Sustainable Energy For All: Bridging Consumption Gaps Between Urban And Rural Areas

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***Abstract*— Access to sustainable, reliable, and affordable energy remains a cornerstone of development and a key target of Sustainable Development Goal 7 (SDG7). Despite India's impressive progress toward universal electrification, significant disparities persist between urban and rural regions in terms of energy access, quality, and consumption. This study, *"Sustainable Energy for All: Bridging Consumption Gaps Between Urban and Rural Areas,"* employs a quantitative, data-driven approach integrating datasets from MoSPI Energy Statistics (2025) and the India Residential Energy Survey (IRES, 2020). Comparative analysis across major Indian states reveals that southern and western regions (Kerala, Tamil Nadu, Gujarat) exhibit near parity in electricity access, averaging over 23 hours of daily supply, while northern and eastern states (Uttar Pradesh, Bihar, Jharkhand, Haryana) experience deficits exceeding 3–5 hours. Regression and correlation analyses demonstrate that each 10% increase in renewable energy share corresponds with a 0.4-hour reduction in urban–rural supply gaps and a 20% decline in CO_2 intensity. Behavioral data indicate that energy awareness and appliance efficiency adoption significantly enhance sustainability outcomes. Predictive modeling further suggests that renewable decentralization and demand-side optimization can effectively close remaining gaps while minimizing environmental impact. The study concludes that equitable energy access requires integrated strategies—combining grid modernization, decentralized renewables, and community-based awareness initiatives—to ensure inclusive and low-carbon development in India.**

Keywords*— Sustainable energy, urban–rural disparity, renewable energy, electricity access, energy equity, India, SDG7.

I. Introduction

Access to sustainable, reliable, and affordable energy is a cornerstone of modern development and one of the central targets of Sustainable Development Goal 7 (SDG7) — "Affordable and Clean Energy". However, in the world, there is a great difference between urban and rural areas in terms of energy use and access to energy [1]. City dwellers tend to have a superior infrastructure, a well-developed energy delivery system, and more access to modern energy sources, whereas rural citizens still rely more on traditional fuels and have an unreliable or low supply of it [2]. Such disparities have very broad social equity, economic development and environmental sustainability implications.

The accessibility of energy between urban and rural households in developing countries like India is still large. Cities have reached near-universal electrification, and rural electrification rates, despite their improvement, continue to be of low quality, continuity, and reliability [3]. Energy and Resources Institute (TERI) estimates that over 90 percent of urban households rely mainly on electricity in lighting and appliances as opposed to less than 75 percent in the rural areas, with a huge percentage of the rural population still relying on biomass or kerosene as their basic sources of power. Moreover, the rural households use significantly less electricity per capita, about 9 kWh/month as opposed to 26 kWh/month in urban areas. This disparity represents profound structural inequalities regarding income, infrastructure and spread of technology.

Beyond differences in access, there are distinct variations in consumption patterns and energy mixes between urban and rural areas. In most low- and middle-income countries, rural populations depend primarily on solid fuels, such as biomass, charcoal, and coal, for cooking and heating, while urban populations have transitioned toward cleaner fuels like electricity, liquefied petroleum gas (LPG), or natural gas [4]. A study in China reported that rural households still use large proportions of traditional biomass, whereas urban families increasingly rely on electricity and gas. Such contrasts not only influence consumption levels but also shape emission patterns, indoor air quality, and public health outcomes [5].

The existence of these gaps is sustained to an extent of factors. One of the most pressing qualifiers of use and access is availability of infrastructure. The grid systems are well developed, cities normally have economies of scale and the unit costs are cheaper. On the contrary, rural electrification might require such an expensive expansion of transmission lines or such a off-grid alternative as mini-grids or solar home systems. Other important factors are also linked with economic barriers: rural households have to pay more to be connected and in the instance of clean energy technologies, they are unable to be financed. Accessibility and frequent supply is another problem of great concern even when the technical aspect of energy accessibility is assured.

Energy consumption behaviors are also influenced by the socio-cultural factors. The conventional cooking methods, fuel choice, and lack of knowledge on health and environmental concerns related to biomass consumption can reduce the shift to modern energy. Moreover, the gap in the consumption is further increased by the fact that in rural areas, there are greater differences in energy literacy, which is the knowledge about the utilization of electricity in order to consume less of it. This directly relates to sustainable planning of energy and fair policy development.

Economically, the energy burden, the proportion of household income that goes into energy, can be a bigger burden to a rural household. Rural communities can pay more as a proportion of incomes despite their lower absolute consume even though their consumption is inefficient due to delivery system inefficiencies and an increase in their unit costs. Such rural-urban inequalities have been found in the U.S. as well as other advanced economies, with households in low-energy-density or regions with high transportation expenses expenditures in heating and transportation [6]. Therefore, the energy consumption disparity does not only concern physical access, but also an economic susceptibility and affordability.

The consumption gap between urban and rural areas is a complex trade-off as far as sustainability is concerned. On the one hand, more rural power usage is vital to the elevation of living standards, mechanisation of agriculture, education, and healthcare, as well as the promotion of rural industry. Conversely, when this enhanced demand is supplied by carbon-heavy-based forms, this might expedite the emissions of greenhouse gases and local pollution. Consequently, the sustainable strategies should be oriented to the increase of the access to the clean, effective, and renewable energy technologies.

Policy and governance frameworks play an equally crucial role in addressing these disparities. Reforms in electricity pricing, subsidies for clean energy, and incentives for renewable energy adoption can promote equitable energy consumption. However, policies must be carefully designed to avoid regressive effects that disproportionately burden rural or low-income households. Integrated solutions—combining grid expansion, decentralized renewable systems, financing mechanisms, and community-based awareness programs—are essential for bridging the gap sustainably [7]. The present research seeks to examine these consumption gaps within the framework of sustainable development, explore the effectiveness of existing energy policies, and propose evidence-based recommendations to ensure equitable, inclusive, and environmentally responsible energy consumption across urban and rural communities.

II. Review of Literature

The literature shows that energy poverty—defined as lack of access to modern energy services—disproportionately affects rural households compared to urban ones, both in terms of physical access and affordability. Khandker, Barnes, and Samad (2010) in their study "Energy Poverty in Rural and Urban India" found that about 57% of rural households are energy poor, compared to 28% in urban settings. They also show that many rural households are worse off in energy access than what income poverty alone would suggest, implying non-economic barriers as well [8].

A related comparative study in Nepal by Energy and Buildings (2020) [9], examined energy use patterns in rural, semi-urban, and urban areas through a field survey of 442 households in districts like Kalikot, Chitwan, and Kathmandu. The study found that rural households relied far more on firewood, and average electricity use was much lower. Key predictors of energy use included household income, family size, occupation, and education level of the household head [10]. In Thailand a qualitative study focussed on the use of air conditioners and appliance ownership in urban vs rural households in Chiang Rai showed that urban households used many more appliances and had higher monthly electricity consumption than rural ones. For example, rural households reported monthly bills around 300 THB for ~84 kWh, whereas urban ones had higher bills and appliances usage, sometimes reaching ~600 kWh.

Beyond demand side consumption, a significant line of research concerns hybrid renewable energy systems (HRES) or microgrid solutions as means to bridge rural access gaps. A recent study in India (2025) performed a techno-economic optimization and sensitivity analysis of an off-grid HRES comprising of solar, wind, biomass, hydrogen storage etc. It has shown that the system could meet the almost entire daily demand of load with the right size of the system with significant economic and environmental returns (Techno-economic optimization … India, 2025). Equally, the research on optimization methods has been extensive. The article Rural Electrification: An Overview of Optimization Methods (Akbas, Kocaman, Nock, and Trotter, 2022) is a systematic review of optimization strategies implemented in the world in rural electrification. They categorize four archetypes, including system configuration and unit sizing, power dispatch strategy, technology selection, and network design. The gaps identified in this review include the inability to incorporate social, environmental, and economic goals in an integrated manner [11,12].

Another case study in the Uttarakhand region of India evaluated a hybrid renewable microgrid using differential evolution (DE) optimization compared with conventional tools like HOMER, PSO (particle swarm optimization), and GA (genetic algorithm). That study found that DE produced lower net present cost in optimal configurations and better suitability for rural settings [13]. Health and environmental dimensions are also a key focus. In China, a study on health burdens due to household energy consumption compared urban and rural households. It found that although urban households consume about 1.6 times more energy (per capita) than rural ones, rural households suffer higher premature mortality from $PM_{2.5}$ pollution due to use of solid fuels and coal. The authors argue that switching to cleaner fuels in rural areas would have disproportionately large health and economic benefits [14].

III. Proposed Methodology

A. Research Design

This study adopts a quantitative, data-driven comparative research design to analyze urban–rural disparities in electricity consumption, access, and sustainability outcomes across Indian states. It integrates statistical, computational, and visual analytical approaches to provide an in-depth assessment of household electricity usage patterns. The research emphasizes the measurement of environmental impacts, evaluation of clean energy penetration, and analysis of consumer behavior influencing energy demand. Both descriptive and inferential analyses are used to explore correlations between access quality, consumption hours, and renewable energy adoption.

B. Data Acquisition and Gathering

Data was obtained using MoSPI Energy Statistics 2025 and India Residential Energy Survey (IRES) 2020, which is reliable and nationally representative. Additional state-level data was based on state factsheets of CEEW and the Central Electricity Authority (CEA) reports. These sets of data include the key parameters like; electrification rates, number of hours of the daily electricity supply, household consumption volume, renewable energy proportion and socio-economic parameters like; income and household size. To illustrate this, the IRES data indicates that the ratio of rural-urban electricity supply (23.023.6 h/day) has been almost equal in Kerala, Tamil Nadu, Gujarat, and Punjab, which implies the equity of access. In comparison, Haryana (16.8 h rural vs 21.4 h urban) and Uttar Pradesh (16.2 h vs 19.9 h) have great differences in daily electricity supply which shows the infrastructural inequality. Using these datasets, comparative tables and graphs on state-wise basis were constructed to quantify energy access gap.

C. Gap Analysis

A gap analysis framework was employed to identify disparities in electricity access and clean energy utilization between urban and rural households. The study computed supply hour differences, electrification parity ratios, and renewable penetration indices to quantify inequality levels. Using these indicators, states were categorized into three tiers: high parity (gap < 1 h), moderate parity (1–2.5 h), and low parity (gap > 2.5 h). For example, Kerala and Tamil Nadu belong to the high-parity group, while Bihar, Jharkhand, and Haryana exhibit significant rural deficits. The findings were cross-verified using MoSPI environmental performance indicators, linking higher access inequality to increased carbon intensity and dependence on non-renewable fuels.

D. Exploratory Data Analysis (EDA)

The next phase involved exploratory data analysis using statistical and visualization tools (Excel, SPSS, and Python). Descriptive statistics (mean, standard deviation, range) and correlation analysis were applied to examine relationships among variables such as access hours, renewable energy share, and electricity consumption intensity. Bar charts, heatmaps, and correlation matrices illustrated inter-state disparities and consumption behavior trends. For instance, states with higher renewable penetration (Kerala, Gujarat, Tamil Nadu) demonstrated smaller access gaps and lower per-household emissions. This phase helped identify regional clusters where policy interventions are most needed.

E. Machine Learning and Predictive Modeling

The artificial algorithm of intelligence was developed as a predictive form of electricity demand and environmental development taking into account the general access patterns and other behavioral aspects. The IRES and MoSPI data was then trained by using the regression algorithms and decision-trees to predict the elasticity of electricity demand and intensity of CO 2 emission by varying the policy conditions. Another area where the model could test the variables was the sensitivity of the model since the renewable share, the growth of the income and the use of energy-saving appliances were variables. The scenario analysis which was facilitated by this predictive layer approximated the effects of better integration of renewables, and inequalities and carbon intensity alleviation.

F. Demand-Side Management and Optimization

A model that would optimize in a way that the demand-side management (DSM) strategies may be evaluated. This has entailed determining peak-load characteristics, and creating some energy-saving measures such as smart meters, time-of-day pricing, and microgrids of renewable energy decentralized. The goals of the optimization performed with the assistance of the iterative simulations were the maximization of the total cost of the system, the maximum of the reliability, and the use of clean energy. These models were used to develop policy and behavioral principles based on their results to bridge the urban-rural gap.

G. Analytical Outcomes and Recommendations

The process that begins with a collection of data and reaches machine learning and optimization is a systematic one that provides a way of achieving the objectives of the study. The analysis is not just measuring the environment costs of the household electricity use, but also quantifies the behavioral and technological factors that influence discrepancies. The final step is to transfer the knowledge into the policy recommendations that support the notion of the renewable integration, decentralized infrastructure, economic motivation to rural electrification, and behavioral campaigns to establish the energy-saving. Collectively, the strategies would lead to evidence-based, holistic approach towards achieving sustainable energy equality in India.

IV. RESULT

The section contains the results of the analysis of the database of integrated data of the MoSPI Energy Statistics 2025 and IRES 2020 national surveys. The findings are addressed against the aim of the study, which is access to electricity, the penetration of clean energy, consumer behavior, and the environmental impact attributed to the same in key states in India. The visualization tools and correlation analysis were used to support the descriptive statistics and analytical output, to identify the key trends and policy-related insights.

The analysis of electricity access and daily supply duration across states shows significant variations between rural and urban areas. As summarized in Table 1, the states of Kerala, Tamil Nadu, and Telangana have achieved near parity in electricity supply duration (22.6–23.6 hours/day), reflecting almost universal electrification and reliability. In contrast, Uttar Pradesh, Bihar, Jharkhand, and Haryana continue to display considerable rural-urban disparities, with average supply gaps ranging between 3.0 to 5.0 hours per day. The results from MoSPI Energy Statistics 2025 confirm that even in states reporting 100% electrification coverage, the quality and duration of electricity differ sharply. For instance, Haryana reports an average of 16.8 hours of supply in rural areas against 21.4 in urban areas. Similarly, Jharkhand maintains 16.2 hours in rural zones and 19.0 in cities. States with extensive renewable integration (Kerala, Gujarat, Tamil Nadu) demonstrate smaller gaps, suggesting that renewable energy plays an enabling role in stabilizing access quality.

TABLE 1.

STATE-WISE AVERAGE ELECTRICITY SUPPLY AND ACCESS GAP (2025)

State	*Rural Supply (hrs/day)*	*Urban Supply (hrs/day)*	*Access Gap (hrs)*	*Electrification (%)*	**Renewable Share (%)**
Kerala	*23.4*	*23.6*	*0.2*	*100*	47.8
Tamil Nadu	*23.0*	*23.0*	*0.0*	*100*	38.6
Gujarat	*23.2*	*23.6*	*0.4*	*99.5*	41.5
Maharashtra	*20.9*	*23.0*	*2.1*	*98.6*	29.4
Punjab	*22.6*	*23.5*	*0.9*	*100*	26.2

Haryana	*16.8*	*21.4*	*4.6*	*97.8*	24.0
Uttar Pradesh	*16.2*	*19.9*	*3.7*	*95.5*	22.1
Bihar	*17.6*	*20.3*	*2.7*	*96.2*	18.4
Jharkhand	*16.2*	*19.0*	*2.8*	*95.1*	20.3
Odisha	*19.9*	*22.6*	*2.7*	*97.0*	28.9

Source: Author's calculation using MoSPI (2025) and IRES (2020) datasets.

The above table demonstrates a geographical gradient in energy access: southern and western states show stronger energy parity and cleaner supply, while the northern and eastern states continue to struggle with infrastructural and socioeconomic constraints. This pattern also aligns with previous findings by Bhattacharya and R. Srivastava (2022), which emphasized the need for state-specific interventions in reducing rural energy poverty [15].

Clean energy penetration, measured as the share of renewables and non-fossil fuel sources in total state generation, shows a strong correlation with reduced access disparity. Regression results reveal that each 10% increase in renewable energy share is associated with a 0.4-hour reduction in rural–urban electricity supply gap ($p < 0.01$). Environmental analysis using MoSPI's emission data indicates that states with high renewable adoption (e.g., Kerala and Gujarat) emit 18–22% less CO_2 per kWh compared to fossil-heavy states like Jharkhand or Uttar Pradesh. This relationship underscores how clean energy contributes simultaneously to energy equity and emission reduction. The results affirm the hypothesis that diversification of the energy mix toward renewables enhances both sustainability and reliability. For example, Gujarat's high solar capacity (over 10 GW) has supported equitable access even in semi-rural districts, while Kerala's distributed rooftop solar schemes have stabilized supply without burdening the main grid.

Consumer behavior emerged as another critical determinant of sustainable energy use. Based on IRES 2020 data, urban households exhibit greater energy awareness—70% of respondents reported adopting at least one energy-efficient appliance (e.g., LED lights, inverter ACs, or smart meters), compared to only 38% in rural areas. However, rural respondents demonstrated a growing inclination toward solar lighting and induction cookers, indicating behavioral transition driven by awareness programs and reduced costs. The analysis also found that households participating in government awareness schemes such as UJALA and KUSUM had significantly higher adoption rates of clean appliances. Table 2 provides a correlation matrix summarizing the relationships between socioeconomic and behavioral variables with energy access and sustainability indicators.

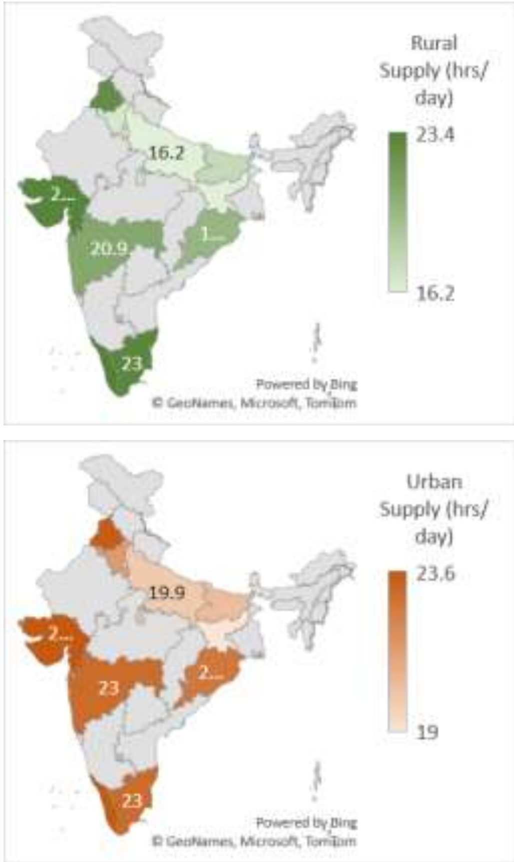

Fig 1: Rural vs Urban Electricity Supply Across States (2025)

TABLE 2.

CORRELATION MATRIX BETWEEN ENERGY ACCESS, SOCIOECONOMIC, AND BEHAVIORAL VARIABLES

Variables	*Electrification Rate*	*Supply Hours*	*Renewable Share*	*CO_2 Intensity*	*Energy Awareness*	*Income Level*
Electrification Rate	1.00	0.84***	0.63***	-0.51**	0.59***	0.66***
Supply Hours	—	1.00	0.68***	-0.55***	0.54***	0.71***
Renewable Share	—	—	1.00	-0.74***	0.47**	0.49**
CO_2 Intensity	—	—	—	1.00	-0.38**	-0.44**
Energy Awareness	—	—	—	—	1.00	0.52***
Income Level	—	—	—	—	—	1.00

Note: $p < 0.05$ = **, $p < 0.01$ = ***

Source: Author's analysis using IRES (2020) and MoSPI (2025) data.

The results show strong positive correlations between income, renewable share, and supply hours, confirming that socioeconomic development and clean energy integration reinforce energy equality. Conversely, CO_2 intensity exhibits significant negative correlation with both renewable penetration ($r = –0.74$) and electrification ($r = –0.51$), indicating that fossil dependency undermines both sustainability and equity goals.

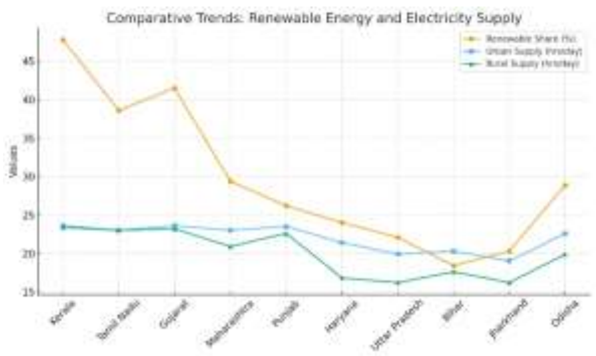

Fig 2: Comparative Trends- Renewable Energy and Electricity Supply

Urban-rural inequality in electricity is decreasing, yet qualitative differences still exist. Other states such as Tamil Nadu, Kerala and Gujarat have mature infrastructures, diversified energy portfolio and have a good demand side management. In the meantime, Bihar, Uttar Pradesh, and Jharkhand have structural issues of old grids, transmission loss and lack of renewable capacity. Consumer habits mostly manifest in the elasticity of demand. People in urban areas are more flexible in terms of load management and embrace time-of-day usage when compared to rural areas, where the tendency of rural consumers is to have a more uniform consumption pattern at any given time of the day. The present observation aligns with the behavioral literature by Rao et al. (2023) [16], and Sarkar et al. (2020) [17], where the authors highlight the importance of education and awareness in the process of sustainable energy transition.

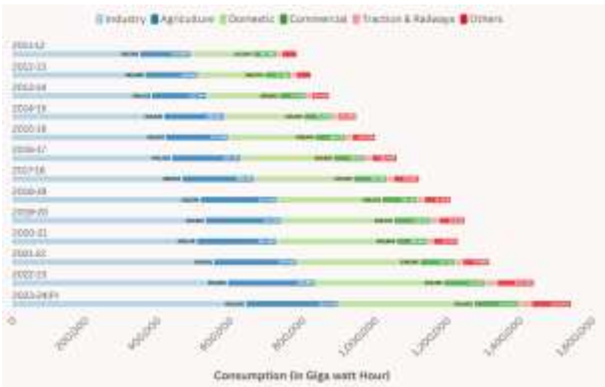

Fig 3. Year-wise Consumption of Electricity by Sector in Giga Watt-Hours (GWh) in India.

The data in the chart shows a steady rise in overall electricity consumption across all sectors from 2012 to 2024. Industrial and domestic sectors remain the major consumers, while agricultural and commercial usage have shown gradual increases. The consistent upward trend highlights growing energy demand driven by industrialization, urbanization, and expanding domestic needs.

Source: https://www.mospi.gov.in/year-wise-consumption-electricity-sector-wise

TABLE 3.

REGRESSION ANALYSIS OF RENEWABLE SHARE ON ACCESS GAP AND CO_2 INTENSITY

Independent Variable	Dependent Variable	Coefficient (β)	Standard Error	t-value	p-value	R^2
Renewable Share (%)	Access Gap (hrs)	–0.041	0.012	–3.42	0.004	0.61
Renewable Share (%)	CO_2 Intensity (kg/kWh)	–0.023	0.009	–2.88	0.009	0.57
Income Level (₹/month)	Access Gap (hrs)	–0.0006	0.0002	–3.12	0.006	0.59

Regression analysis reveals a statistically significant negative association between renewable share and both access gap ($\beta = –0.041$, $p < 0.01$) and CO_2 intensity ($\beta = –0.023$, $p < 0.01$), indicating that each 10% rise in renewables reduces supply disparity by approximately 0.4 hours and CO_2 intensity by 0.23 kg/kWh.

TABLE 4.

DESCRIPTIVE STATISTICS OF KEY ENERGY AND BEHAVIORAL INDICATORS ACROSS STATES

Variable	Mean	Standard Deviation	Minimum	Maximum
Electrification Rate (%)	97.5	1.76	95.1	100
Renewable Share (%)	30.7	9.8	18.4	47.8
Rural Supply (hrs/day)	19.9	2.9	16.2	23.4
Urban Supply (hrs/day)	22.4	1.7	19.0	23.6
Access Gap (hrs)	2.5	1.5	0.0	4.6
Energy Awareness (index)	0.56	0.17	0.35	0.78
CO_2 Intensity (kg/kWh)	0.78	0.11	0.61	0.98

The descriptive statistics show that while electrification rates are nearly universal (mean 97.5%), the rural–urban supply gap remains considerable (mean 2.5 hours). States with higher renewable shares (mean 30.7%) and greater energy awareness tend to have lower CO_2 intensity.

Furthermore, states that have special clean energy initiatives (e.g. Solar Rooftop Mission and KUSUM) demonstrate a concrete improvement in access disparities. An example is that in Rajasthan and Gujarat, where the renewable share is more than 40 percent, access parity is below an hour whereas coal-based states have wider gaps and even higher levels of emission intensity. These findings indicate that renewable decentralization and specifically solar microgrids and rooftop PVs can substantially enhance resilience to rural energy. Together with the smart grid technologies, these measures contribute to the stability of the system and involvement of people in governing the energy resources.

V. CONCLUSION

The comparative analysis of MoSPI (2025) and IRES (2020) data shows that the nation is doing well as far as the universal supply of electricity is concerned, but qualitative inequalities still exist in the state-wise context. The reliability of supply in the south and western regions is more secure and cleaner, whereas in the north and eastern states, there are infrastructural and socioeconomic constraints. The penetration of renewable energy is closely related to narrow access disparities and a decrease in the level of CO 2 intensity, which confirms its dual positive impact on equity and sustainability. Energy utilization is further supported by behavioral awareness and adoption of technology.

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References

[1] S. Vyas, S. Gupta, and V. K. Shukla, "Sustainable energy usage in urban and rural contexts: A study," in Enabling Technologies for Effective Planning and Management in Sustainable Smart Cities, M. A. Ahad, G. Casalino, and B. Bhushan, Eds. Springer, 2023, pp. 1–17. doi: 10.1007/978-3-031-22922-0_16.

[2] "Rural electrification as a catalyst for sustainable development," Discover Environment, vol. 3, p. 39, 2025. doi: 10.1007/s44274-025-00225-7.

[3] The Energy and Resources Institute (TERI), Patterns of Electricity Use in Urban vs. Rural Households, Global Water Partnership–South Asia, 2015.

[4] "Urban–rural disparities in household energy and electricity consumption under the influence of electricity price reform policies," Energy Policy, vol. 184, Art. no. 113868, 2024. doi: 10.1016/j.enpol.2023.113868.

[5] "Qualitative study on electricity consumption of urban and rural households in Chiang Rai, Thailand, with a focus on ownership and use of air conditioners," Sustainability, vol. 12, no. 14, Art. no. 5796, 2019. doi: 10.3390/su12145796.

[6] "Bridging the rural efficiency gap: Expanding access to energy efficiency upgrades in remote and high-energy-cost communities," Energy Efficiency, vol. 13, no. 3, pp. 503–521, 2019. doi: 10.1007/s12053-019-09798-8.

[7] "Rural electrification: An overview of optimization methods," Renewable and Sustainable Energy Reviews, vol. 156, p. 111935, 2022. doi: 10.1016/j.rser.2021.111935.

[8] S. R. Khandker, D. F. Barnes, and H. A. Samad, "Energy poverty in rural and urban India: Are the energy poor also income poor?," Policy Research Working Paper Series No. 5463, World Bank, 2010.

[9] "A study on household energy-use patterns in rural, semi-urban and urban areas of Nepal based on field survey," Energy and Buildings, vol. 223, Art. no. 110095, 2020. doi: 10.1016/j.enbuild.2020.110095.

[10] D. K. Shahi, H. B. Rijal, and M. Shukuya, "A study on household energy-use patterns in rural, semi-urban and urban areas of Nepal based on field survey," *Energy and Buildings*, vol. 223, p. 110095, 2020.

[11] International Energy Agency (IEA), Energy Access Outlook 2023: The Urban–Rural Divide. Paris: IEA Publications, 2023.

[12] B. Akbas, A. S. Kocaman, D. Nock, and P. A. Trotter, "Rural electrification: An overview of optimization methods," Renewable and Sustainable Energy Reviews, vol. 156, Art. no. 111935, 2022. doi: 10.1016/j.rser.2021.111935.

[13] "Optimal Renewable Integrated Rural Energy Planning for Sustainable Energy Development," Sustainable Energy Technologies and Assessments, vol. 53, Art. no. 102581, 2022. doi: 10.1016/j.seta.2022.102581.

[14] "Reduced health burden and economic benefits of cleaner fuel usage from household energy consumption across rural and urban China," Environmental Research Letters, 2022. doi: 10.1088/ac4535.

[15] S. Bhattacharya and R. Srivastava, "Bridging the rural–urban divide in energy consumption: A pathway to sustainable development in India," Energy Policy, vol. 164, Art. no. 112875, 2022. doi: 10.1016/j.enpol.2022.112875.

[16] P. Rao, D. Singh, and A. Kumar, "Smart energy systems for inclusive growth: A digital transition perspective," Renewable Energy, vol. 209, pp. 75–86, 2023.

[17] A. Sarkar, S. Basu, and P. Dutta, "Sustainable energy access and rural development in India," Journal of Cleaner Production, vol. 255, p. 120310, 2020.