SUSTAINABLE SMART SYSTEMS IN CHHATTISGARH THROUGH AMBIENT RENEWABLE ENERGY HARVESTING

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Abstract

Rapid urbanization, growth of the Internet of Things (IoT) and expansion of smart city initiatives in India have created a strong demand for low-power, autonomous electronic systems. Ambient energy harvesting from renewable sources particularly solar, biomass, micro-hydro, and environmental vibrations offers a pathway to power such smart systems without overburdening the conventional grid. Chhattisgarh, a resource-rich state with high solar insolation and strong biomass availability, is still dominated by coal-based electricity generation, but its renewable energy capacity has grown steadily in the last decade. Recent assessments report a total installed renewable energy capacity of around 1.6 GW, of which solar contributes nearly three-quarters. This paper examines the potential of harvesting ambient renewable energy for sustainable smart systems in Chhattisgarh with a focus on applications in smart cities (Nava Raipur Atal Nagar and Raipur), rural smart villages, precision agriculture, and environmental monitoring. A review of state-level energy transition reports, ambient energy-harvesting literature, and policy documents is combined with a conceptual framework for integrating harvested energy into IoT-based smart infrastructures. Key findings indicate that rooftop solar, small off-grid photovoltaic systems, and biomass-supported microgrids already promoted by the Chhattisgarh State Renewable Energy Development Agency (CREDA) can be effectively combined with ultra-low-power electronics and energy-aware communication protocols to realize energy-neutral smart systems. The paper proposes a multi-tier architecture linking ambient energy harvesters, local storage, edge computing nodes, and cloud platforms. It highlights case examples such as solar-powered street lighting, sensorised water-supply schemes, and tourism-oriented smart villages that already rely on renewable energy, and discusses how these can be scaled into a state-wide digital energy-harvesting ecosystem.

Keywords: *Ambient energy harvesting[1]; Renewable energy[2]; IoT; Smart city[3]; Smart village[4]; Solar PV[5].*

1. Introduction

The convergence of renewable energy technologies, low-power electronics, and ubiquitous wireless connectivity is transforming how modern societies produce, distribute, and use energy. Smart cities, smart villages, precision agriculture, and intelligent transport systems depend on dense networks of sensors, actuators, and communication modules [1]. Conventional grid-connected or battery-powered solutions become increasingly unsustainable as the number of devices scales to billions: battery replacement is labor-intensive and environmentally problematic, and grid extension to remote or forested areas is often technically and economically challenging [2]. Ambient energy harvesting capturing small amounts of energy naturally present in the environment, such as sunlight, thermal gradients, vibrations, wind, and radio-frequency (RF) signals has emerged as a promising strategy for powering ultra-low-power devices in a sustainable manner [3]. A growing body of literature recognizes that harvesting from renewable ambient sources can lead to "energy-neutral operation" of IoT nodes, wherein harvested energy balances or exceeds the device's consumption [4]. Chhattisgarh, located in central India, is widely known as a power-surplus state due to its large fleet of coal-fired power plants [5]. However, recent state-level analyses emphasize the need to diversify away from coal, reduce local pollution, and align with India's national commitments to increase the share of renewable energy in the electricity mix. Between 2012–13 and 2023–24, coal-based generation in the state increased from about 67,800 MU to over 162,000 MU, but solar generation grew at an even higher compound annual growth rate (CAGR) of more than 40%, reflecting accelerating adoption of renewable energy [6-10]. Parallel to this energy transition, Chhattisgarh hosts one of India's flagship greenfield smart cities, Nava Raipur Atal Nagar, which is envisioned as an integrated smart and eco-friendly urban centre with 24×7 electricity, underground distribution systems, smart lighting, and a growing share of renewable energy. CREDA has rolled out multiple schemes for rooftop solar, off-grid solar pumps, biogas plants, and solar high-mast lighting, especially in rural and tribal regions [11]. Against this backdrop, the present paper explores how ambient energy harvesting from renewable sources can power sustainable smart systems in Chhattisgarh. Rather than focusing solely on large-scale grid-connected renewable projects, the emphasis is on distributed, device-level energy harvesting for IoT-driven services in urban, peri-urban, and rural contexts [12].

2. Background and Study Area: Chhattisgarh

Chhattisgarh was carved out of Madhya Pradesh in 2000 and is endowed with rich mineral resources, forest cover, and significant solar and biomass potential [13]. The state lies in India's "solar belt", receiving annual global horizontal irradiance suitable for both utility-scale and rooftop solar projects. National assessments and state-level policy documents highlight more than several gigawatts of technically exploitable renewable potential, dominated by solar PV, biomass, and small hydro. Despite this potential, coal continues to dominate electricity generation, contributing the majority of the state's energy mix [14]. Nevertheless, renewable energy installations have expanded, with recent data indicating around 1,615 MW of installed renewable capacity in the state, including roughly 1,264 MW of solar, and smaller contributions from biomass and small hydro [15].

Chhattisgarh presents a diverse energy-use landscape:

- **Urban and smart city areas**, notably Raipur and Nava Raipur Atal Nagar, where the focus is on reliable 24×7 supply, smart metering, automated street lighting, and ICT-enabled governance.
- **Rural and tribal regions**, where access, affordability, and reliability of electricity remain uneven; here, decentralized solar lighting, solar pumps, and microgrids are gaining prominence.
- **Agricultural areas**, where groundwater extraction, irrigation, and post-harvest processing can benefit from renewable-powered pumping and farm-level IoT systems.

This mix makes Chhattisgarh an ideal test bed for exploring ambient energy harvesting concepts that complement state-level renewable energy programmes and smart infrastructure initiatives [16].

3. Literature Review

Research on ambient energy harvesting for IoT and wireless sensor networks (WSNs) has grown rapidly in the last decade [17]. Comprehensive reviews summaries the main energy sources solar, mechanical (vibration, motion, wind), thermal (Seabeck effect), and RF and discuss power management circuits and storage technologies (supercapacitors, micro-batteries) [18]. Sarker et al. (2024) classify micro-energy harvesting systems for IoT platforms, emphasizing the need for application-specific design, hybrid harvesting (e.g., combining solar and vibration), and adaptive duty-cycling of communication protocols to maintain energy-neutral operation [19]. Similarly, Famitafreshi (2021) and colleagues argue that only about one-quarter of existing MAC-layer protocols for wireless technologies satisfy strict energy-neutrality constraints, indicating substantial room for optimization of both hardware and communication stacks [20].

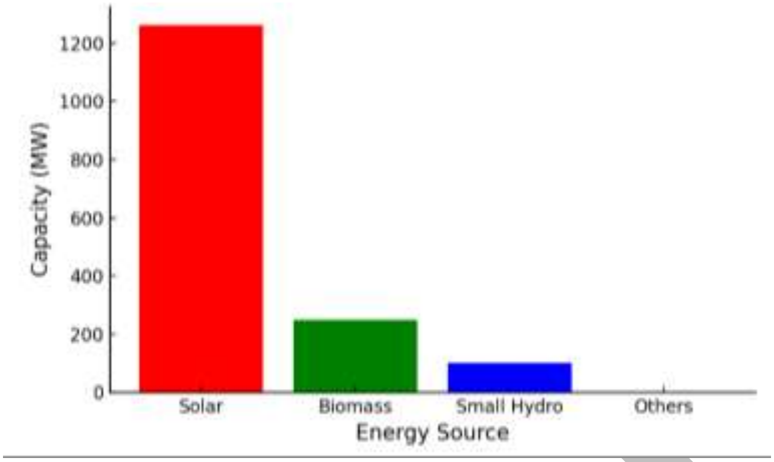

Figure 1 Installed renewable energy capacity in Chhattisgarh (MW)

In the application domain, Khernane et al. (2024) focus on renewable energy harvesting for precision agriculture, demonstrating that solar- and wind-powered sensor nodes can significantly reduce dependence on grid or diesel-powered systems while enabling continuous monitoring of soil moisture, microclimate, and crop health [21]. Such approaches are especially relevant for agrarian regions like Chhattisgarh, where smallholder farmers may not have reliable access to grid power. At the national scale, policy and technical studies emphasize the critical role of distributed generation, rooftop solar, and off-grid systems in India's broader energy transition [22]. Government dashboards and research reports show rapid growth in solar and wind capacity, with rooftop solar and decentralized systems receiving special attention under schemes such as PM Surya Ghar Muft Bijli Yojana.

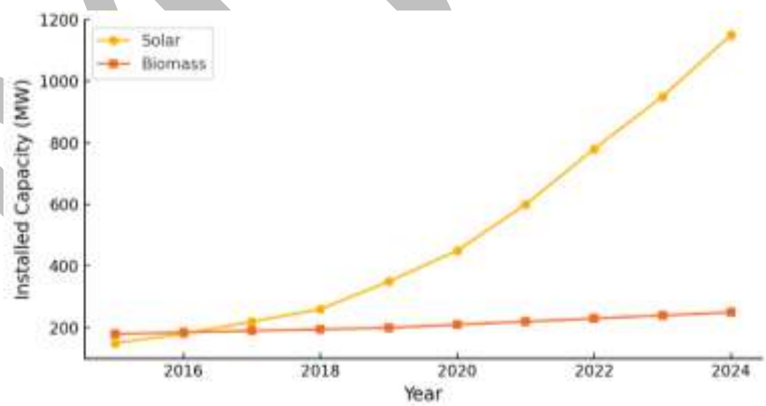

Figure 2 Renewable energy growth trend in Chhattisgarh (2015–2024).

Chhattisgarh-focused studies highlight both the dominance of coal and the emerging role of renewable energy [23]. Recent reports on the state's energy transition point to vigorous growth in solar generation, an expanding pipeline of rooftop solar projects, and CREDA's role in off-grid schemes (solar pumps, solar high-mast lights, and biogas plants). Smart-city case studies of Nava Raipur demonstrate how a greenfield urban environment can employ ICT platforms to manage power, water, and street lighting, with solar PV supplying part of the load and advanced SCADA systems enabling real-time control [24]. However, the intersection of these two lines of research ambient energy harvesting and Chhattisgarh's renewable-energy-driven smart systems remains underexplored [25]. Most state-level documents emphasize megawatt-scale capacity addition, while micro-scale, device-level energy harvesting for smart infrastructure (street lights, environmental sensors, smart meters, and tourism-focused smart villages) is rarely analyzed as a coherent system. This paper seeks to bridge that gap by proposing an integrated framework for ambient energy harvesting tailored to Chhattisgarh's socio-technical context [26].

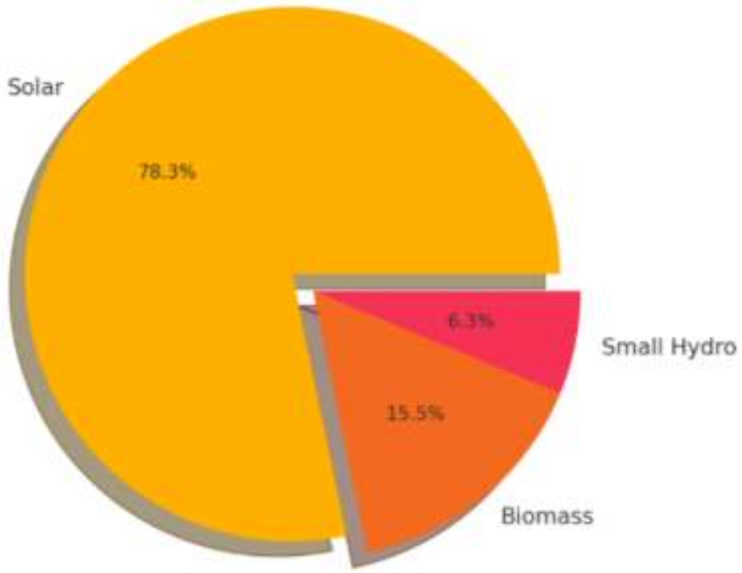

Figure 3 Renewable energy distribution in Chhattisgarh.

4. Ambient Renewable Energy Sources Relevant to Chhattisgarh

For sustainable smart systems, the most relevant ambient renewable sources in Chhattisgarh include:

4.1 Solar Energy

Solar energy is the most abundant and practically accessible ambient renewable source across Chhattisgarh due to its high solar irradiation levels throughout the year [27]. This makes the state highly suitable for deploying small-scale photovoltaic (PV) modules on rooftops, street poles, and standalone sensor stations required for smart applications [28]. The Chhattisgarh Renewable Energy Development Agency (CREDA) has played a central role in expanding solar infrastructure through off-grid solar plants, solar high-mast streetlights, rooftop solar installations, and solar-based community facilities. These initiatives demonstrate the technical feasibility, institutional readiness, and long-term sustainability of integrating solar energy into ambient harvesting systems across both urban and rural regions [29].

4.2 Biomass and Biogas

Biomass and biogas constitute another major ambient renewable energy source for Chhattisgarh, supported by the state's substantial agricultural activity and livestock population. Agricultural residues, forest biomass, and animal waste are readily convertible into biogas, which can be used to power micro-generators or fuel cells [30]. These decentralized power units are well suited for running community-level IoT gateways, village microgrids, and smart rural infrastructure. Government-supported schemes promoting household and community biogas plants further strengthen the potential of biomass-based energy harvesting for sustainable smart village development.

4.3 Small Hydro and Flow-Based Harvesters

Chhattisgarh's extensive network of rivers, streams, and irrigation canals provides considerable scope for small hydro, pico-hydro, and micro-hydro energy harvesters. These systems can extract continuous low-power energy from flowing water, making them ideal for powering hydrology-monitoring sensors, automated irrigation gate controls, and remote environmental monitoring stations [31]. Their reliability and minimal environmental impact make flow-based harvesters particularly valuable for agricultural and tribal regions where grid access is limited.

4.4 Mechanical Vibrations and Human Motion

Urban centers such as Raipur and Nava Raipur generate significant mechanical energy through vehicular movement, pedestrian footfall, and structural vibrations in public spaces like markets, stadiums, and transportation hubs. This kinetic activity can be captured using piezoelectric or electromagnetic vibration harvesters embedded in floors, pavements, and infrastructure components [32]. Such systems can provide a sustainable power source for traffic sensors, structural health monitoring devices, and smart lighting controls, supporting low-power IoT applications without relying on external energy sources.

4.5 Thermal Gradients

Industrial clusters and thermal power plants in Chhattisgarh produce substantial waste heat, creating stable thermal gradients that can be harvested using thermoelectric generators. These devices convert temperature differences directly into electrical energy, making them suitable for powering condition-monitoring sensors in industrial environments [33]. By utilizing waste heat that would otherwise dissipate unused, thermal-gradient-based energy harvesting contributes to improved efficiency, lower emissions, and enhanced industrial automation. Given current technology maturity, solar PV remains the primary practical ambient source for most IoT applications, while other sources provide niche or supplemental contributions in hybrid systems.

5. Proposed Architecture for Ambient-Powered Smart Systems

To leverage the full potential of ambient renewable sources for powering smart infrastructure in Chhattisgarh, a comprehensive multi-tier architecture is proposed [34]. This architecture ensures seamless integration across energy-harvesting devices, local gateways, and centralized monitoring systems, supporting both urban smart city environments and rural smart villages.

5.1 Tier-1: Energy-Harvesting Sensor Nodes

The first level of the architecture consists of autonomous sensor nodes designed to operate on harvested ambient energy. Each node integrates one or more small-scale energy harvesters, typically compact solar panels, with optional vibration, thermal, or hybrid harvesting units. These nodes incorporate power management integrated circuits (PMICs), which regulate energy intake and storage using Li-ion micro-batteries or supercapacitors [35]. Ultra-low-power sensors and microcontrollers form the core of each node, enabling continuous operation with minimal energy consumption. To sustain energy-neutral functionality, sensor nodes employ duty-cycled operation and energy-aware communication protocols such as LoRaWAN with adaptive data rates calibrated to available harvested power [36].

5.2 Tier-2: Local Gateways and Microgrids

The second tier consists of local gateways that collect and relay data from numerous sensor nodes distributed across smart infrastructure networks. These gateways are typically installed at strategic locations such as streetlight poles, community buildings, agricultural pump houses, or smart kiosks. Connectivity with the broader network is maintained through fibre-optic, cellular, or even satellite links depending on regional accessibility [37]. Gateways themselves are powered by larger renewable installations, often standalone solar photovoltaic systems or hybrid systems integrating solar with biogas or micro-hydro power. These configurations align closely with energy solutions already promoted through CREDA's renewable energy schemes across the state.

5.3 Tier-3: Edge and Cloud Platforms

At the third level, data processing and decision-making functions are carried out using edge servers located within the smart city command centre or cloud-based platforms. These systems run advanced analytics, including predictive maintenance algorithms, anomaly detection, and real-time decision-support tools [38]. Integration with Supervisory Control and Data Acquisition (SCADA) systems, as implemented in Nava Raipur, allows synchronized management of critical utilities such as street lighting, water supply, wastewater processing, and public transportation. This ensures that smart operations remain efficient, transparent, and responsive to real-time data.

5.4 Tier-4: User Interfaces and Policy Dashboards

The final tier includes end-user interaction platforms such as mobile applications, public dashboards, and government policy interfaces. These platforms display essential information on energy generation trends, system performance, environmental parameters, and cost savings. By making system data accessible to citizens, administrators, and policymakers, this tier promotes transparency and enhances participatory governance [39]. It also supports evidence-based decision-making by providing insights into energy usage patterns and infrastructure performance.

The proposed architecture complements ongoing smart city initiatives in Chhattisgarh by facilitating integrated utility management and strengthening ICT infrastructure. Incorporating ambient energy harvesting at the device level not only reduces operational expenses but also extends smart system functionality to remote or off-grid regions. Furthermore, it enhances system resilience, ensuring uninterrupted operation during grid outages and contributing to a more sustainable and energy-efficient future for the state [40].

6. Application Scenarios in Chhattisgarh

6.1 Smart City Services in Nava Raipur and Raipur

Nava Raipur Atal Nagar is conceived as an integrated smart and eco-friendly city with underground power distribution, smart street lighting, and SCADA-based monitoring of utilities. Solar PV installations already power a portion of administrative buildings (e.g., Mahanadi Bhawan's 1.1 MW captive plant) and public lighting [41].

Integrating ambient-powered sensor nodes into this framework enables:

- **Smart street lighting** where luminaires host small PV modules powering motion sensors, environmental sensors (air quality, noise), and communication units;
- **Structural and traffic monitoring** on key flyovers and intersections using vibration-powered sensors;
- **Smart parking and public safety** systems using solar-powered cameras and panic buttons in public spaces.

Raipur Smart City proposals emphasize assured electricity supply, efficient urban mobility, and robust ICT infrastructure. Ambient-powered IoT nodes can reduce the burden on distribution infrastructure and help achieve near-real-time monitoring with minimal incremental energy demand.

6.2 Smart Villages and Eco-Tourism Sites

CREDA has implemented solar-powered street lighting, water supply, and educational facilities in rural and tribal areas. Dhudmaras village in Bastar district, recognized as a model tourism village, is now powered by solar streetlights, dual-pump water systems, and solar-equipped schools.

Ambient energy harvesting can extend these initiatives by powering:

- **Environmental monitoring networks** (microclimate, river water quality, biodiversity) to support eco-tourism and conservation;
- **Community information kiosks** providing digital services and local e-governance powered by rooftop solar;
- **Off-grid security and navigation systems** (solar-powered beacons, emergency communication nodes) along trekking and adventure routes.

6.3 Renewable-Powered Precision Agriculture

In Chhattisgarh's agricultural regions, solar pumps, micro-irrigation systems, and farm-level IoT solutions can significantly improve water-use efficiency and crop productivity. State-level energy transition reports have called for expanded support to solar pumps and rooftop systems on farmhouses and rural enterprises.

By deploying solar-powered soil-moisture and weather stations in fields, and using low-power long-range communication, farmers can receive decision support on irrigation scheduling, fertilizer application, and pest management with negligible incremental energy costs. The design of such systems can draw upon global experience in renewable-powered precision agriculture [42].

6.4 Industrial Monitoring and Energy Efficiency

Chhattisgarh's industrial base particularly steel and power plants generates large quantities of waste heat and mechanical vibrations, which can be harnessed using thermoelectric and vibration energy harvesters to power condition-monitoring sensors. Such sensors can improve the reliability of critical equipment, reduce downtime, and contribute indirectly to energy savings and emission reductions.

7. Discussion

The review of renewable energy potential and the proposed multi-tier smart system architecture indicate that Chhattisgarh is well positioned to emerge as a national leader in ambient energy-powered smart infrastructure. Several enabling factors contribute to this potential. First, the state benefits from strong institutional support through the Chhattisgarh Renewable Energy Development Agency (CREDA), which has successfully implemented rooftop solar systems, off-grid solar plants, solar pumps, and biogas units across households and community spaces. These initiatives establish a solid foundation for integrating energy-harvesting technologies at both micro and macro levels [25]. Second, the presence of advanced smart-city infrastructure in Nava Raipur complemented by ongoing digitalization projects in Raipur provides a ready ecosystem for embedding IoT-driven systems, enabling efficient utility management supported by renewable energy. Additionally, national and state-level policies increasingly promote distributed renewable generation, especially rooftop solar systems, with incentives designed to encourage prosumer participation and foster decentralized energy networks. Despite this strong foundation, the deployment of ambient-powered smart systems presents several challenges that require systematic attention [1-7, 26-30]. Technical integration and interoperability pose significant hurdles because ambient-powered devices operate under stringent energy constraints. Their reliable functioning demands optimized hardware, firmware, and communication protocols that must align seamlessly with existing smart-city and utility platforms. Likewise, reliability and maintenance concerns arise from environmental variability such as seasonal changes in solar radiation, panel shading, and dust accumulation—that can directly influence energy-harvesting efficiency. These issues highlight the need for robust power-management strategies and hybrid harvesting mechanisms capable of maintaining consistent service levels.

Another major consideration is the development of local human and industrial capacity. Successful scaling of renewable-powered smart systems relies on skilled technicians, local entrepreneurs, and manufacturing capabilities for PV modules, PMICs, sensors, and IoT components. Strengthening training programs, technical institutes, and incubation centres will be critical for fostering innovation and supporting long-term sustainability. Financing remains an equally important element: although individual energy-harvesting devices are relatively low-cost, city-wide or state-level deployment requires innovative business models such as energy-service companies (ESCOs), public–private partnerships (PPPs), and performance-based contracts to ensure financial viability. Additionally, as sensor networks generate large volumes of data, concerns related to data governance and cybersecurity must be addressed. Ensuring privacy, securing communication layers, and establishing ethical frameworks become particularly important when monitoring extends into public areas and rural communities [21-26, 35-41]. Despite these challenges, the opportunities offered by ambient renewable energy harvesting are substantial and transformative. Such systems can significantly reduce operational expenses, facilitate digital inclusion by extending services to remote and underserved regions, and enhance the resilience of smart infrastructure during grid failures. Moreover, widespread adoption of ambient-powered smart systems aligns with Chhattisgarh's evolving identity as a major energy-producing state, positioning it at the forefront of India's transition toward sustainable, decentralized, and environmentally responsible energy ecosystems.

8. Policy and Research Recommendations

Based on the analysis, the following recommendations are proposed for policymakers, researchers, and practitioners in Chhattisgarh:

1. **Develop a State-Level Roadmap for Ambient Energy-Powered IoT**: Integrate ambient energy harvesting targets into existing renewable energy and smart-city policies, with clear milestones for pilot projects and scale-up.
2. **Launch Pilot Projects in Selected Use-Cases**: Implement demonstration projects in Nava Raipur and model smart villages (e.g., Dhudmaras) focusing on solar-powered environmental monitoring, smart lighting, and precision agriculture networks.
3. **Standardize Architectures and Protocols**: Collaborate with academic institutions and industry to define open standards for energy-harvesting sensor nodes and gateways, ensuring interoperability and long-term maintainability.
4. **Strengthen Capacity-Building Programmes**: Expand training for technicians, local entrepreneurs, and engineers through CREDA and state universities, with modules specifically on ambient energy harvesting, low-power IoT design, and system integration.
5. **Encourage R&D and Local Innovation:** Provide grants and innovation-challenge programmes for start-ups and research groups working on Chhattisgarh-specific applications such as forest-fire detection, mine-safety monitoring, and eco-tourism support systems powered by harvested energy.
6. **Integrate Socio-Economic Evaluation:** Conduct rigorous assessments of cost, reliability, social acceptance, and environmental impact of ambient-powered smart systems to inform large-scale policy decisions.

9. Conclusion

This paper has explored the concept of harvesting ambient energy from renewable sources to power sustainable smart systems in Chhattisgarh. Drawing upon recent state-level energy transition studies, smart-city case reports, and international literature on energy-harvesting IoT, it argues that the state's high solar potential, expanding renewable capacity, and proactive institutional framework provide fertile ground for such systems. A multi-tier architecture linking energy-harvesting sensor nodes, renewable-powered gateways, and smart-city/cloud platforms has been proposed, with application scenarios in smart cities, smart villages, precision agriculture, and industry. While technical, financial, and governance challenges remain, targeted pilot projects, capacity-building initiatives, and supportive policies could allow Chhattisgarh to become a national leader in ambient energy-powered smart infrastructures. By focusing not only on megawatt-scale generation but also on micro-scale, device-level energy autonomy, Chhattisgarh can create a more resilient, inclusive, and environmentally sustainable energy ecosystem one in which smart systems and renewable energy mutually reinforce each other for long-term societal benefit.

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