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(Research/Review) Article

From Data to Decarbonization: The Role of Big Data Analytics in Building a Sustainable Digital Economy

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Abstract: This paper investigates how Big Data Analytics (BDA) can accelerate the transition to a low-carbon digital economy. We present a systematic literature-based research framework (2015–2025) that synthesizes applications of BDA in energy systems, transportation, industry and supply chains. The methodology combines systematic review and conceptual modelling to identify pathways through which BDA reduces emissions: (1) demand-side optimization, (2) operational efficiency, (3) predictive maintenance and (4) data-driven policy and market instruments. Results highlight concrete case examples smart grids, digital twins, and green supply-chain analytics and quantify benefits reported in recent literature. Key challenges such as data governance, carbon costs of computing, and policy integration are discussed. The paper concludes with policy recommendations and a research agenda to align digitalization with decarbonization goals.

Keywords: Big Data Analytics; Decarbonization; Digital Economy; Smart Grids; Digital Twin; Green Supply Chain

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1. Introduction

In the modern digital era, the global economy is rapidly evolving toward digitalization, where people, businesses, devices, data, and processes are increasingly interconnected through online platforms interactions that occur billions of times each day. The advancement of digital technologies has transformed many aspects of human life, including the structure and dynamics of the global economy [6]. This transformation, generating zettabytes of data annually, is supported by the emergence of Big Data Analytics (BDA), which enables the collection, processing, and interpretation of massive datasets to derive meaningful insights for strategic and sustainable decision-making.

Big Data refers to extremely large and complex datasets generated from diverse sources such as internet traffic, digital transactions, sensors, Internet of Things (IoT) devices, social media platforms, and other digital activities. Big Data Analytics involves the systematic process of managing and extracting valuable information from these datasets to inform accurate and timely decisions [4]. Within this ecosystem, IoT devices serve as physical instruments that collect, transmit, and process data across interconnected systems, forming a growing infrastructure that supports various sectors from government and enterprises to households due to their operational efficiency and environmental benefits.

This integration occurs against the backdrop of an escalating climate crisis, demanding urgent and large-scale decarbonization across all economic sectors. In this context, the integration of Big Data and IoT technologies plays a pivotal role in advancing economic decarbonization, which refers to reducing greenhouse gas (GHG) emissions associated with economic activities. Big Data Analytics provides real-time and continuous monitoring of carbon emissions, supports carbon taxation policies, and optimizes energy consumption for greater efficiency, especially within integrated urban infrastructure [7]. These capabilities enable industries and governments to design data-driven strategies that balance productivity growth with sustainability goals.

Simultaneously, international institutions such as the International Energy Agency [10] and the Organisation for Economic Co-operation and Development (OECD, n.d.) have emphasized the dual nature of digitalization. This duality presents a core paradox: while digital technologies can significantly accelerate the clean energy transition, they also introduce new challenges, such as the rising energy demand of data centers and AI workloads [11]. This energy footprint, if left unmanaged, could potentially offset the environmental gains achieved elsewhere. Therefore, the alignment between digital transformation and environmental policy is essential to ensure that digitalization supports rather than undermines decarbonization efforts.

2. Literature Review

The literature on BDA for sustainability has expanded rapidly. Studies review applications in smart grids [8], predictive maintenance, supply-chain optimization [1] and carbon forecasting [3]. Smart grid reviews demonstrate that predictive analytics stabilises variable renewables and improves load balancing. Digital twin and ML-based carbon estimation papers [13] show how near-real-time monitoring can reduce waste and improve process efficiency. Supply chain and green logistics literature highlight route optimization and inventory efficiencies that cut transport emissions and operational waste.

While these studies provide crucial insights into siloed applications, a significant portion of the literature focuses on either the technical implementation of BDA or high-level policy discussions. A clear, synthesized framework that connects specific BDA mechanisms (e.g., optimization algorithms, predictive models) directly to measurable decarbonization outcomes (e.g., CO2 reduction, energy intensity improvement) across multiple sectors is less developed. This paper seeks to bridge this gap by proposing a conceptual framework derived from a systematic synthesis of these disparate research streams.

3. Methodology

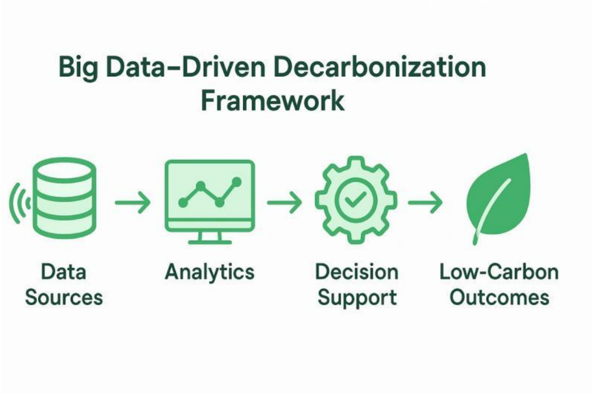
This research uses a systematic literature analysis focusing on peer-reviewed journal articles, conference papers and international policy reports published between 2015–2025. The search was conducted on major academic databases (including Scopus and Web of Science) and authoritative institutional websites (IEA, OECD). Key search strings included combinations such as: ("Big Data" OR "BDA") AND ("decarbonization" OR "carbon emissions" OR "sustainability") and ("digital twin" OR "smart grid" OR "green supply chain") AND ("emissions") . Selection criteria for inclusion were: (1) empirical studies, case analyses, or systematic reviews; (2) direct discussion of BDA application for environmental impact; and (3) publication within the 2015–2025 timeframe. Exclusion criteria were: (1) articles not in English; (2) papers focusing purely on the social or economic aspects of digitalization without environmental metrics; and (3) grey literature not published by major international bodies. We synthesized findings from 20 selected articles into a conceptual framework, thematically coding the mechanisms through which BDA impacts emissions: demand response, operational efficiency, predictive maintenance, and policy instruments.

4. Results and Discussion

Conceptual Framework

Figure 1 (below) illustrates the Big Data–Driven Decarbonization Framework: data collection (sensors, IoT, transaction logs) → data processing (streaming, ML/AI) → decision layers (optimization, prediction, policy support) → decarbonization outcomes (reduced energy use, lower transport emissions, improved industrial efficiency).

Figure 1. Conceptual Framework



Case Applications

- **Smart Grids:**

BDA enables load forecasting, renewable integration, and demand-side management [8]. This is critical for managing the intermittency of renewable sources. For instance, predictive algorithms analyze weather patterns, historical consumption, and grid status to forecast solar/wind generation, allowing utilities to balance supply and demand in real-time, thereby maximizing renewable penetration and reducing reliance on fossil-fuel peaker plants.

- **Digital Twins and Industry:**

Digital twin systems allow process-level emissions tracking and scenario testing, reducing idle time and material waste [13];[15]. Recent empirical studies suggest substantial emission reductions in manufacturing when digital twins and BDA are deployed to optimize complex processes like chemical production or CNC machining.

- **Supply Chains and Logistics:**

Optimization algorithms powered by large datasets cut transport emissions through routing, load consolidation, and modal shifts [1]. Green supply chain analytics also supports supplier selection with lower carbon intensity, moving beyond simple cost metrics to include Scope 3 emissions data in procurement decisions.

Benefits vs Risks

Benefits: increased energy efficiency, quicker policy feedback loops, better asset utilization, and lower operational emissions.

Risks: This analysis reveals a significant paradox. The primary risks include the rising energy demand from data centers and AI [11];[18] and data governance challenges. Furthermore, we must consider potential "rebound effects" as noted in [14], a socio-economic phenomenon where efficiency gains lead to increased overall consumption (e.g., cheaper data processing leads to more data processing), potentially negating the savings. Tech giants' indirect emissions have also risen, highlighting that the digital economy's own supply chain (Scope 2 and 3 emissions) remains a systemic challenge [17].

Table 1. Comparison of Traditional and Data-Driven Strategies for Industrial Sustainability

Dimension	Traditional Strategy	Data-Driven Strategy
Energy Management	Static audits, manual scheduling	Real-time load forecasting [8], demand response
Maintenance	Reactive maintenance	Predictive maintenance via ML [13]
Supply Chain	Periodic route planning	Continuous optimization, emissions-aware routing

5. Comparison

International frameworks from [20] and [10] highlight the dual nature of digitalisation as an enabler for decarbonization but also a new energy demand source. Our synthesis aligns with IEA's view that digital tools can help integrate renewables and improve end-use efficiency, while OECD stresses governance and policy alignment [12]. Our framework builds upon these by offering a more granular, operational view that maps specific BDA functions to outcomes, rather than focusing solely on high-level policy.

6. Conclusions

Big Data Analytics offers multiple, measurable pathways to accelerate decarbonization across sectors. Key contributions of this paper include: (1) a conceptual framework mapping BDA functions to decarbonization outcomes, (2) synthesis of case studies showing practical benefits, and (3) policy recommendations to manage the inherent risks of digitalization.

To ensure BDA becomes a net positive for climate, we propose concrete policy recommendations:

a. Invest in Green Computing: Move beyond generic incentives and implement targeted policies such as carbon taxes on computation or preferential tariffs for data centers using 100% renewable energy.

b. Standardize Data Governance: Mandate data-sharing protocols for non-sensitive emissions data (following FAIR principles "Findable, Accessible, Interoperable, Reusable") to accelerate research and accountability.

c. Embed Carbon in Digital Procurement: Public and private sectors must incentivize BDA for emissions reduction [9]; [16] by embedding carbon costs and lifecycle assessments into all digital procurement and service contracts.

Limitations of this study include a reliance on published case studies and secondary data. Future work should prioritize developing macro-models to quantify the net sector-level emission impacts of digitalization, moving beyond isolated case benefits [5]. Further research must also explore the socio-technical barriers to implementation, ensuring that the benefits of this digital transition are equitable.

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