Intelligent Energy Optimization for Sustainable 5G Telecommunications in Costa Rica: ISO 50001, IoT, Machine Learning, and Renewable Energy

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Abstract*– As 5G networks continue to expand across Latin America, telecommunications operators face the dual challenge of increasing connectivity while reducing energy consumption, operational costs, and environmental impacts. This study proposes an intelligent energy optimization framework for Costa Rica's telecommunications infrastructure by integrating ISO 50001 energy management principles, Internet of Things (IoT)-based monitoring, machine learning techniques, and renewable energy strategies. A mixed-method approach combining literature review, real-time data analysis, field observation, energy audits, and comparative evaluation of telecommunications facilities was employed to assess the effectiveness of the proposed model. Results demonstrated energy consumption reductions ranging from 12.5% to 16.7% in base stations and data centers, while enhancing operational visibility, predictive capabilities, and decision-making processes. In addition, strategic opportunities for hybrid renewable systems and smart energy management were identified across five pilot sites in Puntarenas province: Chomes, Isla Venado, the El Roble data center, Isla de Chira, and Montes de Oro–Miramar. The study also presents a technological roadmap toward digital energy twins, predictive analytics, and AI-assisted decision support systems aimed at improving resilience and sustainability. The proposed framework provides a scalable and replicable approach for Latin America, demonstrating how digital transformation and energy efficiency can jointly support the development of intelligent, low-carbon, and sustainable 5G telecommunications infrastructures. Energy-consumption values reported here were generated through a triangulated energy simulation — combining engineer interviews, audit checklists, direct field observation, and literature-derived savings margins — rather than continuous field metering; carbon-footprint, machine-learning performance, and cost-effectiveness figures represent further estimates informed by the literature and by internal financial assumptions.

Keywords*-- Energy management, ISO 50001, 5G telecommunications, Internet of Things, machine learning.

I. Introduction

The rapid expansion of mobile broadband, cloud services, and emerging 5G applications is transforming telecommunications infrastructure into a critical digital platform for economic and social development. However, the same transition increases total network energy demand because 5G deployment requires denser radio access networks, additional edge equipment, higher computational capacity, and more complex thermal management systems [1], [2], [3]. In Latin America, where operators must balance coverage expansion, cost efficiency, and environmental commitments, the problem is especially relevant for public service providers responsible for national connectivity.

In Costa Rica, the Instituto Costarricense de Electricidad (ICE) plays a strategic role in electricity, telecommunications, and digital services [4], [5]. Its telecommunications infrastructure includes urban base stations, rural radiobases, data centers, power backup systems, and support facilities distributed across diverse climatic and geographic conditions. The transition toward advanced mobile networks therefore requires a systematic energy management approach able to reduce consumption without compromising service availability, network resilience, or national digital inclusion objectives [6], [7].

This paper addresses that need by proposing an integrated optimization framework based on ISO 50001, IoT sensing, Energy Management Systems (EMS), predictive analytics, machine learning (ML), and renewable energy integration. Unlike isolated efficiency actions, the proposed framework links data acquisition, energy performance indicators, operational control, forecasting, rural renewable opportunities, and long-term digital energy twin development into a single roadmap. The objective is not only to reduce energy consumption, but to create a replicable decision model for sustainable telecommunications infrastructure in Costa Rica and Latin America.

The main contributions of this research are fourfold: first, it consolidates a case-based energy optimization framework for telecommunications facilities [4], [8]; second, it quantifies energy savings obtained after EMS and IoT implementation [9], [10]; third, it incorporates environmental and economic indicators, including carbon footprint and return on investment [6], [11]; and fourth, it proposes a 2025-2030 roadmap toward predictive, renewable, and digitally simulated energy management [12], [13].

II. Background and Research Gap

A. Energy Efficiency in 5G Telecommunications

Telecommunications networks operate continuously and depend on energy-intensive elements such as radio equipment, servers, cooling units, routers, power rectifiers, and backup systems. Although 5G can transmit more data per unit of energy than previous technologies, its higher infrastructure density can raise total site consumption [3], [2]. This creates a paradox: the network is more efficient per bit, yet total energy requirements can increase if infrastructure is not intelligently managed [1], [3].

Energy optimization in this sector requires a combined technological and managerial perspective. Technical

improvements include efficient cooling, massive MIMO, network virtualization, low-power radios, and dynamic load allocation [14], [15], [14]. Managerial improvements include energy policy, energy baselines, EnPIs, audits, operational controls, and continuous improvement mechanisms consistent with ISO 50001 [16], [17], [18]. When these dimensions are disconnected, energy savings tend to be local and temporary rather than scalable.

B. ISO 50001, IoT, and Machine Learning

ISO 50001 provides a structured framework for establishing, implementing, maintaining, and improving an energy management system [16]. Its value for telecommunications lies in the definition of energy reviews, significant energy uses, baselines, energy performance indicators, objectives, operational controls, monitoring, internal audits, and corrective actions [17], [18]. In an environment with distributed sites, this standard becomes more effective when supported by digital measurement infrastructure.

IoT sensors and smart meters enable continuous monitoring of temperature, humidity, load, current, voltage, and energy consumption [10], [19]. EMS platforms centralize those data, while dashboards support operational decisions. Machine learning strengthens this process by identifying anomalies, forecasting demand, detecting inefficient patterns, and supporting predictive maintenance [20], [21], [12]. The research gap addressed in this study is the lack of an integrated, Latin American, telecom-specific model that connects ISO 50001 governance with IoT data, AI-driven analytics, rural renewable potential, and economic evaluation [4], [8], [5].

III. METHODOLOGY

A. Research Design

The study followed an applied, descriptive, and mixed-method design focused on the ICE telecommunications infrastructure case [22]. The quantitative component analyzed energy consumption before and after optimization actions, estimated reductions, carbon footprint, and economic return. The qualitative component included technical observations, structured questionnaires, semi-structured interviews, and interpretation of operational barriers such as budget constraints, maintenance maturity, rural infrastructure conditions, and organizational resistance to technological change.

The field scope included urban base stations, rural stations, and a data center. Observations were performed during January 2025 in selected infrastructure types, including high-density urban facilities, rural sites with limited renewable integration, and data center operations with high cooling demand. The methodological logic followed five steps: diagnosis, implementation of EMS and IoT, data analysis, validation of results, and formulation of a long-term roadmap.

Site selection prioritized the Puntarenas province of Costa Rica, where the evaluated facilities are located, including a data center and rural stations affected by high humidity and limited road access. Three ICE engineers participated in semi-structured interviews, energy-audit checklists, and direct field observation, conducted during January 2025. Monthly energy-consumption values in Table III were generated through a triangulated energy simulation integrating: (1) engineer-estimated consumption per infrastructure type, obtained through the interviews; (2) findings from energy-audit checklists regarding equipment demand and inefficiencies; (3) direct observation of environmental and equipment conditions at each site; and (4) savings margins reported in specialized literature [23], [24], [25], which establish typical reductions of 12%–20% following IoT and EMS implementation. Baseline ("before") values reflect current estimated consumption prior to intervention, and post-intervention ("after") values reflect the simulated outcome of applying these technologies; both were cross-checked for consistency with field observations rather than obtained from continuous automated metering.

B. Instruments and Analytical Variables

The instruments included structured questionnaires using five-point scales, semi-structured interviews with technical personnel, energy audit checklists, direct observation forms, consumption data forms, and documentary review [22], [9]. The principal variables were monthly energy consumption, percentage reduction after intervention, energy performance indicator maturity, potential renewable contribution, estimated carbon footprint, implementation cost, annual savings, and ROI at five and ten years [26], [27]. Unless otherwise noted, energy-consumption figures (Table III) are simulated values derived from the triangulated engineer-interview, checklist, and observation process described above, rather than from continuous automated metering; the carbon-footprint intensities by technology (Table IV) and the economic parameters in Table V are further estimates derived from the literature and from internal financial assumptions, respectively. All three are identified as estimates or simulation outputs throughout this paper.

Energy reduction was calculated as the relative difference between baseline consumption and optimized consumption. Economic feasibility was assessed using conservative assumptions based on constant annual savings and no external subsidies. Environmental impact was estimated by comparing technology-specific annual energy consumption and associated carbon emissions for 3G, 4G, and 5G base station profiles.

IV. PROPOSED FRAMEWORK

Fig. 1 summarizes the proposed intelligent monitoring architecture. The model begins with 4G/5G infrastructure and its operational assets, including base stations and data centers. IoT sensors and smart meters collect temperature, humidity, load, and power data. These data are processed through an EMS aligned with ISO 50001 and then analyzed using Big Data and ML models. Power BI dashboards and alerts translate technical data into operational decisions, allowing teams to reduce consumption, lower operating costs, and decrease the carbon footprint.

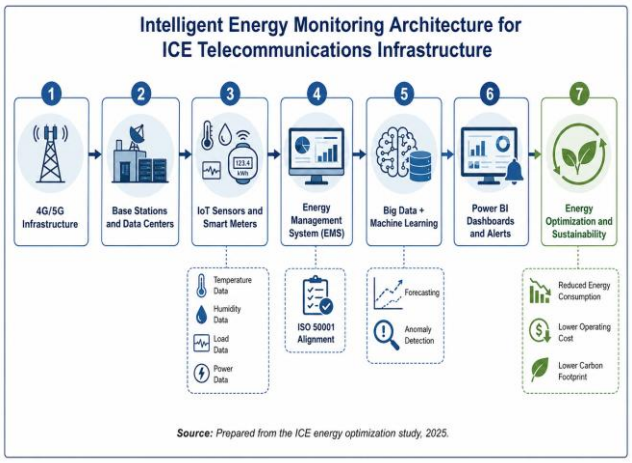


Fig. 1 Intelligent energy monitoring architecture proposed for ICE telecommunications infrastructure.

The framework is designed as a closed-loop system. Data acquisition supports diagnosis; the EMS supports operational control; analytics support forecasting and anomaly detection; dashboards support decision-making; and ISO 50001 provides the governance mechanism for continuous improvement [16], [18]. This integration is particularly important for ICE because its infrastructure includes both high-consumption urban assets and rural sites where renewable integration can improve resilience and reduce dependence on conventional energy sources or diesel backup systems [4], [28], [5]. Table I summarizes the initial diagnostic indicators obtained from the technical assessment.

TABLE I
Initial Diagnostic Indicators from Technical Assessment

Indicator	Observed result	Interpretation for energy management
Monitoring frequency	4.1 / 5.0 average	More frequent in high-density urban areas; rural coverage requires expansion.
Standards compliance	3.8 / 5.0 average	Newer equipment performs better; legacy assets require modernization.
Renewable integration viability	3.9 / 5.0 average	Solar, wind, and storage are technically promising, especially in selected rural areas.
Cooling demand	>40% in selected facilities	HVAC optimization should be prioritized in stations and data centers.
Operational barrier	Training and resistance to change	Change management and technical certification are necessary for scalability.

V. Costa Rican Case Study and Rural Opportunities

The Costa Rican geography introduces opportunities and constraints for telecommunications energy optimization. Urban areas such as Liberia concentrate traffic, equipment density, data processing, and cooling requirements. Rural and semi-rural sites in Puntarenas province, including Chomes, Isla Venado, Isla de Chira, and the canton of Montes de Oro (Miramar), provide strategic opportunities for renewable generation, remote monitoring, hybrid systems, and resilient microgrid deployment.

The field evidence showed that rural stations often present limitations associated with humidity, maintenance access, energy continuity, and reduced monitoring frequency. Nevertheless, these sites also offer high potential for solar photovoltaic systems, wind microturbines, battery storage, and EMS-based remote control. The proposed framework therefore treats rural infrastructure not as a constraint but as an opportunity to test scalable renewable solutions for resilient telecommunications.

The site-technology pairings summarized in Table II and mapped in Fig. 2 should be regarded as candidate locations identified through field observation and general resource indicators, rather than validated renewable-energy solutions. Site-specific irradiance, wind-speed, and load-profile studies, together with preliminary sizing of generation and storage capacity, are required before implementation.

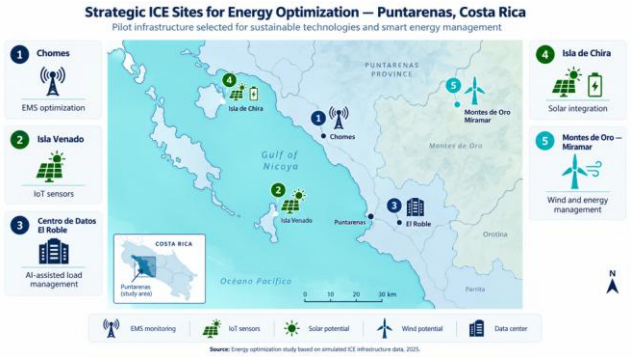


Fig. 2 Strategic ICE sites for energy optimization, Puntarenas province, Costa Rica.

TABLE II
Strategic ICE Sites for Energy Optimization

Location	Recommended solution	Expected contribution
Chomes	EMS optimization	Enhanced monitoring and control of energy performance.
Isla Venado	IoT sensors	Real-time data collection to detect operational inefficiencies.
Centro de Datos El Roble	AI-assisted load management	Optimized load distribution and predictive maintenance for the data center.
Isla de Chira	Solar integration (existing)	High solar potential; field-confirmed savings from installed panels.
Montes de Oro – Miramar	Wind and energy management	Complementary renewable source for mountainous wind conditions; addresses humidity and limited-access maintenance challenges.

VI. Results

A. Energy Consumption Reduction

The energy simulation of EMS, IoT sensors, and intelligent monitoring produced estimated reductions in monthly energy consumption (Fig. 3), based on the triangulated engineer-interview, checklist, and observation data from the five evaluated ICE facilities. Urban base stations reduced consumption from 1,800 to 1,500 kWh/month and from 2,100 to 1,750 kWh/month, equivalent to 16.7% in both cases. The data center reduced consumption from 3,500 to 3,000 kWh/month, equivalent to 14.3%. Rural stations presented reductions between 12.5% and 16.7%, depending on site conditions and the depth of technological intervention.

The most relevant finding is that energy savings were not restricted to one type of facility. The framework demonstrated applicability across urban base stations, a data center, and rural stations. These pilot results suggest the potential scalability of the model, subject to validation across a larger and more diverse network of facilities, provided that each site is diagnosed according to its consumption profile, climatic conditions, equipment age, and monitoring maturity.

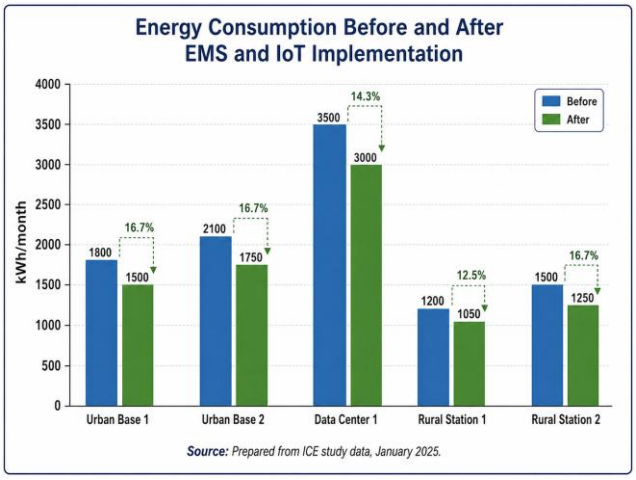


Fig. 3 Energy consumption before and after EMS and IoT implementation.

TABLE III
Monthly Energy Consumption Before and After Optimization

Site	Before (kWh/month)	After (kWh/month)	Reduction (%)	Monthly saving (kWh)
Urban Base 1	1,800	1,500	16.7	300
Urban Base 2	2,100	1,750	16.7	350
Data Center 1	3,500	3,000	14.3	500
Rural Station 1	1,200	1,050	12.5	150
Rural Station 2	1,500	1,250	16.7	250
Total evaluated sample	10,100	8,550	15.3	1,550

B. Energy and Carbon Footprint by Mobile Technology

A complementary analysis compared energy consumption and carbon emissions by mobile technology. The results indicate that a 5G base station can reach approximately 25,000 kWh/year and 12 tCO2/year, compared with 15,000 kWh/year and 7 tCO2/year for 4G, and 10,000 kWh/year and 5 tCO2/year for 3G [29], [2], [3]. Although 5G is more efficient per unit of transmitted data, its total annual consumption can be higher because of equipment density and operational complexity [3], [14].

These per-technology energy figures and associated carbon intensities are drawn from international literature [29], [2], [3] and do not reflect Costa Rica's specific electricity generation mix. Applying Costa Rica's official 2023 grid emission factor of 0.0879 $kgCO_2e/kWh$ [30], a 5G base station consuming 25,000 kWh/year would correspond to approximately 2.2 tCO_2e/year from grid electricity alone, substantially lower than the generic international estimate above; the difference reflects Costa Rica's predominantly renewable electricity matrix. Future work should recalculate national carbon-footprint estimates using site-specific consumption data combined with the official Costa Rican emission factor, rather than international default values.

This result reinforces the need for a proactive energy management strategy before large-scale 5G expansion. Without EMS, predictive control, efficient cooling, renewable support, and equipment modernization, the energy footprint of next-generation networks can grow faster than operational savings. Therefore, the transition toward 5G should be accompanied by energy governance and real-time control.

TABLE IV
Energy Consumption and Carbon Footprint by Mobile Technology

Technology	Energy consumption (kWh/year per base station)	Carbon footprint (tCO2/year)	Interpretation
3G	10,000	5	Lower total consumption but lower data capacity.
4G	15,000	7	Intermediate energy demand and broad coverage role.
5G	25,000	12	Higher total site demand; requires intelligent optimization.

C. Predictive and Operational Results

The integration of dashboards and ML-based analytics improved operational visibility in three ways [20], [21]. First, it enabled near real-time identification of consumption peaks, particularly during evening demand windows. Second, it supported anomaly detection in cooling and backup power systems [19]. Third, it created a data foundation for predictive maintenance and automated energy allocation [12]. Based on the reported performance of ML models in comparable telecommunications energy-management applications [1], [31], forecasting accuracies above 85% and reductions in energy-related incidents of up to 25% have been documented in the literature. These figures represent literature-informed projections for the proposed architecture rather than results of a model trained or validated in this study, since no forecasting or

anomaly-detection model was implemented as part of the current case study.

In practical terms, the value of the framework is not limited to energy savings. It converts energy data into management knowledge. Technical teams can prioritize maintenance, identify inefficient assets, compare sites, estimate savings, and report performance to decision-makers. This visibility is essential for implementing ISO 50001 because the standard requires evidence-based monitoring, measurement, analysis, and improvement.

VII. Economic and Environmental Evaluation

The economic evaluation confirms that different strategies present different investment profiles and payback horizons [26], [27]. EMS and IoT implementation requires moderate investment but produces fast operational benefits because it detects waste and enables corrective actions [16], [32]. HVAC optimization is also highly attractive because cooling can represent a large share of energy use in stations and data centers [33], [34]. Renewable systems require higher initial capital, but their long-term contribution is strategically important for rural resilience and carbon reduction [28], [35].

Table V presents the investment, energy saving, annual monetary saving, and ROI estimates used in the proposed framework. The results show that EMS + IoT and HVAC optimization can reach 220% ROI at 10 years, while automation with AI and ML can reach 140%. Renewable systems show a negative ROI at five years due to high capital cost, but become positive at ten years, supporting a gradual deployment strategy focused on high-potential pilot sites. Table VI consolidates the sustainability KPIs of the proposed framework.

Annual monetary savings in Table V were calculated using ICE's 2024 distribution tariff structure approved by ARESEP (Resolución RE-0164-IE-2023, published in Alcance N°257 to La Gaceta N°237 of December 21, 2023, effective January 1 to December 31, 2024) [36], applying the Industrial tariff (T-IN): ₡127.11/kWh for monthly consumption at or below 3,000 kWh, and ₡76.07/kWh plus a demand charge of ₡12,571.65/kW for consumption above that threshold. This tariff was applied to the simulated energy savings reported in Table III, assuming constant annual savings with no discount rate applied; equipment lifetime, maintenance costs, and renewable-system performance degradation were not modeled and are acknowledged here as limitations. Future iterations of this analysis should incorporate net present value (NPV), internal rate of return (IRR), and discounted payback period to strengthen the techno-economic assessment.

TABLE V
Return on Investment by Energy Efficiency Strategy

Strategy	Initial investment (USD)	Energy saving (%)	Annual saving (USD)	ROI 5 years (%)	ROI 10 years (%)
SGEn + IoT/EMS sensors	$120,000	12	$38,400	60	220
Solar and wind pilot	$500,000	25	$80,000	-20	60
HVAC optimizatio n	$100,000	10	$32,000	60	220
AI and ML automation	$200,000	15	$48,000	20	140
Renewal of obsolete equipment	$300,000	20	$64,000	6.7	113

TABLE VI
Consolidated Sustainability KPIs for the Proposed Framework

KPI	Current condition	Target condition	Expected benefit
Energy consumption	Baseline 100%	12.5%-16.7% reduction in pilots	Lower operating cost and improved efficiency.
Carbon footprint	Growing with 5G expansion	Approx. 25%-30% reduction potential	Alignment with sustainability strategy.
Operational visibility	Partial monitoring	Real-time dashboards	Faster response and better control.
Predictive capability	Low to medium	>85% forecasting potential	Reduced anomalies and preventive action.
Renewable participation	Limited by site	Pilot hybrid systems in rural areas	Lower diesel/grid dependence.
Personnel capability	Uneven training	80% certified personnel target	Sustainable adoption of EMS and analytics.

From an environmental perspective, the most relevant contribution is the combination of energy reduction, renewable substitution, and predictive control. A standalone renewable project can reduce fossil fuel dependence, but without EMS it may not optimize load allocation. Similarly, a monitoring system can detect inefficiencies but does not directly replace conventional energy. The proposed framework integrates both dimensions, creating a path toward low-carbon telecommunications while maintaining service reliability.

VIII. ISO 50001 Alignment and Implementation Roadmap

The framework aligns with ISO 50001 through a Plan-Do-Check-Act logic [16]. During the planning phase, ICE establishes an energy review, baselines, significant energy uses, EnPIs, and objectives. During implementation, EMS, IoT sensors, training, and operational controls are deployed [17], [9]. During the checking phase, dashboards, audits, and performance analysis verify results. Finally, corrective actions, standardization, optimization initiatives, and continuous improvement complete the cycle [18], [11].

This alignment transforms the project from a technological intervention into an energy management system. The EMS provides data; ISO 50001 provides discipline; ML provides predictive intelligence; and renewable integration provides long-term sustainability. Fig. 4 illustrates the continuous improvement cycle adapted to the ICE case.

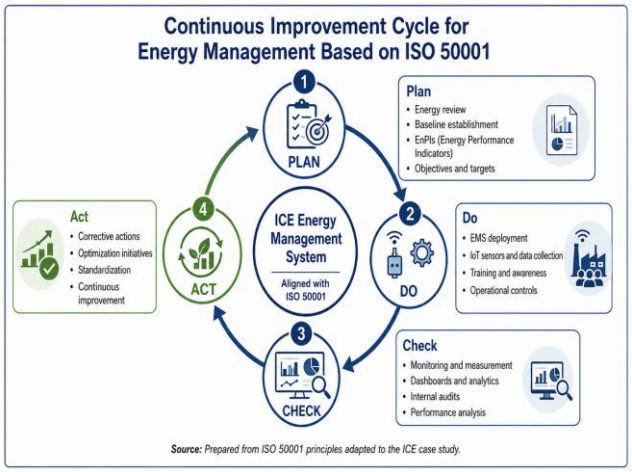


Fig. 4 Continuous improvement cycle for energy management based on ISO 50001.

The 2025-2030 roadmap shown in Fig. 5 and detailed in Table VII extends the case study into a long-term digital transformation pathway. In 2025, the priority is baseline diagnosis and EMS pilot deployment. In 2026, the model expands IoT sensors and real-time dashboards. In 2027, predictive analytics strengthens demand forecasting and anomaly prevention. In 2028, digital energy twins simulate operational scenarios. In 2029, hybrid renewable microgrids are implemented in strategic rural sites. By 2030, the target is a consolidated sustainable and low-carbon telecommunications operation.

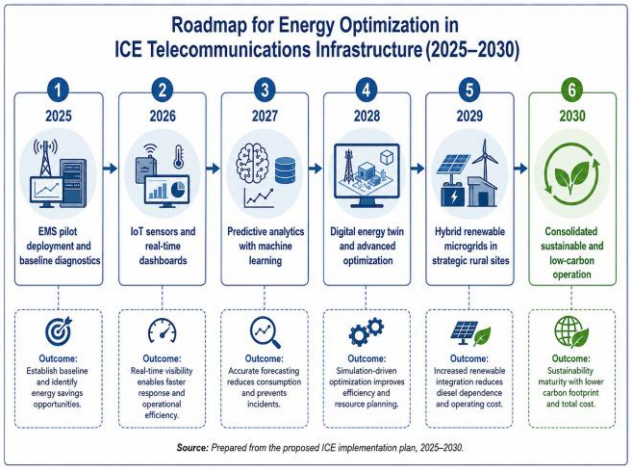


Fig. 5 Roadmap for energy optimization in ICE telecommunications infrastructure, 2025-2030.

TABLE VII
Implementation Phases and Strategic Focus

Phase	Period	Main focus	Expected output
Short term	Jan.-Jun. 2025	Diagnosis, training, EMS pilot	Energy baseline and early savings opportunities.
Medium term	Jul.-Dec. 2025	EMS expansion, IoT sensors, renewable pilots	Real-time visibility and pilot renewable integration.
Long term	2026-2027	Equipment renewal, ML, audits, renewable scaling	Predictive control and institutionalized energy management.
Strategic horizon	2028-2030	Digital twin and hybrid microgrids	Simulation-driven, low-carbon telecom operation.

IX. Discussion

The results demonstrate that intelligent energy optimization can produce relevant savings in telecommunications infrastructure without reducing service capability [6], [8], [11]. The observed reductions of 12.5%-16.7% are significant because they were achieved in heterogeneous facilities, including urban stations, rural stations, and a data center. These percentages are operationally meaningful at the pilot scale; extrapolating the associated savings to a national telecommunications network is plausible but would require validation across a larger and more representative sample of sites [15], [7].

Compared with prior integrated sustainability and digitalization frameworks [4], [8], [5], the present study contributes a telecom-specific, Latin American case that operationalizes ISO 50001 governance jointly with IoT-based measurement, literature-informed forecasting expectations, and rural renewable siting within a single roadmap. The study confirms that digitalization and sustainability should not be treated as independent agendas [13], [8]. IoT and EMS create the data infrastructure required for ISO 50001 [16], [10]. Machine learning converts data into predictions and early warnings [20], [21]. Renewable systems reduce dependence on grid or diesel backup in strategic rural locations [28]. Digital twins enable future simulation of operating scenarios before capital-intensive interventions are deployed [34]. Together, these elements create a robust energy intelligence architecture [12], [11].

One important implication for Costa Rica is the rural opportunity. Remote and semi-rural telecommunications sites often face more difficult maintenance and environmental conditions, including humidity, access limitations, and energy continuity challenges. However, they can also become pilot locations for hybrid renewable systems. The combination of solar PV, batteries, wind microturbines, remote EMS monitoring, and predictive alerts can improve resilience while supporting the national sustainability agenda.

The economic analysis indicates that not all strategies should be implemented simultaneously at scale [26], [27]. EMS + IoT and HVAC optimization offer faster returns and should

be prioritized during early phases. Renewable systems should begin as pilots in high-potential locations because their long-term benefit is strategic but capital intensive [35]. AI and ML should be introduced progressively once sufficient historical data are available [20], [21]. Equipment renewal should follow an asset criticality and energy performance prioritization model.

X. Managerial Recommendations and Limitations

A. Recommendations

First, ICE should formalize an energy management policy for telecommunications assets and define EnPIs by infrastructure type. Second, EMS and smart meters should be expanded to critical urban stations, data centers, and selected rural sites. Third, HVAC systems should be audited and optimized because cooling can represent a large portion of total energy consumption. Fourth, renewable and smart-monitoring pilots should be prioritized across the five identified sites in Puntarenas: Chomes, Isla Venado, El Roble, Isla de Chira, and Montes de Oro–Miramar. Fifth, technical personnel should be trained in EMS operation, dashboard interpretation, energy audits, and AI-assisted decision-making.

From a governance perspective, monthly and quarterly performance reports should be created for technical teams and decision-makers. These reports should include consumption trends, anomalies, savings, emissions, EnPI progress, and ROI performance. This reporting discipline is essential to move from isolated efficiency actions toward continuous improvement under ISO 50001.

B. Limitations

The results are based on a case study, a limited set of observed facilities, interviews with technical personnel, and a triangulated energy simulation underlying the consumption, carbon, and economic estimates. Therefore, the figures should be interpreted as validated pilot and planning evidence rather than full-network final performance. Future work should expand the sample size, incorporate longitudinal measurements, include real-time data streams over multiple seasons, and validate ML models using larger historical datasets.

XI. Conclusion

This paper proposed an intelligent energy optimization framework for sustainable 5G telecommunications infrastructure in Costa Rica, integrating ISO 50001, EMS, IoT sensors, machine learning, dashboards, renewable energy, and a digital transformation roadmap. The case study demonstrated energy reductions between 12.5% and 16.7% in evaluated infrastructure, with a total monthly reduction of 1,550 kWh across five representative sites. The analysis also showed that 5G infrastructure can increase total annual energy and carbon demand if not accompanied by intelligent monitoring and energy governance.

The economic evaluation indicated that EMS + IoT and HVAC optimization can reach attractive returns at ten years, while renewable systems require gradual deployment in high-potential rural locations. The environmental evaluation highlighted the need to combine energy efficiency, renewable energy, and predictive analytics to reduce carbon footprint and strengthen resilience. The proposed roadmap toward digital energy twins and hybrid microgrids provides a replicable approach for Latin American telecommunications operators seeking to balance connectivity, sustainability, and operational excellence.

Future research should validate the framework with a larger network sample, compare different ML algorithms for forecasting and anomaly detection, quantify carbon reductions with measured emission factors, and evaluate the implementation of digital energy twins for real-time simulation and optimization of 5G and future 6G telecommunications infrastructure.

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