The Sustainability Future of the Age of Electricity

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Abstract

This article examines the implications of rapid electrification of power demand and supply on energy sustainability, reliability, and accessibility. The upcoming Age of Electricity is generally positive for the Sustainable Energy Future, but there are potential threats that policymakers should be aware of.

The IEA's *World Energy Outlook 2024* report indicates a rapid global transition into the "Age of Electricity," driven by soaring power demand. Substantial new electricity requirements emerge across lighting, cooling, data centers, electrical appliances, and transportation sectors. From 2010 to 2024, electricity consumption grew annually at approximately 2.7%—nearly twice the rate of overall energy demand (IEA, 2024). Scenario analysis projects that unabated fossil fuels will be substantially replaced by clean electricity generation across nearly all sectors and regions. How will the electrification of energy demand and supply affect pathways toward a sustainable energy future? This article discusses potential opportunities and threats, following a "Sustainability, Reliability, and Accessibility" framework.

1. Sustainability

Electrification shapes the renewable energy revolution profoundly. By shifting end-use consumption from fossil fuels to electricity, electrification establishes a foundation for incorporating renewable options like wind, solar, and hydro power. Despite the reliance on coal and oil for power generation in many countries, end-use electrification is a crucial first step. This is why, even though China primarily depends on coal for electricity, promoting the penetration of electric vehicles is still regarded as an important strategy for energy transition. The economic logic, or assumption, behind this is that the demand-side electrification can motivate the supply-side transition. Market outlook and prospects shaped by the demand-side electrification, instead of policy incentives, are the most critical drivers for renewable energy investments and applications. This surge in electricity demand also sparks green technological and managerial innovation.

However, a potential threat is that the rapid increase in electricity demand may widen the supply gap, leading to greater dependence on fossil fuels in the energy structure. This demand-driven "lock-in effect" has three potential mechanisms. First, new coal or gas power generation infrastructure may be built to mitigate the energy gap. Once established, these facilities could continue to emit carbon for 30 years or even more, posing a significant threat to the decarbonization goal (Davis and Socolow, 2014). Second, the retirement of old non-renewable facilities may be delayed. Aging units typically exhibit lower thermal and carbon efficiency (Tong et al., 2018). If demand surges outpace new infrastructure deployment, average fleet age could increase. Third, the integration of a large number of variable renewable energy (VRE) units raises the demand for flexible generation. If ramping services are primarily provided by coal or gas units, the carbon emissions from these flexible plants could offset the environmental benefits of VRE integration.

Although renewable generation expansion hasn't fully met rising electrification needs, renewable capacity continues to accelerate rapidly. Global electricity demand increased by approximately 5,400 TWh from 2010 to 2020, representing an average annual growth rate of about 2.3%[1]. During this period, newly installed renewable electricity generation grew by roughly 3,312 TWh, achieving an average annual growth rate of approximately 6.0%[2]. Between 2010 and 2024, global solar photovoltaic capacity expanded 45-fold while wind power capacity grew sixfold.

While renewable energy growth globally is narrowing the electricity demand gap, regional heterogeneity requires careful assessment. Developing Asian nations like China and India are leading global energy transitions despite simultaneously building significant new coal-fired capacity (Wang et al., 2023). Conversely, geopolitical conflicts and volatile international energy prices have pushed Europe toward resurrecting coal power. These back-and-forths underscore significant uncertainties on the path toward a sustainable energy future. For instance, government-mandated energy policies and subsidies are essential for renewable energy's swift advancement. Yet this reliance implies that subsidy reductions could severely disrupt new energy investments and construction (Droste et al., 2024). Whether related technological innovation and diffusion advance rapidly enough to achieve market-competitive prices remains essential (Bretschger et al., 2017).

2. Reliability

The upcoming electrification era has significant implications for energy reliability and security. Electrifying both power generation and consumption increases socio-economic dependence on grid stability. The intermittency of VRE poses a key challenge for grid management. In April 2025, widespread areas in Spain and Portugal experienced an 11-hour power outage, severely disrupting business operations and daily activities. While investigations are ongoing to assess VRE's potential role in this incident, the event has cast a shadow across the renewable energy sector.

The rapid electrification amplifies the vulnerabilities of the power system. Existing software and hardware for electricity dispatch and voltage management may require modernization to address next-generation load challenges. Cascading risks in power networks indicate that localized disruptions, like sudden voltage loss, can rapidly escalate into system-wide crises. This is not exaggerated concern but a documented hazard: transient, unpredictable extreme weather events could disturb the delicate balance between electricity supply and demand on the grid (Liang et al., 2025). Within current technical frameworks, as increasing proportions of renewable generation connect to grids, matching scales of flexible units are needed for delivering ramping services. Thus, developing resilient grid systems through innovations and advancing clean flexibility solutions are core policy priorities.

Compared to rapidly expanding renewable capacity, the shortfall in clean flexibility provision solutions is more concerning. Grid-scale storage refers to technologies linked to power grid that store electricity for later use, which are urgently needed to handle hourly and seasonal fluctuations in renewable generation while maintaining network stability. The most widely used technologies are pumped-storage hydropower and batteries. Battery manufacturing costs have fallen sharply in recent years due to economies of scale from the electric vehicle boom. BloombergNEF data indicates that the global average turnkey storage system price in 2024 was US$165/kWh, approaching economic viability for large-scale commercial applications. However, the escalating geopolitical rivalries are intensifying competition for critical resources, particularly lithium, which may increase the costs of grid-scale storage in the future.

Building a resilient power system appears more urgent and challenging in developed economies for two reasons. First, developing nations' younger grid infrastructure allows lower-cost adoption of new resilience technologies, whereas developed countries face higher upgrade expenses and sunk costs. Second, liberalized electricity markets in some advanced economies complicate grid management with increased uncertainties, though developing countries are rapidly introducing similar market reforms. Currently, the relationship between electricity market structures and system resilience remains poorly understood, requiring further empirical investigation.

3. Accessibility

Electrification and growing power demand signify improved energy accessibility. Electricity-based low-cost appliances and infrastructure have substantially enhanced modern energy availability and affordability in the least developed and economically challenged nations and communities (Li et al., 2024). World Bank data indicate the population share with electricity access increased from 87% in 2015 to 92% by 2023. Even traditionally isolated regions now have electricity access opportunities thanks to leapfrog developments in off-grid technologies, distributed solar power, and modular systems.

There is a concern about whether swiftly increasing electricity demand could elevate electricity prices, compromising energy affordability. However, precisely answering this question is exceptionally difficult. Electricity markets and regulatory frameworks differ substantially across nations and regions. In countries and regions with advanced electricity markets like the United States and Europe, rising electricity demand may induce capacity shortages, increasing end-user electricity prices. Conversely, transitioning and emerging economies are typically featured by government-directed electricity market structures. In developing countries, cross-sector subsidies (industrial users subsidizing the residential sector) and other subsidies in different forms are widespread. For instance, in China, electricity prices are heavily regulated by the government. The government sets end-user electricity prices based on the generating costs (primarily influenced by coal prices) (Xiang et al., 2023). Therefore, even if demand growth influences electricity prices, the direct burden falls mainly on industrial users rather than households. Certainly, these costs would be passed on to consumers at the end of the day, but in a more gradual way. Institutional and policy shifts, such as electricity market liberalization and phase-outs of renewable energy subsidies, likely exert greater influence than demand expansion alone.

Heightened attention should target vulnerable economies and low-income communities. Electricity price adjustments could profoundly impact energy poverty and equitable energy access, where electricity expenditure growth outpaces household disposable income growth. Electrification presents an opportunity for achieving "universal modern energy accessibility" under the UN's SDG 7 framework. However, related progress may be jeopardized if inappropriate policy choices lead to soaring electricity prices, making power accessible but not affordable. This reflects a dilemma in governments' energy policy practice, particularly in economies reliant on fossil fuels. A rapid phase-out of coal and gas power systems could result in increases in electricity prices (Greenstone, 2024). Whether borne by businesses or households, these utility costs may ultimately have a negative impact on overall resident welfare, even when environmental benefits are considered.

4. Conclusion and discussion

Overall, electrification has a positive impact on energy sustainability and accessibility. It is important to note that there remains a significant gap in clean electricity, although this gap is narrowing. Thus, fossil fuel electricity sources, such as coal and gas, are still being constructed. For these new fossil fuel energy infrastructure, governments must balance the stranded asset costs of phasing out fossil fuel energy with committed emissions. More innovative insights are needed to optimize pathways for decarbonization. For example, recent research suggests that retrofitting coal-fired units for flexibility could reduce the costs of energy transition in coal-dependent countries (Wang et al., 2025).

The increasing share of variable renewable energy in the energy supply mix may impact energy reliability and security. Technological innovation and investment in resilient grids, energy storage, and clean flexibility provisions should be prioritized. Demand-side management and market-based peak-shifting policies are also crucial to help achieve load balancing with minimal welfare loss, such as through time-of-use pricing (Di Cosmo et al., 2014; Pon, 2017). In extreme situations, such as heatwaves, rationing measures should be considered to avoid systemic blackouts (Hao et al., 2025). Institutional reforms and contingency plans are needed to address potential energy security risks and the impacts of transitory shocks.

Electrification benefits a just energy transition, particularly as the costs of off-grid and distributed energy systems decrease and their widespread adoption, ensuring greater accessibility and affordability. However, economically challenged communities remain highly vulnerable to energy poverty. Targeted subsidies or transfer payment policies may help alleviate specific concerns without sacrificing the overall market efficiency.

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Notes

[1] Based on IPCC SSP2 scenario estimates.

[2] Data sourced from Energy Institute's Statistical Review of World Energy 2025.