieves an impressive accuracy of up to 95.8%, with a precision of 90%, a recall of 88%, and an F-measure of 89%, demonstrating its effectiveness in predicting smart grid sustainability and operational stability.

In [38], global concerns about environmental conservation and energy sustainability are intensifying, driven by the escalating energy demands and the pervasive impacts of climate change. In response, technological advancements in smart grids, edge computing, and Metaverse-based applications highlight the deficiencies of traditional private power networks in meeting the rigorous needs of industrial applications. The distinctive features of 5G technology, including its capacity for numerous connections, high reliability, low latency, and extensive bandwidth, render it particularly suitable for smart grid applications. As the 5G network sector expands, it will increasingly depend on the Internet of Things (IoT) to advance, positioning IoT as a pivotal component in the evolution of future smart grids.

The contribution of this article commences with the definition of a Smart Grid, drawing on the definitions provided by IEEE, IEC, and the U.S. Department of Energy. Additionally, the article examines the impacts of a changing climate and energy system. To achieve carbon emissions reduction, substantial financial investment is necessary, with projections indicating an annual requirement of USD 25 billion. Of this amount, USD 22 billion is earmarked for the development and enhancement of power grids, particularly focusing on distribution networks. Subsequently, the article scrutinizes the role of grids in urban energy transitions. It is projected that global distributed photovoltaic (PV) capacity will increase more than 7.5 times by 2028 relative to 2018 levels. In Latin America, this growth is anticipated to be even more pronounced, with an expected increase of 68 times. Nigeria is expected to add 5 GW of distributed solar PV capacity within this timeframe, while Angola and Kenya are each projected to add 2 GW. Brazil is poised to deploy 7 GW annually up to 2028. In contrast, global sales of electric vehicles (EVs) have surged remarkably, rising from approximately 6.5 million units in 2021 to 13.7 million units in 2023. This growth marks a significant acceleration compared to the modest increase of 950,000 units from 2018 to 2020. By 2022, the global stock of electric cars reached around 27 million units. The article anticipates a substantial expansion in the global EV fleet, with an increase to nearly 230 million units by 2030. Furthermore, the transition to a more flexible and resilient power grid increasingly relies on innovative technologies such as batteries, various forms of energy storage, and demand response mechanisms. These technologies are pivotal for dynamically balancing power supply and demand.

Section 2 elucidates the conceptual framework and defining characteristics of smart grids. **Section 3** delineates the ramifications of climate change and evolving energy systems. **Section 4** explores the pivotal function of grids within the context of urban energy transitions. **Section 5** examines the prospects for sustainable energy transitions in metropolitan areas. **Section 6** addresses the necessity for novel sources of flexibility in future grid systems. **Section 7** provides a comprehensive conclusion.

2. Definition of Smart Grid

The term "smart" typically denotes qualities such as intelligence, efficiency, cleanliness, orderliness, or automation, while "grid" refers to a network designed to deliver electricity to consumers. Currently, there is no universally accepted definition of a smart grid, allowing for both simplistic and complex interpretations of the concept. In layman's terms, a smart grid might be colloquially described as "electricity with a brain." However, the National Institute of Standards and Technology (NIST) in the United States provides a more technical definition, stating that a smart grid is as follows [39]:

"A modernized electric grid that enables bidirectional energy flows and uses bidirectional communication and control capabilities that will lead to a range of new functionalities and applications".

The IEEE definition of a smart grid is [40] "A revolutionary endeavor-with new communications and control capabilities, energy sources, generation models, and compliance with cross-jurisdictional regulatory structures".

The IEC definition of a smart grid is [41,42] the following:

"It is a power grid that can intelligently integrate the actions of all connected users-generators, consumers, and those who do both-to efficiently provide a sustainable, economical, and secure power supply".

According to the U.S. Department of Energy, a smart grid is defined as "A smart grid uses digital technologies to improve the reliability, security, and efficiency (both economic and energy) of the electric system-from large-scale generation to utility systems to electricity consumers and a growing number of distributed generation and storage resources" [43,44].Based on the provided descriptions, the smart grid can be conceptualized as an advanced infrastructure that facilitates a bidirectional flow of energy and information. These dynamic enables utility companies to efficiently manage the transmission and distribution of energy, while simultaneously empowering consumers to actively participate in energy-related decisions [45,46]. The smart grid leverages real-time communications and data from information technology to maintain an equilibrium between energy demand and supply. The primary distinction between a smart grid and a traditional power grid lies in the smart grid's capability for bidirectional energy exchange and reciprocal knowledge transfer between utilities and consumers [47-48]. Enhancements associated with the smart grid include improved reliability and infrastructure efficiency, economic growth, and fortified defenses against cyber threats and power disruptions. Hence, a working definition of the smart grid might be articulated as follows: A smart grid is a sophisticated, digital communication system within the electric power flow, characterized by its self-healing capabilities, interoperability, and predictive abilities under varying conditions of uncertainty, all while being equipped with cybersecurity measures to deter malicious attacks [49,50].

3. Impacts of a Changing Climate and Energy System

Power grids across numerous countries have increasingly been strained to their operational limits in recent years, a situation exacerbated by climate change-related challenges. These grids have frequently been pushed beyond their limits, resulting in supply disruptions due to events like storms, as observed in the United States, Europe, and Japan. The power sector also grapples with disruptions from extreme temperatures, amplifying concerns in regions where electricity demand is highly sensitive to sudden increases in the need for heating and cooling—demands primarily met through electricity [51-53].

Moreover, urban areas are particularly affected by these grid-related challenges, with approximately 70% of cities already experiencing adverse impacts. Some studies forecast a tripling of peak electricity demand in urban settings by 2030, particularly if the decarbonization of heating and transport systems advances rapidly before the grids can adapt to these heightened demands. While cities represent critical nodes where grid adaptation needs are most pronounced—especially at the lower-voltage distribution levels [54-58]—they are also increasingly becoming focal points for providing grid flexibility [59-64]. This dual role underscores the importance of enhancing grid resilience and incorporating adaptive measures to manage and mitigate the evolving demands on urban power systems [65-68].

In an evolving trend, some cities that traditionally experienced a single period of peak electricity demand are now encountering a second peak period. In cooler climates, the decarbonization of heating systems is driving up electricity demand during the winter months, leading to higher peaks during cold spells. Historically, in the United States, peak demand periods occurred during the summer; however, many states are now projected to transition to winter peaking systems. A notable example of this shift was evident in February 2021, when Texas experienced a record-setting winter storm. This extreme weather event led to power outages that affected more than 4.5 million homes and disrupted public water and heating systems [69-72]. The storm impacted nearly 15 million people across the state and is considered the costliest winter storm on record, with damages exceeding USD 20 billion [73-75]. Concurrently, as global average temperatures continue to rise, there is an increasing demand for cooling systems during prolonged heatwaves. This surge in cooling demand adds another layer of complexity to managing electricity grids, particularly in regions that are simultaneously dealing with the challenges of integrating renewable energy sources and upgrading infrastructure to handle diverse peak demand scenarios [76-82].

Climate change is intensifying extreme weather events globally, with record-breaking heatwaves, storms, floods, droughts, and wildfires becoming increasingly frequent and severe. These events are having pronounced impacts on the reliability of power supplies. Clearly, 2023 was recorded as the hottest year, with summer temperatures soaring above 50°C in the United States, the Middle East, and China. Europe has emerged as the fastest warming continent. This surge in temperatures is reflected in consumer behavior; for instance, online sales data from China in June 2023 showed a nearly 70% year-on-year increase in air conditioner sales, indicating a robust response to rising temperatures. The trend of escalating temperatures continues, as evidenced by 2024 beginning with the warmest January and February on record, extending a streak of nine consecutive months of record highs. This ongoing increase in extreme temperatures globally is driving a corresponding rise in cooling needs, highlighting the growing demand for energy solutions that can efficiently meet these challenges while mitigating environmental impacts [83-87]. Figure 3 displays the global energy consumption by region from 2000 to 2022, measured in exajoules (EJ), alongside the corresponding total carbon emissions, indicated by circles on the right axis, measured in gigatonnes of CO2 (Gt CO2).

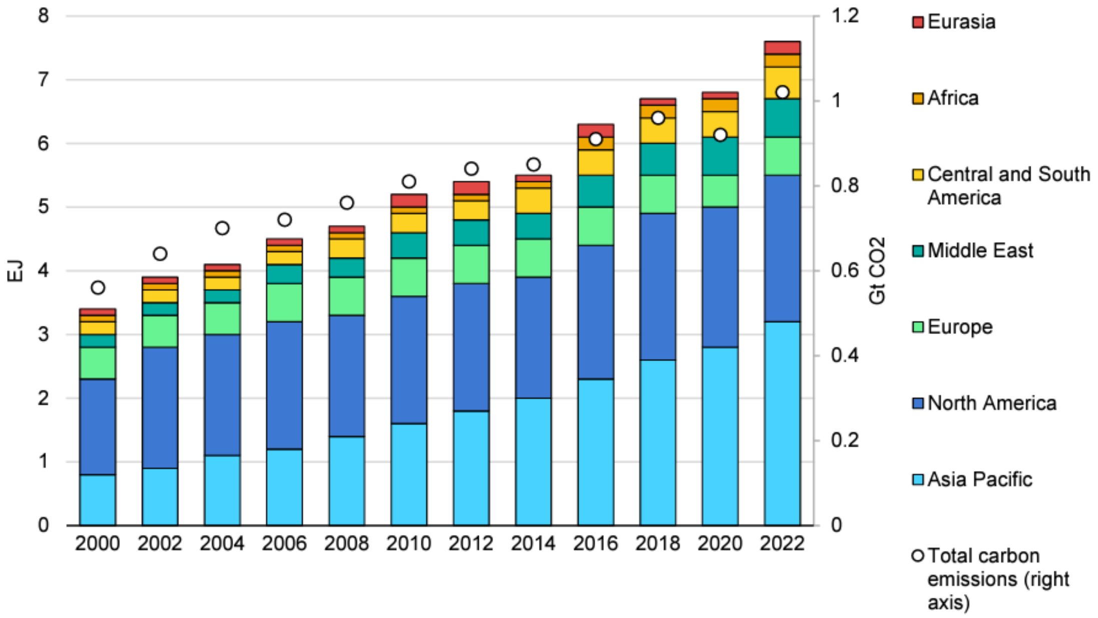

Figure 3. The final energy consumption and carbon emissions resulting from space cooling, categorized by region, for the years 2000 to 2022.

Between 2000 and 2022, the global final energy demand for space cooling increased by an average of approximately 4% per year, a rate that is double that of the increase for water heating. The number of residential air-conditioning units has also seen a significant surge, tripling since 2000 to reach over 1.5 billion units by 2022. This sharp rise is largely driven by extreme heat, which significantly boosts the purchase of air conditioners and leads to increased electricity demand. In the hottest regions, the electrical grid must be capable of supporting a doubling of electricity demand compared to milder months, with cooling often accounting for more than 70% of peak electricity demand. The impact of temperature on electricity demand varies significantly by region due to differences in air conditioner penetration [88].

For instance, in India, where air conditioner ownership remains relatively low, each 1°C increase in the average daily temperature above 24°C results in a roughly 2% increase in electricity demand [89]. Conversely, in Texas, where air conditioner ownership is much higher, the same temperature increase leads to a 4% surge in demand [90]. A comprehensive assessment across 13 cities in various countries indicates that each degree of temperature increase typically causes an average increase in peak electricity demand of almost 4%. This data underscores the critical need for power systems to adapt to the increasing demands imposed by higher temperatures and more widespread air conditioning usage.

Sub-Saharan Africa is currently home to 80% of the global population without access to electricity, a challenge that extends beyond rural communities to include urban areas as well. To attain universal access to reliable electricity across the continent by 2030, it is estimated that approximately 20 million people in urban areas would need to be connected each year starting from 2022 [91,92]. Achieving this goal would necessitate substantial financial investment. Specifically, it is projected that an annual investment of USD 25 billion is required, with USD 22 billion of this total dedicated to the development and enhancement of power grids, particularly focusing on distribution networks [93]. This investment is critical for expanding electricity access and ensuring that it meets the needs of a growing urban population. While mini-grids have proven to be a vital solution for providing electricity and enhancing resilience in rural communities, grid-based electricity services are essential in urban settings. Table 1 presents the major findings from recent studies on the effects of a shifting climate and energy system on a global scale.

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

Ref.	Year	Key findings	Region
[94]	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.	China
[95]	2024	▪ 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.	Saudi Arabia
[96]	2024	▪ 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.	Germany
[97]	2024	▪ 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.	Canada
[98]	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. If all existing wind, solar, and	Africa

hydropower plants operate at full capacity and all proposed plants are implemented, 76% (1,225 TWh) of the projected electricity needs for 2040 (a total of 1,614 TWh) could be met by RE sources. This includes 82% from hydropower, 11% from solar power, and 7% from wind power.

- Hydropower has been the predominant RE resource. However, the substantial decline in costs for solar photovoltaics (90% decline since 2009) and wind turbines (55–60% decline since 2010) indicates that solar and wind energy have the potential to lead the sustainable RE pathways in the future, while simultaneously protecting freshwater ecosystems.

To mitigate and address the challenges related to environmental insecurity, it is imperative for the global community to implement prompt and effective measures to safeguard the climate, ensuring a more promising future. This entails actively seeking alternative energy options while reducing reliance on petroleum-based energy sources. In response to this pressing issue, the research aims to demonstrate the capabilities of various renewable energy sources (RES), including wind, solar, hydroelectric, and biomass. The study [99] begins with a brief overview of energy-related issues and prospects, followed by a comparative analysis of RES and non-RES. It provides a comprehensive overview of several Sustainable Energy Sources (SES), such as wind, solar, hydroelectricity, and biomass, supplemented with relevant illustrations and statistical data on the global energy potential of each source.

In [100], the article highlights the significant decrease in the cost of solar photovoltaic energy, which has dropped from $0.417 per kilowatt-hour in 2010 to just $0.048 in 2021. Similar reductions have been observed in the prices of onshore wind (68%), offshore wind (60%), concentrated solar power (68%), and biomass energy (14%). The article also finds that wind energy and hydropower production could decline by as much as 40% in some regions due to environmental changes, whereas solar energy remains relatively less affected. Despite these challenges, renewable energy sources hold the potential to decarbonize up to 90% of the electricity sector by 2050.

The paramount sustainability challenge confronting humanity today is greenhouse gas emissions and global climate change, primarily driven by fossil fuels such as coal, natural gas, and oil, which accounted for 61.3% of global electricity generation in 2020. The cumulative outcomes of the Stockholm, Rio, and Johannesburg conferences have underscored sustainable energy development (SED) as a crucial element in achieving sustainable global development [101].

The research [102] investigates the relationship between the adoption of electric vehicles (EVs) and clean energy technologies and their subsequent impact on carbon footprints. Utilizing the Generalized Method of Moments (GMM) on data from the International Energy Agency (IEA) and the World Development Indicators (WDI) for the period 2011–2021, encompassing 27 countries, the study reveals a significant correlation between EV adoption and reductions in carbon footprints. Specifically, the findings indicate that a 1% increase in renewable electricity output corresponds to a 0.5% decline in carbon footprints.

According to [103], the commitment to decarbonizing economies, which entails replacing fossil fuels with renewable energy sources (RES) and electrifying transportation and heating to combat global warming and climate change, will result in a significant increase in global electricity consumption. Therefore, it is imperative that the electric power sector incorporates the principles of sustainable development into its operations. Additionally, events such as the recent European gas crisis, which arose from the large-scale deployment of renewables, must be thoroughly studied and mitigated. the article aimed to evaluate the role of renewable energy in the sustainable development of the electrical power sector. Furthermore, the article also addressed the impact of renewables on utility operations and their benefits to the grid.

4. The Role of Grids in Urban Energy Transitions

Ensuring the adequacy of power grids is essential for achieving decarbonization goals. Electrification plays a pivotal role in diminishing the reliance on fossil fuels, complemented by enhancements in efficiency and the augmented adoption of low-emissions fuels. The expanding role of electricity within the energy mix necessitates substantial adjustments to power systems. Load-based indices prioritize assessing the connected load (measured in kVA) instead of the number of customers. These indices are particularly valuable for evaluating system performance in regions that serve a small number of customers but have substantial demand concentrations, typically from industrial or commercial sectors. The most frequently used load-based indices are the Average System Interruption Frequency Index (ASIFI) and the Average System Interruption Duration Index (ASIDI). In environments where the load distribution is homogeneous, ASIFI and ASIDI are expected to correspond with SAIFI and SAIDI, respectively.

$$\text{ASIFI} = \frac{\sum \mathit{Connected\ kVA\ of\ Interrupted\ Load}}{\sum \mathit{Connected\ kVA\ \ Served}} \tag{1}$$

$$\text{ASIDI} = \frac{\sum \mathit{Connected\ kVA\ Duration\ of\ Interrupted\ Load}}{\sum \mathit{Connected\ kVA\ \ Served}} \tag{2}$$

In 2023, electricity accounted for 20% of the total final energy consumption; projections suggest that this proportion will surpass 50% by 2050 [104,105]. Consequently, power systems must undergo extensive transformations to accommodate these evolving demands. Figure 4 displays 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.

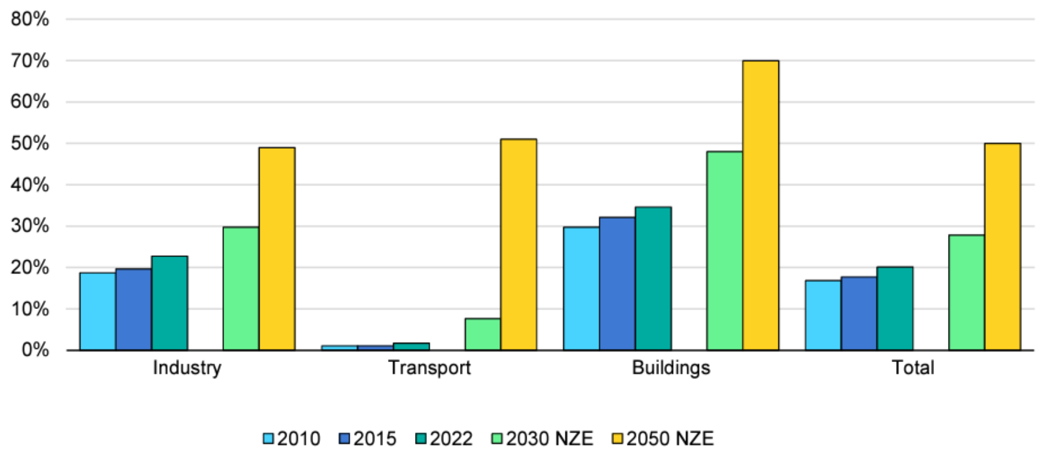

Figure 4. The proportion of electricity in the total consumption of energy for different sectors from 2010 to 2022, as well as in the NZE Scenario for 2030 and 2050.

Indications that the transition towards net zero is gaining momentum are evident, particularly through the rapid adoption of efficient electric vehicles (EVs) in numerous cities [106-109]. In 2023, the sales of new EVs were estimated to be 35% higher than the previous year [110-114]. This trend in EV ownership is anticipated to persist, alongside an increase in the deployment of electrical equipment, such as heat pumps and air conditioners, and distributed energy generation systems, including rooftop solar photovoltaic (PV) installations. These developments are expected to continue escalating in the forthcoming years, reflecting a robust commitment to sustainable energy practices within urban settings [115-122].

Global sales of electric vehicles (EVs) have exhibited a remarkable surge, escalating from approximately 6.5 million units in 2021 to 13.7 million units in 2023. This growth represents a significant acceleration compared to the modest increase of 950,000 units from 2018 to 2020. By 2022, the worldwide stock of electric cars reached around 27 million units. Projections suggest a substantial expansion in the global EV fleet, with an anticipated increase to nearly 230 million units by 2030 under the International Energy Agency's Announced Pledges Scenario (APS). This growth is primarily driven by significant contributions from China. Furthermore, in the more ambitious Net Zero Emissions (NZE) Scenario, the global stock of electric cars could rise to as much as 315 million units, underscoring the accelerating momentum towards electrification in the automotive sector.

The International Energy Agency's [115] report forecasts a robust expansion in renewable energy capacity, with nearly 3,700 GW of new capacity expected to be installed between 2023 and 2028. This growth is propelled by favorable policies in over 130 countries. While mature markets continue to expand, significant increases are also projected in emerging markets and developing economies. Specifically, global distributed photovoltaic (PV) capacity is projected to increase more than 7.5 times by 2028 relative to 2018 levels. In Latin America, this growth is even more pronounced, with an expected increase of 68 times. Nigeria is slated to add 5 GW of distributed solar PV capacity within this timeframe, while Angola and Kenya are each anticipated to add 2 GW. Brazil is on track to deploy 7 GW annually up to 2028. An obvious trend is the rapid escalation of residential solar installations, especially in Latin America. In this point, the proportion of residential solar PV in the total distributed capacity—which includes commercial, industrial installations, and off-grid solutions—is expected to nearly double, reaching 58% by 2028. This shift highlights the increasingly significant role that residential solar is playing in the broader context of renewable energy deployment across various regions.

5. Opportunities for Sustainable Energy Transitions in Cities

Local governments exert considerable authority in defining urban sustainability via urban planning and policy formulation. By endorsing policies that promote intelligent and inclusive sustainable energy solutions, these governments cultivate resilient communities and contribute to climate change mitigation. Initiatives such as district-wide renewable energy deployment and the adoption of low-emission transportation policies facilitate the rapid uptake of clean energy within urban settings. Additionally, cities are instrumental in enacting resilient power strategies and incorporating clean energy solutions into regulatory frameworks, thus enabling socially inclusive energy transitions. The subsequent examples illustrate the proactive engagement of cities in fostering a more people-centered approach, while simultaneously advancing national climate objectives.

Municipal governments have the capacity to enact policies that facilitate smart and inclusive sustainable energy solutions, enhancing urban resilience and environmental sustainability. These policies can support the deployment of renewable energy on a neighborhood or district scale and the implementation of low-emissions transportation strategies. Additionally, community bulk buying programs can expedite the integration of energy efficiency measures and the adoption of local renewable energy sources. A noteworthy example from 2023 is Rio de Janeiro, which became the first Latin American city to utilize a renewable power purchase agreement (PPA) to supply public buildings with clean energy through the Río de Energía Verde Initiative.

This agreement establishes a long-term contractual relationship between the city and a renewable energy producer, enabling the municipality to secure stable electricity prices and advance its environmental goals, while providing the developer with predictable revenue streams and simplifying the operation of the generation facility. This initial phase of the project is anticipated to prevent the emission of 40,000 tonnes of CO2 over the next five years and to generate over USD 6 million in electricity cost savings, which will be allocated to health and education initiatives. In Indonesia, the expansion of the TransJakarta bus system between 2016 and 2020, which included tripling its routes and doubling its fleet, enabled the bus rapid transit system to serve one million passengers daily by 2020. The goal of fully electrifying the bus fleet by 2030 is projected to increase life expectancy by an additional four days for residents within the service area, demonstrating the significant health and environmental benefits of transitioning to sustainable transportation solutions.

Cities play a pivotal role in facilitating clean energy transitions by embedding smart and sustainable energy solutions within their regulatory frameworks and building codes. For instance, Vancouver has mandated that every residential parking space in new developments be equipped with Level 2 electric vehicle (EV) charging outlets. This regulation specifically targets the challenge of accessing EV charging infrastructure in multifamily residential buildings, a task that is typically more complex than in single-family homes. Furthermore, cities can leverage their collective purchasing power by acting as aggregators of demand. By procuring clean electricity in bulk for the combined needs of their residential and business communities, cities can enhance competition, mitigate risk, and secure more favorable electricity rates for their inhabitants. This strategic approach not only promotes the adoption of clean energy but also supports economic efficiency and sustainability at the local level.

Cities can enhance their planning functions by utilizing geographical information systems (GIS) to map out renewable energy potential at the city level, which helps in identifying optimal locations for distributing network infrastructure. This advanced mapping can guide strategic decisions regarding the placement and development of renewable energy installations, ensuring that they are both efficient and effective in meeting the energy demands of urban areas.

An illustrative example of this approach is the Clean Energy Program initiated by the New York City government, which is dedicated to increasing the deployment of solar photovoltaics (PV) and other distributed energy resources across its array of public buildings. The program has set an ambitious target to install 100 MW of solar PV on city-owned buildings by 2025. In pursuit of this goal, New York City conducted a comprehensive assessment of all public buildings exceeding 1,000 gross square meters to evaluate their solar readiness, ultimately identifying nearly 55 MW of feasible rooftop solar potential. This proactive assessment underscores how cities can leverage their own assets to advance renewable energy goals, reduce carbon emissions, and lead by example in the transition towards sustainable urban energy systems.

Cities have the capacity to formulate resilient power strategies that ensure continuous operation of both public and private critical facilities during power disruptions. Implementing resilient power technologies, such as solar panels paired with battery storage, can significantly mitigate the impact of power outages on essential services and infrastructure. For example, in response to increasing frequency and intensity of heatwaves, the city of Utrecht in the Netherlands has been actively expanding its vehicle-to-grid (V2G) infrastructure. This innovative system allows electric vehicles (EVs) to store electricity during periods of low demand (typically midday when solar generation peaks) and then feed this power back into the grid during evening peak hours, when demand is higher. This initiative aims to connect approximately 10,000 bidirectional charging EVs to the grid, which is the number estimated by Utrecht University to be necessary to alleviate the city’s grid congestion issues. Similarly, Cape Town in South Africa, which faced over 100 days of rolling blackouts in 2022, is seeking to bolster its energy resilience. The city is collaborating with the C40 Cities Finance Facility to establish a large-scale solar power plant. This project aims not only to reduce dependence on the unstable national grid but also to enhance Cape Town’s overall energy security, demonstrating a proactive approach to addressing energy challenges in urban settings.

6. Future Grids Need New Sources of Flexibility

Currently, dispatchable thermal power plants and pumped hydropower, which remains the largest source of renewable energy, play pivotal roles in providing the necessary flexibility within power systems. Flexibility, fundamentally, refers to the capacity of power systems to adjust promptly to fluctuations in electricity supply and demand. As the global energy landscape transitions towards lower carbon sources, the role of thermal power plants is set to diminish due to environmental concerns and regulatory changes aimed at reducing greenhouse gas emissions. This anticipated decline in thermal power generation underscores the need for new sources of flexibility to ensure grid reliability.

To address this, it is essential to integrate alternative flexible energy solutions such as battery storage, demand response technologies, and further development of renewable energy sources like solar and wind, which can be complemented by energy storage systems. Additionally, advancements in grid technology, including smarter grid management systems and enhanced interconnectivity, can facilitate the seamless integration and management of diverse energy sources, thereby maintaining stability and reliability in the power grid as the role of traditional thermal plants diminishes.

The transition to a more flexible and resilient power grid increasingly relies on innovative technologies such as batteries, other forms of energy storage, and demand response mechanisms. These technologies are crucial for balancing power supply and demand dynamically. Demand response is a strategy that involves adjusting consumer electricity usage patterns to better align with periods of high energy availability or lower overall demand. This not only helps in stabilizing the grid but also in making energy use more efficient and cost-effective for consumers. Electricity storage, particularly through batteries, plays a pivotal role in enhancing grid flexibility. These batteries can be categorized into two types:

- Distributed (behind-the-meter) batteries: Typically installed in residential or commercial settings, these systems allow for energy storage at the point of consumption. They can store excess power generated during peak production hours (often from solar PV systems during the day) and release it during peak demand times in the evening.
- Grid-scale battery installations: These larger systems are crucial for managing energy at a macro level, helping to absorb and redistribute energy across the grid. This capability is particularly important in power systems with a high penetration of renewable sources like solar PV, which tend to generate power intermittently based on weather conditions.

Another aspect of grid flexibility, though less desirable, is curtailment. This involves the deliberate reduction of power output from renewable sources when the energy produced exceeds the grid's capacity to absorb or when demand is low. Curtailment serves as a measure to prevent grid instability but is generally seen as a wasteful practice since it does not utilize the renewable energy being generated. Together, these systems form a critical backbone for modern power systems, facilitating the integration of renewable energies, enhancing grid stability, and promoting more sustainable energy consumption patterns. Figure 2 illustrates the requirements and availability of power system flexibility on a global scale.

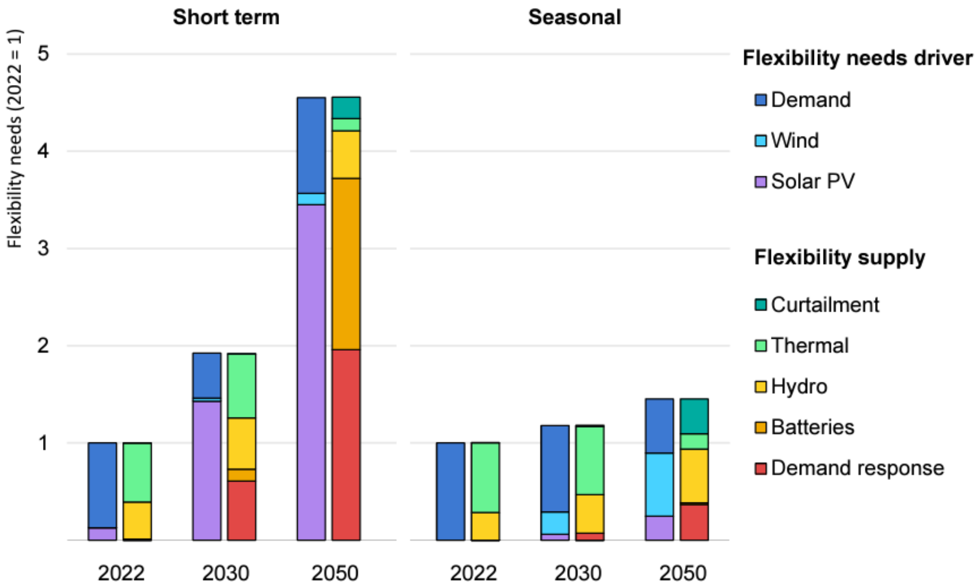

Figure 5. The requirements and availability of power system flexibility on a global scale.

While the overall incidence of curtailment is on the rise in numerous countries, the proportion of wind and solar PV generation that goes unused is still relatively low. Curtailment rates typically hover between 1.5% to 4% in most major renewable energy markets. These rates tend to be higher in regions where there is a significant need for grid infrastructure expansion to adequately connect renewable energy installations with areas of high consumption.

In the United Kingdom, the financial repercussions of wind curtailment have become increasingly significant. In 2021, the cost associated with curtailing wind power production reached a record high of over GBP 500 million. The following year, consumers paid GBP 215 million to deactivate wind farms. These substantial costs highlight the missed opportunities for energy utilization and economic efficiency. If the curtailed electricity had been stored and subsequently dispatched as needed, it could have saved nearly GBP 720 million, which was instead spent on purchasing gas-fired power to balance supply and demand discrepancies. This would not only have mitigated financial outlays but also prevented additional greenhouse gas (GHG) emissions associated with gas-fired electricity.

The ongoing electrification of various end uses presents novel opportunities for load shifting within urban environments, with electric vehicles (EVs) and electric heating and cooling systems playing pivotal roles. As cities and countries aim to transition towards a net zero energy system, the potential and necessity for implementing demand response strategies are becoming increasingly evident. Demand response involves adjusting or shifting energy consumption patterns to better align with electricity supply dynamics, particularly during periods of high renewable generation or low demand.

To effectively progress towards a net zero energy future, the scale of demand response needs to be significantly expanded. Estimates suggest that the contribution from demand response would need to increase to as much as 500 GW by 2030, representing a tenfold increase from the levels recorded in 2020. Achieving this level of demand response capability would not only help in managing the variability and intermittency associated with high shares of renewable energy sources but also play a crucial role in enhancing grid stability and efficiency, ultimately supporting the broader goals of energy sustainability and carbon neutrality.

In urban settings, where EV adoption is likely to create dense clusters of residential charging stations, the impact on local grids can be particularly pronounced, especially during peak demand periods. This clustering effect can lead to grid congestion, underscoring the need for local grid upgrades to accommodate the increased load. For instance, a cost-benefit analysis of EV deployment in New York highlighted the potential financial challenges associated with this transition. It estimated that an additional USD 2.3 billion in grid upgrades would be required unless peak demand is managed more efficiently. This analysis emphasizes the critical importance of strategic planning and investment in grid infrastructure to mitigate the impact of increased EV penetration and ensure a smooth transition to electrified transport systems within urban environments.

In Palo Alto, the ambitious goal set by the city's Sustainability and Climate Action Plan requires that 80% of all vehicles be electric vehicles (EVs) by 2030, translating to approximately 100,000 vehicles. This transition, while crucial for meeting environmental targets, presents significant challenges to the existing grid infrastructure. A recent impact study highlighted that, without substantial upgrades, over 95% of Palo Alto's low-voltage transformers would face overloading due to the increased demand from EV charging. This situation underscores the need for robust enhancements to the grid to accommodate such a significant shift towards electric mobility. Similarly, New York faces daunting challenges with its grid capacity, particularly during summer peak loads. These peak periods often find large urban areas struggling to manage the surge in electricity demand, including that from high EV usage. This issue is compounded in neighborhoods that typically suffer from underserved or outdated infrastructure, many of which are also identified as disadvantaged communities. The correlation between low grid capacity and disadvantaged communities highlights a broader issue of inequality in energy access and resilience, necessitating targeted investments not only to support the transition to electric vehicles but also to ensure equity in how these upgrades are implemented.

7. Conclusion

In conclusion, urban populations now constitute more than half of the current 8 billion people on Earth, with this proportion continuously rising. From 2015 to 2020, the global urban population increased by approximately 400 million, with over 90% of this growth occurring in cities within emerging markets and developing economies (EMDEs). By 2050, the urban population share is anticipated to rise from 56% today to around 70%, resulting in an increase of approximately 1.8 billion urban inhabitants. Projections indicate that urban land areas will expand by roughly 1 million square kilometres by 2050, a figure comparable to the combined land area of Japan, Germany, and Italy.

As global temperatures rise, the demand for cooling is increasing significantly. The installed capacity of space cooling equipment is projected to nearly double by 2030 from its current 850 GW, and then double again by 2050. This growing demand for cooling also drives peak electricity demand, presenting challenges for grid operators and raising access and affordability issues for consumers. By 2040, cooling is expected to account for 30% of peak electricity demand in ASEAN countries, predominantly in urban areas, up from approximately 10% today. Further studies indicate that each degree Celsius increase in temperature globally results in an average increase of almost 4% in peak electricity demand.

To remain aligned with international clean energy transition commitments, it is imperative to expedite the implementation of large-scale projects. Many regions are already encountering challenges during the planning phase, resulting in delays in deploying renewable energy. Currently, approximately 3,000 GW of renewable power projects are awaiting grid connection, and reports indicate that energy efficiency schemes are also stalling. Analysis reveals that due to outdated grid planning in certain European Union countries, over 200 GW of new solar capacity is being planned beyond what is accounted for in national grid plans, potentially leading to an infrastructure investment shortfall of at least EUR 5 billion.

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