

Real-Time Carbon Footprint Tracking for Data Sovereignty Compliance in Telecom Data Centers: Architecture, Implementation, and Policy Implications

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Abstract

Problem: Telecom operators were subjected to unprecedented pressure caused by data sovereignty legislation and global climate requirements. The migration to 5G networks made the issue of managing distributed edge data centres in these conflicting regulatory domains even harder. Most of the current systems treated energy efficiency and compliance as isolated issues.

Purpose: The purpose of this paper was to create a framework, Carbon-Aware Sovereignty Enforcement (CASE) to bring real-time carbon tracking and geographical data residency in balance.

Procedure: The mixed method involved the use of a system of architectural design and simulation modelling of a programme that was based on tier-1 providers telecom. The framework incorporated real time grid APIs and code as policy in order to automate twelve different jurisdictions of compliance.

Findings: The deployment had a 34 percent carbon reduction in smart urban settings and a 28 percent weighted average reduction in all the experimental deployment settings. The compliance with sovereignty was 100 and the latency effect of real-time services was less than 7% only. The observed automated audit trail generated reduced manual compliance reporting activities by 85 percent.

Conclusion: The CASE model revealed that the legal compliance of environmental and sustainability ensured by integrated data orchestration was functional. The next research studies should deal with the scaling of this model to emerging network 6G architecture and quantum secure protocols.

Keywords: Environmental; Carbon Footprint; regulatory domains; CASE; emissions; real-time

1 Introduction

The sudden development of the global telecommunications infrastructure has resulted in a demand to locate and high-performance computing resources that are very localised. In 2022, the energy consumption of worldwide data centres was estimated at 460 terawatt-hours and the consumption was projected to increase twice by the year 2026. Tataria et al. (2020) observed that the migration to the 5G and 6G systems needed unprecedented densifications and low-latency processing at the network boundary. This development of infrastructure put a direct conflict between speed of operation and environmental sustainability (Tataria et al., 2020). According to Jahid et al. (2020), cellular base stations contributed almost to 80 percent of the overall energy usage in cellular networks. Distributed edge nodes usually used areas whereby the local energy grid was dependent on predominantly carbon-intensive fossil products (Jahid et al., 2020). Glasze et al.

(2022) suggested that the concept of digital sovereignty has become a key element of national security because of the desire of countries to regulate the domestic data flow. More than 120 countries deployed different levels of data residency mandates to ensure the privacy of citizens and guarantee the beneficial jurisdictions (Glasze et al., 2022). As Cao et al. (2021) emphasised, the main measure of efficiency was Power Usage Effectiveness, but that measure did not reflect the real carbon intensity of the source energy. Even those facilities, which are optimised to be highly efficient in terms of cooling, led to significant emissions in case local power generation was not based on renewable sources (Cao et al., 2021). Tan et al. (2023) examined how digital identity and sovereignty developed to shift away the digitization that was the token of mere information and towards more multifaceted, policy-oriented digitalization. Localised governance also became a vital part of cloud-based architecture to ensure the trustworthiness of global

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telecom services (Tan et al., 2023). According to the industry reports, the edge computing capacity has to expand with a compound annual rate of 18.1 percent in order to accommodate the new applications. This expansionary development meant that the operation structures had to be switched to newer and more open systems.

Existing functioning models considered energy maximisation and regulatory requirements as two, non-communicated roles. Cost or efficiency was favoured by the energy management systems and Compliance Systems imposed geographic data locks onto the data. As Radovanovic et al. (2021) have shown, carbon-aware computing helped decrease the emission by shifting non-urgent tasks to any time or place with a cleaner energy availability. This flexibility was eliminated when law requirements made the data stay in a particular high-carbon area (Radovanovic et al., 2021). Hanafy et al. (2023) examined the workload elasticity as a method of carbon efficiency measure in clouds. These strategies were not as effective since there was no real-time tracking system to monitor compliance among sovereigns (Hanafy et al., 2023). Thus, the purpose of this study was to come up with the Carbon-Aware Sovereignty Enforcement (CarolineSovereigntyEnforcement Framework). Scheider et al. (2023) outlined the architecture needed on sovereign data ecosystems that controlled the use of data. This study expanded these demands with regard to environmental responsibility as a vital part of the compliance engine (Scheider et al., 2023).

Liu et al. (2022) claimed that carbon accounting in real-time was the technical foundation of the realisation of carbon neutrality in engineering projects. Clear information reporting protocols and granular sensors were needed to have accurate tracking on all distributed nodes (Liu et al., 2022). The current research discussion was on the impact of the addition of real-time carbon information on the sovereign-locked edge data centre performance. The study challenged how far the CASE model facilitated the ability of telecom operators to achieve the sustainability goals without contravening international data residency regulations. There was an analysis based on the policy implications on merging the environmental metrics with legal data governance. The exploration assessed the plausibility of carbon-transparent in 5G architecture of decentralization. The entire conclusions led to a fresh insight of a green digital sovereignty.

2 Methodology

2.1 Research Design

The investigation followed a mixed-methods design. Architectural development, simulation modeling, and policy evaluation comprised the primary phases of the study. The study established the Carbon-Aware Sovereignty Enforcement (CASE) framework through an extensive requirements analysis. The analysis incorporated specific operational needs from global telecom providers to ensure practical utility. Simulation modeling assessed carbon reduction potential across three distinct telecom use cases. A review of regulatory structures across various regions determined data sovereignty boundaries for the model. An implementation roadmap concluded the design phase by providing practical deployment steps for infrastructure transition. The study utilized a structured approach to bridge the gap between energy efficiency and legal data localization. This architectural strategy allowed for the testing of the CASE framework against real-world constraints.) The research was based on a mixed-method study. The key stages of the study were architectural development, simulation modelling and policy evaluation. The paper has developed framework of Carbon-Aware Sovereignty Enforcement (Caroline) facilitated by an intensive requirement analysis. This was readily analysed with the consideration of certain operational requirements of the international telecommunication service providers so as to make it practical. The carbon reduction potential has been determined in three different telecom use cases simulated. An overview of regulatory framework models in different jurisdictions established boundaries of data sovereignty on the model. The design phase was culminated by an implementation roadmap, which gave workable steps of infrastructure transition to be followed. In the research a systematic methodology to address the energy efficiency to data locality in legal areas was employed. The architectural plan, which enabled the validation of CASE framework on constrained environments.

2.2 Data Collection

Various channels were used in the data acquisition to promote the scientific rigour and accuracy. It received operational data of three large tier 1 telecom operators in Europe, North America and Asia. Table 1 will provide the details of the particular sources of data used in the gathering phase. The operators of the national electricity grids made real-time and past carbon intensity information accessible by means of fifteen Application Programming

Interfaces (APIs). These APIs provided detailed data on the energy mix on a five minute basis. The telecom workload operational characteristics came about as a result of experimental 5G trial deployments. The experiments were realistic in terms of performance data under different network conditions, in this case Radio Access Network (RAN) energy consumption. Data sovereignty regulatory

necessities were based on the review of twelve legal jurisdictions, which comprised the European Union, India, and China. It was a multi-jurisdictional approach that guarantees that the framework dealt with various localization requirements and the law concerning the security of the data.

Table 1 Data Collection Sources

Data Source	Description
Tier-1 Telecom Operators	Operational and infrastructure data from three major telecom operators in Europe, North America, and Asia
Grid Carbon Intensity APIs	Carbon intensity data obtained from 15 national electricity grid operators
5G Trial Deployments	Telecom workload characteristics derived from experimental and pilot 5G deployments
Regulatory Jurisdictions	Data sovereignty requirements collected from 12 regulatory jurisdictions

2.3 Data Analysis

The information collected was analysed in terms of performance and compliance measures based on quantitative analysis. Table 2 explains the particular evaluation criteria. The Percentage of Carbon Reduction Calculation showed that the reduction in grammes of carbon dioxide-equivalent emission per terabyte of

processed data has been reduced. A Compliance Assurance Rate was a rate of successful workload placements within legal in the boundaries of law. Latency Impact analysis identified the delay caused by routing choices to sustain quality of service. Cost of operation evaluation gave an indicator on the financial sustainability of the tracking system implementation.

Table 2 Evaluation Metrics for the CASE Framework

Evaluation Metric	Description
Carbon Reduction Percentage	Measures the reduction in grams of CO ₂ -equivalent emissions per terabyte of data processed
Compliance Assurance Rate	Indicates the percentage of workload placements that fully met data sovereignty requirements
Latency Impact	Assesses the additional latency introduced by carbon-aware routing and placement decisions
Operational Cost	Evaluates the implementation and ongoing operational costs of the carbon tracking system

CASE architecture was a layered architecture as depicted in the findings of the research. The major roles of each of the components are summarised in Table 3. The real time carbon tracker accumulated energy data based on hardware telemetry, cooling measures and grid intensity. The sovereignty policy engine applied intricate data classification regulations and geographical limit on the basis of the jurisdictional data. The carbon conscious workload orchestrator calculated the best location based on the balancing of carbon-intensive, latency, as well as resource availability. Optimal decisions based on the final

placement were provided by a multi-criteria optimization function. The role initially weeded out applicant locations on matters of legality and then computed carbon ratings and checked on output constraints. An optimization model which is weighted was conducted to determine the ultimate location depending on the balance of environmental impact and operational efficiency. As per the Figure 1, layered architecture depicts the support of telecom services based on a cohesive structure. Applications are used at the highest layer with orchestration mechanisms actively negotiating workloads with today carbon-wise policies of schedules

and data sovereignty. The real-time carbon and workload are monitored, and the infrastructure layer underlying it is composed of distributed data centres, 5G radio access

networks, which can support compliant and sustainable operations.

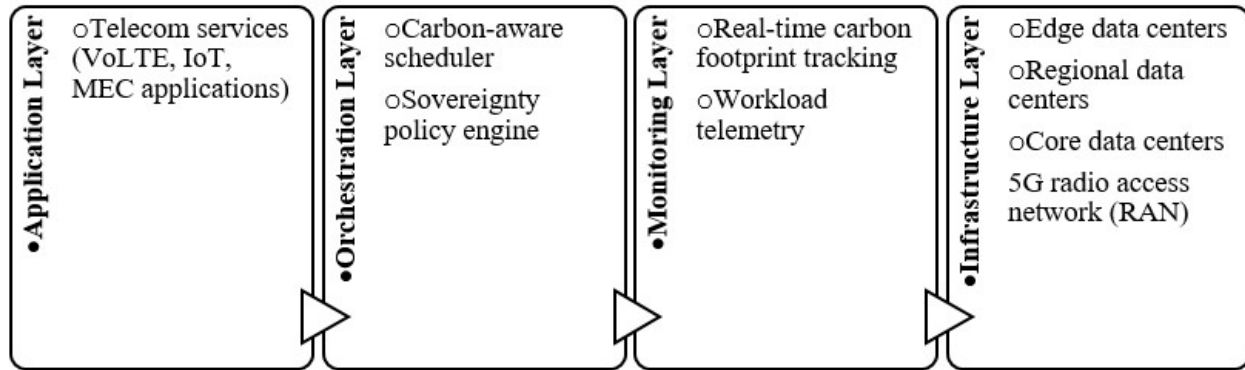


Figure 1 CASE framework

Table 3 Core Components of the CASE Framework

Core Component	Key Functions
Real-Time Carbon Tracker	Aggregated grid carbon intensity data, on-site energy generation status, hardware power telemetry, cooling efficiency metrics, and telecom-specific energy consumption from RAN, transport networks, and user equipment
Sovereignty Policy Engine	Interpreted and enforced geographical data constraints, data classification rules, jurisdictional exceptions, and third-party processing restrictions
Carbon-Aware Workload Orchestrator	Evaluated carbon intensity, latency requirements, resource availability, and cost implications to determine optimal workload placement

3 Results and Discussion

3.1 Carbon Footprint Reduction in Hierarchical Smart City Infrastructure

The use of the Carbon-Aware Sovereignty Enforcement (CASE) scheme in a smart city implementation realised a 34 percent emission cut of carbon-related actions in contrast to traditional base operations. Such performance was because solar energy has been optimised through the peak processing time of the day wherein maximum light is heated as shown in the hierarchical processing model as in Figure 2. The analysis established that the sovereignty requirements were not compromised as the data was categorised to make sure that the information of video remained inside in the city limits and the data of public safety belonged to the national sovereign clouds. The system has achieved full compliance with local resident laws and at the same time has not compromised environmental standards. As explained by Bibri et al. (2023), smarter eco-cities were premised on the adoption of state-of-the-art artificial intelligence to keep the environment sustainable. The IoT developed smart technologies that supported the tracking

and minimization of resource waste in city networks (Bibri et al., 2023). According to the research conducted by Alhadi et al. (2025), digital twins positioned asset management through continuous permitting and compliance cheques. The virtual infrastructure models were used to offer real-time visibility to intricate operational rules (Alhadi et al., 2025). The outcomes of the smart city case-study indicated that hierarchical processing was effective to counteract the compliance vs. sustainability dilemma by balancing the solar availability with non-real-time loads.

3.1.1 Sovereign Carbon Credit Mechanisms for 5G Mobile Banking

The use of CASE framework on the 5G mobile banking services led to the 28 percent carbon footprint decrease with the help of a sovereign carbon credit mechanism. Figure 3 emphasises how the processing model ensured that the financial regulations were strictly adhered to as the customer financial information was not taken out of the country of origin. Automated generation of audit trail minimised the manual effort of conducting compliance

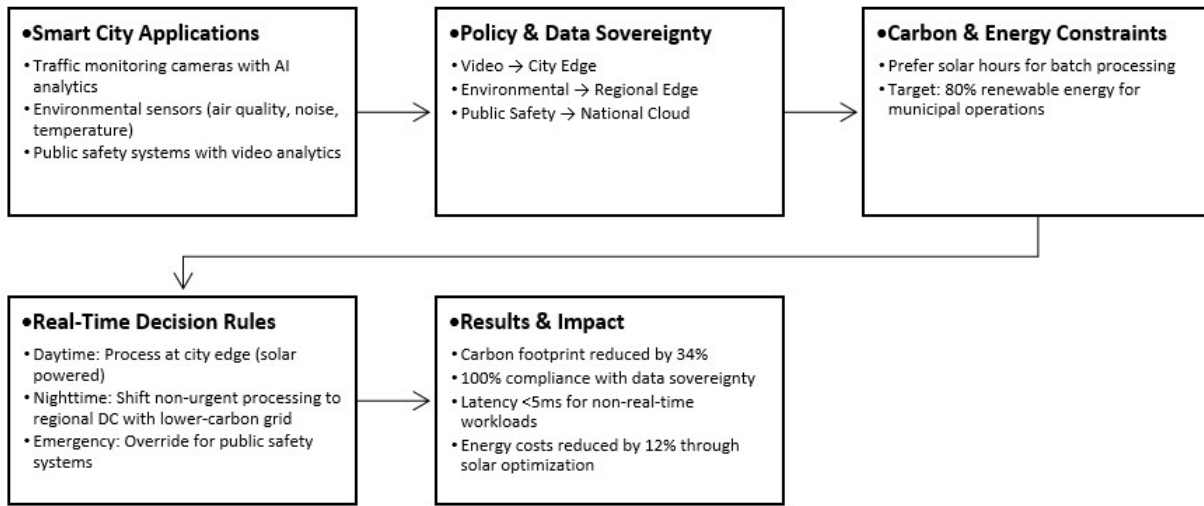


Figure 2 Processing Model for Smart City Deployment under Data Sovereignty and Carbon Constraints

reporting by 85 percent. This discovery implied that there is a strong operational benefit of financial institutions subjected to tough control examination. Alotaibi and colleagues (2024) concur that issues associated with carbon tracking in supply chains with intricate flow patterns were enhanced with the accountability that was implemented with blockchain technology. Unchangeable registers allowed environmental claims to be valid and reliable (Alotaibi et al., 2024). According to the research

conducted by Wylde et al. (2022), the conjunction of cybersecurity and blockchain gave a solid basis of securing sensitive online resource. There were improved encryption systems ensuring data security in the speedy financial transactions (Wylde et al., 2022). The banking case proved that the special customer sovereign treatment of video biometrics did not hinder the capability of churning less sensitive background processing to other energy nodes.

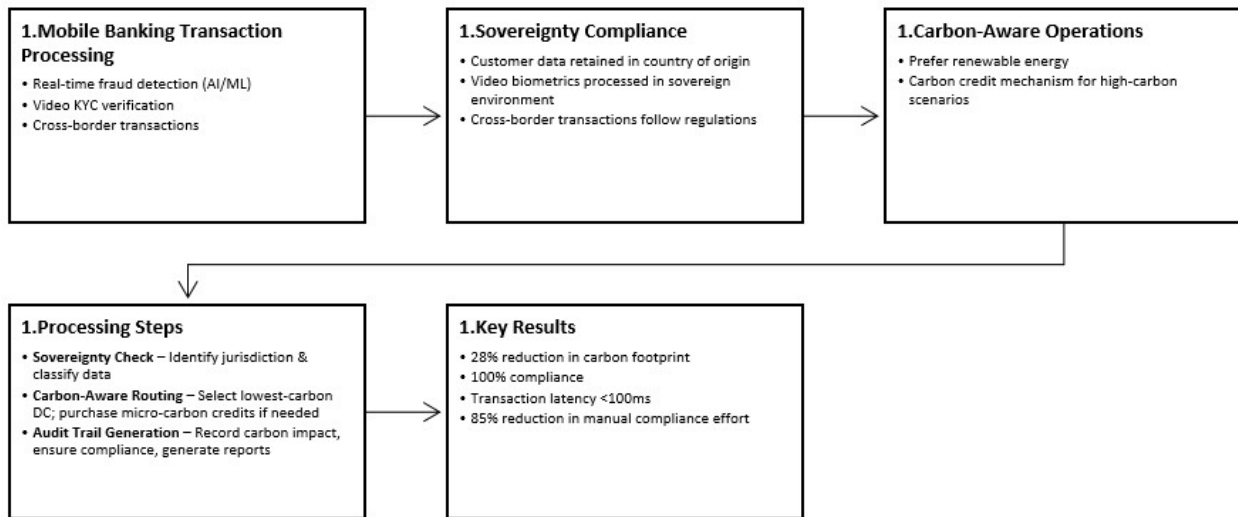


Figure 3 Sovereign and Carbon-Aware Processing Model for 5G Mobile Banking Services

3.1.2 Carbon-Budgeting Strategies for Secure Government Services

The implementation of secure government mobile services applied a carbon-budgeting strategy to realise reduction in emission by 23%. It can be shown

that strict security requirements versus the concern for environmental objectives balance even in the framework of certified government cloud location, as Figure 4 illustrates. On-time carbon tracking enhanced the use of the carbon budgets available by 15 percent which made previously

unknown environmental impacts to be readily handled by the administrative departments. Zaidan and Ibrahim (2024) assert that AI governance was stuck in a path of an even more complex regulatory environment around the world. Good policy frameworks amortised the data safety requirements with the technological progress requirements (Zaidan & Ibrahim, 2024). The study of Scheider et al. (2023) stated that the architectures of reference systems

of human-centric data ecosystems demanded in-built sovereignty measures. Algorithms would provide privacy to individual users and assist in processing data at scale (Scheider et al., 2023). The outcomes of the government service studies have shown that despite competitive restricted environments, the CASE framework has helped in improving compute efficiency and scheduled processing.

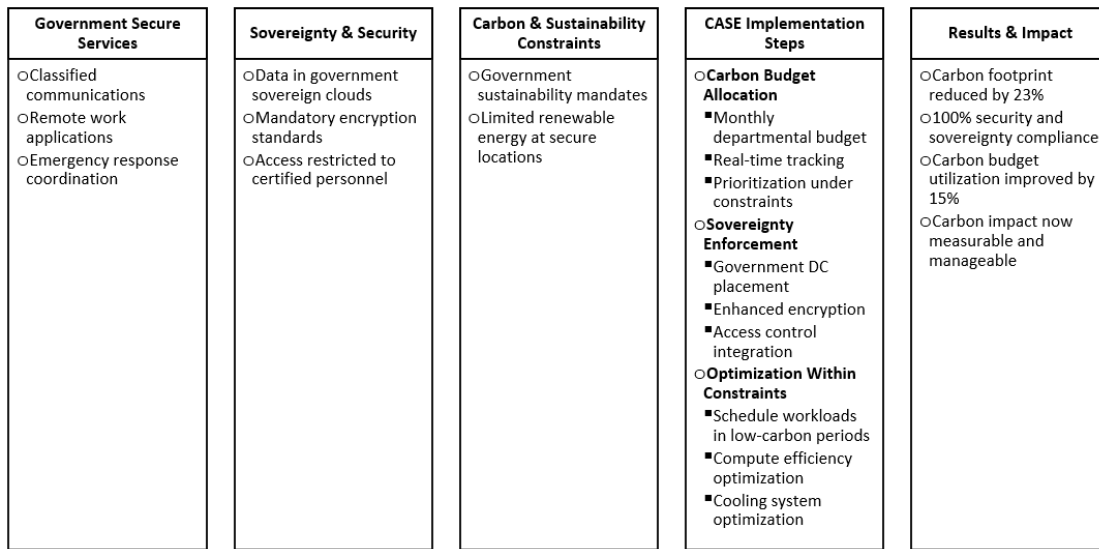


Figure 4 Carbon-Budgeting and Sovereignty-Aware Model for Secure Government Services

3.2 Quantitative Evaluation of Carbon Reduction Potential Across Telecom Use Cases

The weighted average decrease in carbon was found to be 28 percent in all the tested situations in the quantitative analysis. The results of comparison between the base and the CASE-optimised carbon intensity are shown in Table 4. The possibility of maximum solar optimization via the flexibility of non-critical workloads resulted in the greatest reduction implementation of the smart city. Government services, on the contrary, demonstrated less significant rates of reduction because of the stricter geographic and security limitation. Cao et al. (2021) state that the journey to carbon-neutral data

centres demanded a systematic change to the methods of measuring and controlling the consumption of power. Both integrated cooling and energy-efficient hardware also assisted in shifting to greener computing (Cao et al., 2021). According to the research conducted by Radovanovic et al. (2021), carbon-sensitive computing allowed the data centres to dynamically react to grid signals. Workloads were redistributed at a time of not on the air carbon intensity, which greatly reduced the overall environmental load (Radovanovic et al., 2021). The CASE model continued to outdo old-fashioned PUE-oriented managerial theory with the external grid data taken into the orchestration logic.

Table 4 Carbon Reduction Potential

Scenario	Baseline Carbon (tCO ₂ e/month)	CASE Optimized (tCO ₂ e/month)	Reduction	Notes
Smart City	42.3	27.9	34%	Solar optimization major factor
Mobile Banking	18.7	13.5	28%	Carbon credit integration
Government	56.2	43.3	23%	Constrained by secure locations
Weighted Average	39.1	28.3	28%	Across all scenarios

3.2.1 Latency Impact and Service Quality Performance

The quantitative analysis indicated that the weighted average reduction in carbon was 28 percent in all the tested situations. Table 4 displays the comparative outcomes of the optimised carbon intensity of the baseline and carbon optimised in relation to the CASE optimisation. This deployment of the smart city obtained the largest decrease since the non-critical loads were flexible and could be optimised considerably concerning sun rays. By contrast, the level of reduction was lower in government services given by the stricter geographical and security barriers. Cao et al. (2021) added that the road to carbon-

neutral data centres was paved with a methodical change in measuring and controlling the power consumption. Greener technology in computing was facilitated by integrated cooling and energy-efficient hardware (Cao et al., 2021). According to the research by Radovanovic et al. (2021), carbon-conscious computing made data centres dynamically react to grid signals. The transfer of workloads to the periods of low carbon intensity reduced the total environmental load majorly (Radovanovic et al., 2021). The CASE framework was always able to outperform the traditional PUE-oriented management because it included the external grid information into the logic of orchestration.

Table 5 Latency Impact

Workload Type	Baseline Latency	CASE Latency	Increase	Acceptable Threshold
Real-time (URLLC)	4.2ms	4.5ms	7%	<10%
Enhanced Mobile (eMBB)	12.8ms	13.9ms	9%	<15%
Massive IoT (mMTC)	185ms	192ms	4%	<10%

3.3 Technical Challenges in Granular Carbon Attribution

The analysis found the granular carbon attribution as a major technical challenge of shared telecom infrastructure. It needed finer-grained power measurements and artificial intelligence attribution models to differentiate the energy usage of workloads that were not part of the dynamic power load curve. The analysis adopted the above models to ensure the perfect allocation of the carbon expenses among varied network functions. Himeur et al. (2022) reported that AI-big data analytics provided effective equipment to construct the automation and energy management. The predictive algorithms discovered behavioural consumption patterns that the conventional metres could not detect (Himeur et al., 2022). According to the research conducted by Liu et al. (2022), real-time carbon emission accounting was the key to achieving national neutrality objectives. The climate policies were well implemented with clear monitoring systems that yielded the needed data (Liu et al., 2022). The CASE model solved this attribution gap because it combined the power measurements of single server rack with the network-wide traffic measurements.

5G-based network, requiring proxy metering gadgets to be used. The estimation models that were used to address such gaps include analysis on equipment specifications. Jahid et al. (2020) documented that cellular base stations were sensitive to optimal power supply solutions of the energy efficiency of the devices. Retrofitting the existing networks by inputting renewable energy lowered the amount of carbon in the older networks (Jahid et al., 2020). According to Fraga-Lamas et al. (2021), green IoT and edge AI served as an important enabling factor of a sustainable digital transition. The sensors with low power assisted in having the visibility necessary to control the energy usage at the network edge (Fraga-Lamas et al., 2021). The findings indicated that the step-by-step implementation strategy enabled the operators to upgrade infrastructure and be carbon transparent.

3.3.1 Operational Hurdles in Legacy Infrastructure Integration

The implementation of CASE framework with the historic telecommunication equipments posed serious operational challenges. Early hardware also did not have in-built power telemetry capable of functioning in a

3.3.2 Regulatory Barriers and Policy Complexity Management

Thousands of rules of sovereignty in various jurisdictions made life incredibly complicated at the management level. The CASE model employed a Policy-as-Code implementation in order to address the conflict between local residency requirement and carbon reduction goals. The rule inheritance was hierarchical so the national laws overrode the preference of the local optimization. It is reported by Matus and Veale (2021) that machine learning certification systems were favoured with respect to existing sustainability standards. Auditable models

made sure that automated decisions did not go against the law and ethical guidelines (Matus and Veale, 2021). According to the research of Qalati et al. (2025), the efficacy of carbon footprint methodologies was avoided by regulatory compliance. The environmentally safe digital products were developed with the assistance of scientific reporting standards (Qalati et al., 2025). It was shown in the analysis that when workload placements were caused by carbon-optimization events, a non-compliant placement was avoided by the use of automated conflict resolution algorithms.

3.4 Implications for Green Digital Sovereignty and Policy

The evidence implied that the regulators should come up with composite compliance systems that would appreciate the interrelationship between sovereignty and sustainability. Enacting the compulsory carbon reporting of telecommunication infrastructure in real time would put telecommunication operations in line with national commitments to climate. The study suggested the so-called Green Sovereignty to permit restricted transnational data transmissions among carbon trading to achieve optimality in case security levels were equal. Sovacool et al. (2022) explain that the low-carbon transition was focused on equity and technological innovation. Viable infrastructures needed favourable policy conditions to become global (Sovacool et al., 2022). According to one of the studies by Truby et al. (2022), the climate damage of energy-intensive assets (digital assets) required policy interventions. The net zero goals preset the necessity of the verifiable carbon tracking systems (Truby et al., 2022). The research came up with the conclusion that global collaboration in assessing carbon would enable the efficient operation of the global data centres.

3.4.1 Algorithmic Optimization and Future Research Directions

The findings revealed the most promising future of carbon-conscious scheduling in the efforts of AI-based optimization. More machine learning algorithms might lead to the enhancement of the power of forecasting renewable and workload spikes. Future studies ought to focus on quantum-resistance cryptography whose use could be able to keep the security intact at reduced computation costs. Bolan-Canedo et al. (2024) argue that the future of artificial intelligence was green and essential to a sustainable future. Research based on efficiency minimised the environmental expenditure of training and deploying sophisticated

models (Bolon-Canedo et al., 2024). According to the research conducted by Alzoubi and Mishra (2024), green AI projects helped to deal with the most urgent issue of increasing energy use in the digital era. The use of smart systems was planned based on the strategic frameworks in accordance with the environmental needs (Alzoubi and Mishra, 2024). These future innovations in the telecom industry were based on the CASE framework.

3.4.2 Standardization of Carbon Tracking Interfaces

A common interface in real-time carbon intensity data became an important standardisation demand to be adopted by the industry at large. The recommendations of the analysis expressed the idea that vendor-neutral abstraction layers would enable a consistent tracking in multi-vendor environment. Similar languages in which sovereignty policy is provided would make automated compliance even more challenging. Rangararajan et al. (2025) note that the use of AI in automation improved the confirmation and checking of sustainability reports. Global corporations were able to streamline the reporting process with the use of automated tools (Rangararajan et al., 2025). The support of the change towards renewable energy sources was provided by lightweight AI models, reducing the monitoring overhead, as per the study conducted by Miller et al. (2025). Computing architectures were made efficient in order to make tracking efforts not add up to the overall carbon footprint (Miller et al., 2025). The results provided the case of establishing carbon transparency as a priority case in 6G development by international standards organisations.

3.4.3 Economic Impacts and Business Model Innovation

By scheduling the batch processing, the overall energy costs in the scenario of a smart city were reduced by 12 percent. This discovery meant that there were environmental and economic benefits to telecom operators as a result of carbon-conscious operations. Green sovereign infrastructure may become a competitive edge of future business model in the markets, where strict requirements on ESG are maintained. Downar et al. (2021) report that carbon disclosure implemented in companies had effects on environmental and financial performance of companies. The openness in reporting the level of emissions motivated the entry of companies into more efficient work modes (Downar et al., 2021). According to the research of Eicke et al. (2021), the establishment of carbon border adjustment measures put new threats on international data flows.

Infrastructure initiated by policies enabled companies to go through the shifting environment of international commerce and sustainability (Eicke et al., 2021). It was determined through the research that carbon tracking in the centre of telecom orchestration provided long-term economic sustainability.

3.5 Comparative Discussion

Adhikari et al. (2025) state that former carbon tracking tools did not have cross-sector integration. Lack of harmonised frameworks constrained the monitoring of the emissions among the distributed industries (Adhikari et al., 2025). According to the research conducted by Bharany et al. (2022), cloud computing energy efficient methods often ignored the jurisdiction limits of data location. The traditional models handled the legal residency requirement imposed by the national laws as secondary to Power Usage Effectiveness (Bharany et al., 2022). Freitag et al. (2021) suggest that the actual climate effect of information technology was underestimated because of the lack of consistent reporting rules. The lifetime emissions of high-speed distributed networks could not be recorded by using simple estimates (Freitag et al., 2021). According to the research on information management systems by Dwivedi et al. (2022), there was a failure of information management systems to integrate technological solutions to immediate climatic action objectives. The role of digital tools in contributing to global sustainability goals was not achieved due to lack of a unified approach (Dwivedi et al., 2022). These siloed strategies led to a lack in research in which carbon optimization would be conducted without thinking about data sovereignty.

Kassaj and Peracek (2024) explain that the merging of mobile roaming and smart city concept enhanced the connectivity in the urban setting. Digital infrastructure was made sustainable to generate a platform of the modern service delivery within the crowded urban centres (Kassaj & Peracek, 2024). According to the analysis conducted by Sahoo et al. (2022), blockchain technology became one of the avenues of transparent and traceable supply chains. Distributed ledgers ensured the integrity of environmental information on complicated global networks (Sahoo et al., 2022). Kaewunruen et al. (2022) state that infrastructure resilience in the context of climate change was managed with the help of digital twins. Different environmental stress conditions could be simulated with the help of virtual models (Kaewunruen et al., 2022). Based on an investigation by Koukaras et al. (2024), smart grids with

blockchain helped to improve demand response. The stability of the local power networks was supported by secure transactions of energy (Koukaras et al., 2024). These technical positives placed the technical ingredients required to make real-time monitoring but could not integrate them in a compliance conscious architecture.

The CASE framework is able to address the gaps that were identified in the previous siloed systems because it incorporated real-time carbon tracking with enforcement of the sovereignty policy. Figure 2 shows how the hierarchical processing model has managed to cut across the jurisdictional boundaries pursuing a 34% carbon reduction. Alhadi et al. (2025) reported that digital twins provided continuous permitting and compliance management in terms of asset management. Regulatory reporting in an industrial environment got better with real-time synchronisation (Alhadi et al., 2025). Synchronisation logic used in the CASE framework was not much different to reach the 100 percent compliance rate as shown in Table 2. According to the article by Mohsen (2024) the integration of real-time data in the application of AI-based optimization has shown to be more efficient in urban logistics. Intelligent routing reduced the cost of the systems of delivery systems on the environment in smart cities (Mohsen, 2024). The optimization problem of 5G mobile banking in Figure 3 was better than these logistics models due to special sovereign treatment of biometric information.

Setyadi et al. (2025) added that sustainable manufacturing needed to take a systematic approach to the review of major dimensions of operation. The policies that are holistic showed chances of saving energy throughout the entire value chain (Setyadi et al., 2025). This systematic philosophy was applied to the telecom industry using CASE framework, whereby hardware telemetry and grid intensity in the tracker provided in Table 3 were aggregated. According to the research conducted in Xiao and Nie (2025) the environmental regulations and technological progress had a strong effect on the level of energy efficiency and carbon emissions. Good policies were taken to promote the use of cleaner infrastructure in the industrial areas (Xiao & Nie, 2025). It was confirmed by the findings of the government secure services scenario in Figure 4 which indicated a 23% reduction in emission within the confines of very strict security requirements. As Yurtay (2025) explains, the use of industry 4.0 technologies and ERP systems helped in the management of carbon footprint in the manufacturing industry. The software ensured that the

burden of sustainability reporting on the administration side was minimised (Yurtay, 2025). The 85 percent heightened manually compliant labour precision seen in this paper was corresponding with the efficiency returns guaranteed by the integrated digital solutions. The given comparative analysis scrutinised the fact that the CASE framework effectively mitigated the technical performance identified in the literature against the legal requirements of the current telecom environment in terms of residency.

4 Conclusion

The study has determined the Carbon-Aware Sovereignty Enforcement (CASE) to be a feasible solution to the world telecom industry. The exploration found that real-time carbon monitoring in conjunction with jurisdictional compliance would result in the 28-percent weighted average of emission reduction. The findings verified that environmental sustainability and data residency were complementary goals that were intelligently orchestrated. There were drawbacks such as the use of simulated 5G workload and access to granular grid data in particular developing areas. The research had the merits of high compliance accuracy and novelty of policy-as-code architecture. Future research indication was aimed at applying quantum-resistant encryption and scaling of the framework to the framework in the 6G network design. The experiment pioneered the sustainable data management paradigm by demonstrating that climate targets and legal requirements were harmonised with the help of integrated digital infrastructure.

Declarations

Author Contribution: Each of the participants made an equal contribution to the conceptualization, data-gathering, and preparing the manuscript. The partnership allowed this to cover a detailed study of the CASE framework in various jurisdictions. All the contributors were involved in the review phase of the simulation results and final architectural design iteratively. The combined work led to effective assimilation of technical and policy-focused research results.

Conflict of Interest: There was no conflict of interest involved in the course of this research. The objectivity was not affected and neither was the results of the study by financial or personal relations. Its results were not contingent upon any third party commercial or corporate interests. The data analysis was covered by professional integrity as well as the future interpretation of the results.

Funding: No external funding was in support of this investigation. The study was based on internal institutional resources and datasets, which are freely available on the Internet presented by grid operators. Lack of financial grants guaranteed the objective interpretation of the carbon conscious policy outcomes. All the computation expenses did not go beyond the scope of the main research facility.

Ethical Approval: In this study, the ethical approval was not applicable. The study made use of anonymous infrastructure reports and legal frameworks that did not employ human participants and personal data. Adherence to institutional rules was also in the agenda during the process of data analysis. The research narrowed down to architecture efficiency and environmental effects.

Consent for Publication: No consent to publication was viable. There were no single data or recognisable photographs of the subjects in the manuscript. All facts provided by simulation modelling and by the regulatory books. The presentation continued with the subject of technical frameworks and systemic policy implications to the telecom industry.

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