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Digitalization and Sustainability: Explore the Role of Digital Technologies in Promoting Sustainability and Reducing Environmental Impacts

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ABSTRACT

One of the most relevant points of intersection between the twenty-first century technological innovation and environmental responsibility is green digital transformation. As the digital technologies of artificial intelligence, cloud computing, blockchain systems, infrastructures of the Internet of Things, robotics, high-level analytics, and automation platforms are introduced into economic systems, they change the nature of production, consumption, and governance. As much as these technologies have been linked to unprecedented rise in efficiency and productivity, they have also caused a new form of environmental pressure because of the rise in use of electricity, emergence of electronic wastes, mining of rare earth minerals, and computing practices that release carbon emission. The study sets a ground on sustainable digital transformation as a theory in accordance to the principles of digital innovation and its influence on environmental impact reduction. The respondents interviewed under a qualitative interpretivist research design were the sustainability executives, IT architects, digital transformation strategists,

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http://amresearchreview.com/index.php/Journal/about

environmental policy advisors, and infrastructure engineers in different sectors of the industry like manufacturing, telecommunications, finance, renewable energy, public administration, and smart city governance. The findings indicate that digital technologies are not to be considered neutral artifacts that may be indifferent to the environment, but instead, they are sociotechnical systems that are embedded and anchored in economic incentives and the institutional framework. Digital systems that are handled well would have a massive impact on energy wastage, efficiency in supply chains, help in the incorporation of renewables, facilitate transparency in the supply chain, and advance environmentally responsible activities. However, sustainability tales are more challenging due to the risks of rebound, carbon leakage, algorithmic energy intensity, greenwashing, digital inequality and extractive hardware supply chains. The article presents an Integrated Sustainable Digital Transformation Model, according to which the digital infrastructure is located in the frames of the world and regulatory responsibility frameworks.

Keywords: Sustainable digital transformation, green IT, carbon reduction, digital sustainability, circular economy, environmental governance, AI energy consumption, digital carbon footprint

1. Introduction

The international developments that occurred at the start of the twenty-first century are dual: the additional impetus to digitalization and the increase of environmental crisis (IPCC, 2023; UNEP, 2022). The digital change has radically altered the economic structure, political processes, labour market, communication systems and even the cultural practices (Vial, 2019; Yoo et al., 2010). However, due to the proliferation of high-speed internet connectivity, and cloud computing networks, artificial intelligence (AI), distributed ledgers, mobile systems, and interconnected devices, previously unknown quantities of computing power and coordination on the global scale can be achieved (Brynjolfsson and McAfee, 2014; Schwab, 2016). Simultaneously, the planet faces growing ecological pressures that have been made by the processes of climate change, biodiversity degradation, ocean acidification, freshwater deficiency, land degradation, and reduction of resources (Rockström et al., 2009; Steffen et al., 2015). These environmental risks are structural threats of

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http://amresearchreview.com/index.php/Journal/about

economic prosperity, societal peace, and generational justice (IPCC, 2023).

The digital revolution has been proclaimed as a means to attain efficiency, innovation, and economic growth (Brynjolfsson and McAfee, 2014). The production business can be made simpler with the help of automation; AI is employed to streamline logistics networks; data analytics help to allocate resources more effectively; smart grids can be used to balance the supply and demand of renewable energy; collective consumption models are possible as a result of digital platforms (GeSI, 2015; Porter and Heppelmann, 2014). This means that the digitalization can be applied as a powerful instrument of environmental sustainability.

However, the cost of environmental impact of a digitalization can also be underestimated (Hilty and Aebischer, 2015). They are 24/7 data centres that consume a lot of electricity and have a high-quality cooling system (IEA, 2023). The process of AI training models needs a lot of computational resources and some big data models generate significant volumes of carbon emissions (Strubell, Ganesh and McCallum, 2019; Patterson et al., 2021). The electricity consumption of certain nations is similar to the mining of cryptocurrency (Cambridge Bitcoin Electricity Consumption Index, 2023). Smartphones, servers and networking devices are manufactured by using rare earths and minerals, which are mined in a way that is disruptive to the environment (UNEP, 2020). E-waste is arguably one of the fastest growing types of waste in the world (Baldé et al., 2020).

Digital transformation is a paradox in that it may be the solution to the degradation of the environment, but, on the other hand, it introduces the ecological pressure (Hilty and Aebischer, 2015). Sustainable digital transformation is a strategic and theoretical paradigm that tries to deal with this paradox. It integrates the environmental sustainability objectives during the design, implementation, management, and evaluation of the digital technologies (George et al., 2021). The current digital change is not a split between digital innovation and environmental protection as two different agendas but two processes that cannot exist independently of each other (Brenner and Hartl, 2021). The digital systems are not just to be considered in terms of an economic payoff but of carbon emissions, material mining, waste creation, societal fairness and planetary constraints

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http://amresearchreview.com/index.php/Journal/about

(Rockström et al., 2009; Steffen et al., 2015).

The research question will be the following: How can digital transformation be planned and managed to reduce the environmental impact and guarantee the technological advancement and economic development? The paper applies a synthesis of sustainability science, environmental economics, digital sociology, and information systems research to give an answer to this question and empirical background is given by the practitioners who are working on the crossroads of technology and sustainability.

2. Conceptual and Theoretical Foundations

2.1 Sustainable Development and Institutional Frameworks

The principle of sustainable digital transformation has its normative basis in the idea of sustainable development, which is officially stated in Brundtland Report (WCED, 1987). Sustainable development focuses on the satisfaction of the current needs of the people without jeopardizing the position of the future generations to satisfy their needs. It incorporates environmental protection, economic growth and social inclusion into the singular framework (Elkington, 1997).

The modern sustainability discourse has developed past the general principles to include measurable goals and institutionalized mechanisms. The international frameworks, like the Paris climate accord and Sustainable development goals by the United Nations define the expectations of governmental and corporate responsibility (UN, 2015; IPCC, 2023). Sustainability measures are also institutionalized in environmental reporting standards, ESG frameworks, and sustainable finance taxonomies (Friede, Busch and Bassen, 2015). These governance structures need to be complemented with digital transformation as digital infrastructures are found in the global supply chains, energy systems, and administration processes (Vial, 2019).

The planetary boundaries model narrows sustainability thinking by suggesting ecological limits that human beings should not surpass to stay within the stability of the Earth system (Rockström et al., 2009; Steffen et al., 2015). Key boundaries or limits are climate change, biosphere integrity, land-system change, freshwater use and biogeochemical flows. Plans of digital transformation have to be

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considered according to these environmental limits. Technological innovation that makes overall energy input higher or faster material mining without compensating gains elsewhere has a threat of making the planet enter an overshoot (Parrique et al., 2019).

2.2 Digital Carbon Footprint and Lifecycle Assessment

The effect of digital technologies on the environment is complex. Operation emissions also involve the use of electricity of data centres, network structures, and end-user devices (IEA, 2023). Embodied emissions occur during the manufacturing of the semiconductors, servers, fibre-optic cables and consumer electronics (Belkhir and Elmeligi, 2018). Indirect emissions are in supply chains of raw materials, transportation, and infrastructure construction (Freitag et al., 2021).

Lifecycle assessment (LCA) is a methodological tool which may be applied to evaluate environmental impacts of the production, use and end-of-life stage (ISO 14040, 2006). Sustainable digital transformation requires lifecycle transparency. As an example, the local energy usage may be reduced, but data centres will be centralized, and they will use fossil fuels because of cloud migration (Freitag et al., 2021). Similarly, the hardware that will save energy can also be based on the exploitation of rare earth minerals, the mining of which also causes the ecological degradation (UNEP, 2020).

The accounting of carbon digitally is a complicated process that needs to be measured using standardized procedures. Scope 1 emissions are the ones associated with the direct operational outputs; Scope 2 is associated with that of purchased electricity and Scope 3 deals with the supplying chain and disposal processes (GHG Protocol, 2011). In an attempt to attain meaningful sustainability results, digital transformation strategies must address all the three scopes.

2.3 Green Information Technology and Energy Efficiency

The term green IT is applied to explain greener computing practices in which there is reduced consumption of energy and material waste (Murugesan, 2008). The innovations in the virtualization, server consolidation, dynamic workload delivery, and the acquisition of renewable energy have improved energy efficiency (IEA, 2023). Hyperscale data centres are also considering wind and solar power purchase

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http://amresearchreview.com/index.php/Journal/about

agreements in order to decarbonise its operations (IEA, 2023).

However, the growth in the computational power does not always result in the absolute reductions of emissions. A decrease in the price of energy will contribute to more demand on the digital services, which instigates the back effects (Jevons, 1865; Hertwich, 2005). This interaction is particularly true in the scenario of the digital ecosystem where computation marginal costs are declining. A sustainable digital change should therefore consist of efficiencies enhancement coupled with decarbonization planning of the buildings, including renewable energy transformation, carbon levies, and regulatory measures (Parrique et al., 2019).

Table 1: ***Environmental Dimensions of Digital Technologies***

Dimension	Operational Impact	Lifecycle Impact	Governance Requirement
Data Centers	Electricity consumption	Construction emissions	Renewable energy sourcing
AI Systems	High training energy demand	Hardware replacement cycles	Energy disclosure standards
IoT Devices	Distributed electricity use	Electronic waste generation	Extended producer responsibility
Blockchain	Intensive computational processes	Mining hardware waste	Regulatory oversight
Cloud Platforms	Consolidated infrastructure	Global carbon outsourcing	Transparent carbon reporting

3. Research Methodology

The current research uses a qualitative approach in the interpretivist approach to understand how organizations define and implement sustainable digital transformation in environmental governance systems. This inquiry is especially well addressed using interpretivism since sustainable digital transformation cannot be considered a purely technical phenomenon but a sociotechnical process that is influenced by institutional norms, regulatory environment, corporate culture,

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Print ISSN 3007-3189

http://amresearchreview.com/index.php/Journal/about

infrastructural limitations, and structure of political economy.

3.1 Research Design

Multi-sectoral qualitative design was considered in order to accommodate the industry variation. The respondents of the study were the employees in manufacturing, financial services, telecommunications, renewable energy firms, technology service providers, and players in the government in the smart cities governance in the government sector. The diversity of the industries offered the opportunity to research sustainable digital change with references to multiple regulatory requirements, infrastructural capacities, and organizational objectives.

Forty-five respondents who had senior roles such as sustainability directors, chief information officer, digital transformation lead, environmental compliance officer and infrastructure architect participated in semi-structured interviews. The interviews took between sixty and ninety minutes and were conducted using encrypted video conferencing programs to ensure the confidentiality.

3.2 Data Collection Procedure

Purposive and snowball sampling techniques were applied in recruiting the participants. Conditions of recruitment demanded first- hand experience in digital change strategy and integration of environmental policies. Some of the themes examined by the interview questions were carbon accounting practices, decisions related to digital infrastructure, integration of renewable energy, lifecycle assessment procedures, implementation of the circular economy, regulatory compliance, and perceived risks of the rebound effects.

The audio-taping of interviews was with the consent of the participants and transcribing was done verbatim. Anonymity of transcripts was done to ensure institutional confidentiality.

3.3 Analytical Framework

Due to inductive coding, thematic analysis was carried out. First open coding found common patterns in relation to infrastructure, governance, environmental measures, optimization systems and risk dimensions. These patterns were grouped into higher-order conceptual themes by the use of the axial coding. Younger comparative techniques were used to make sure that the interviews were consistent. The

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Volume 4, Issue 3 (2026)

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http://amresearchreview.com/index.php/Journal/about

researcher positionality and analytic decisions were written in the form of reflexive journaling.

Member checking, triangulation with publicly available sustainability reports, and peer debriefing with environmental governance scholars were used to improve their trustworthiness.

4. Empirical Findings

The thematic analysis yielded 6 dimensions of sustainability digital transformation that are interrelated namely energy-conscious infrastructure, carbon-conscious algorithm design, smart environmental optimization system, circular digital material governance, sustainability data integration, and institutional regulatory alignment.

4.1 Energy-Aware Infrastructure Transformation

The interviewees repeatedly stressed how crucial energy sourcing is to sustainable digital transformation. The migration to the cloud plans were only defined as environmentally advantageous in cases when combined with the acquisition of renewable energy. A number of companies had introduced carbon intensity dashboards which enabled computation loads to be shifted dynamically to regions where the carbon grid intensity was lower.

A chief infrastructure architect said that the concept of sustainability was no longer treated as a non-negotiable design constraint, but as something that was afterwards tacked on. The location of data centers is becoming more and more focused on the distance to renewable energy sources, climatic factors minimizing cooling needs, and decarbonizing the grid trends.

Participants however also observed that renewable procurement contracts do not remove embodied emissions in hardware production or construction of infrastructures.

Table 2: ***Infrastructure-Level Sustainability Practices***

Practice	Implementation Mechanism	Environmental Impact	Limitations
Renewable Power Purchase	Long-term energy contracts	Reduced operational carbon intensity	Dependent on grid transparency

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Volume 4, Issue 3 (2026)

Online ISSN 3007-3197
Print ISSN 3007-3189

http://amresearchreview.com/index.php/Journal/about

Practice	Implementation Mechanism	Environmental Impact	Limitations
Agreements			
Carbon-Aware Workload Scheduling	Geographic computational shifting	Lower marginal emissions	Infrastructure complexity
Liquid Cooling Technologies	Advanced thermal management	Reduced cooling electricity	High capital investment
Edge Computing Optimization	Distributed processing efficiency	Reduced transmission energy	Hardware proliferation

4.2 Carbon-Aware Algorithmic Design

Both artificial intelligence and better analytics were identified as environmental risk and mitigation measures. Training an AI may be very energy-intensive, particularly regarding large language models and predictive AI. Nevertheless, AI can also be used to predict the maintenance, optimize the supply chain, and predict the energy, reducing waste to the environment.

Participants discussed the effort on measuring the carbon intensity of algorithms and re-designed models to become efficient. Additional practices such as model compression, federated training as well as adaptive training schedules were welcomed to reduce the energy requirements. Several companies also introduced energy consumption in software development lifecycle.

Table 3: ***Algorithmic Energy Optimization Approaches***

AI Optimization Technique	Environmental Benefit	Organizational Adoption Rate
Model Compression	Reduced computational load	Moderate
Federated Learning	Lower centralized processing	Emerging
Carbon-Aware Training	Off-peak renewable	Limited

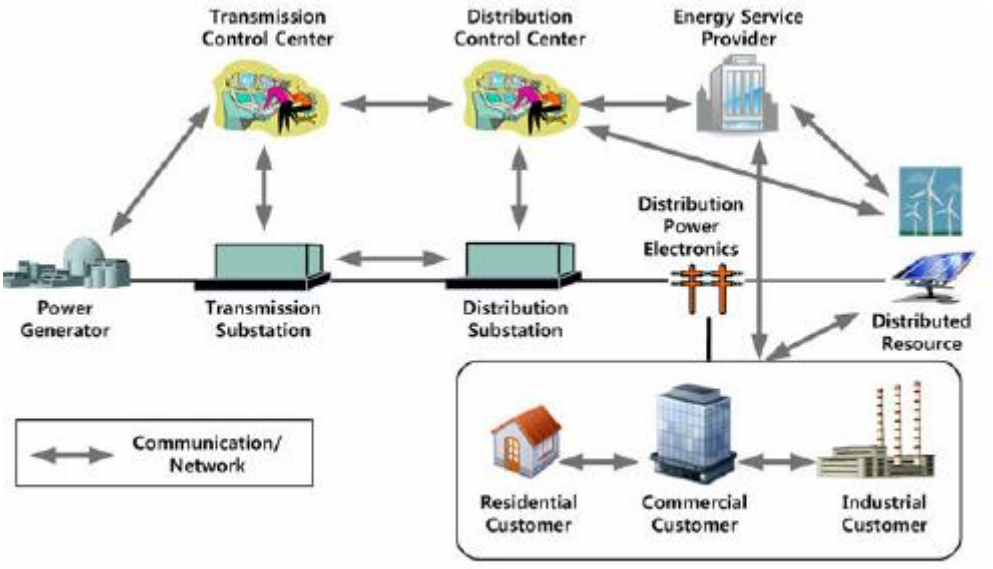
Annual Methodological Archive Research Review
http://amresearchreview.com/index.php/Journal/about
Volume 4, Issue 3 (2026)

Online ISSN 3007-3197
Print ISSN 3007-3189

http://amresearchreview.com/index.php/Journal/about

AI Optimization Technique	Environmental Benefit	Organizational Adoption Rate
Scheduling	utilization	
Efficient Neural Architecture Search	Reduced training cycles	Growing

4.3 Smart Environmental Optimization Systems



Control Center in all parts of grid

Smart systems were always mentioned as being transformative to the management of the environment. The municipal governments wrote about AI-based traffic control systems that minimized the emission levels due to congestions. Farming companies have implemented IoT sensors that enable farmers to use accurate methods to water their farmlands and apply fertilizers to minimize water wastage and chemical erosions.

Digital twins helped manufacturing companies to simulate production processes, discovering its inefficiencies and reducing material waste. The predictive analytics was used by the renewable energy suppliers to balance fluctuations in supply.

Nevertheless, the net benefit of smart systems on the environment was determined by the energy sources and the efficiency of the data infrastructure.

Annual Methodological Archive Research Review
http://amresearchreview.com/index.php/Journal/about
Volume 4, Issue 3 (2026)

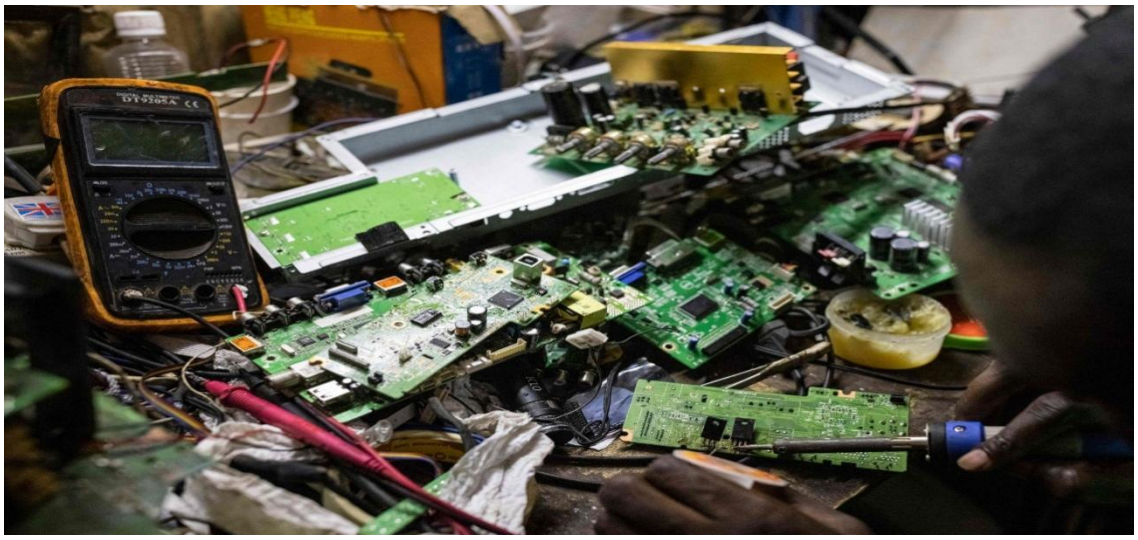
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http://amresearchreview.com/index.php/Journal/about

Table 4: ***Smart Systems and Environmental Outcomes***

Sector	Digital Application	Environmental Outcome
Agriculture	IoT irrigation sensors	Water conservation
Urban Governance	AI traffic optimization	Reduced fuel emissions
Manufacturing	Digital twin simulations	Material efficiency
Energy Sector	Renewable forecasting algorithms	Grid stability

4.4 Circular Digital Material Governance



The main issues were electronic waste and extraction of materials. The participants also admitted that sustainable digital transformation involves dealing with hardware lifecycle effects. The use of digital product passports, blockchain traceability, and predictive maintenance systems was implemented as the way to improve circularity. The concept of extended producer responsibility frameworks was addressed as an important regulatory tool that makes manufacturers design in such a way that their items could be used more actively and recycled.

Table 5: ***Circular Digital Strategies***

Strategy	Mechanism	Sustainability Outcome
Digital Product Passports	Lifecycle traceability	Reduced material leakage
Blockchain Supply Chain Tracking	Transparent sourcing	Ethical mineral procurement

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http://amresearchreview.com/index.php/Journal/about
Volume 4, Issue 3 (2026)

Online ISSN 3007-3197
Print ISSN 3007-3189

http://amresearchreview.com/index.php/Journal/about

Strategy	Mechanism	Sustainability Outcome
Modular Hardware Design	Repairability	Extended device lifespan
Recycling Automation	AI-based sorting	Reduced landfill waste

4.5 Sustainability Data Integration and ESG Alignment

The respondents highlighted the need to incorporate sustainability metrics in enterprise resource planning systems. Live carbon display allowed the top management to track emissions on supply chains. The digital transparency was becoming essential in the frameworks of ESG reporting.

The governance of data became one of the core pillars. Proper carbon accounting demanded standard procedure and reporting frameworks.

Table 6: ***Sustainability Governance Integration***

Governance Layer	Digital Tool	Accountability Outcome
Corporate	Carbon dashboards	Executive oversight
Regulatory	Emission reporting software	Compliance monitoring
Financial	ESG analytics platforms	Sustainable investment flows
Public	Open environmental data portals	Civic transparency

4.6 Rebound Effects and Structural Risks

The energy consumption used per unit was often lowered but in other cases, the aggregate demand was raised. When asked to give instances of how optimized logistics reduced the cost of shipping their goods, the participants had instances when this led to increased amounts of consumption.

Outsourcing to carbon intensive areas via the cloud pushed the emissions out of the country and they were not factored to global levels. Lifecycle accounting was sometimes not transparent in inflating digital sustainability claims.

Table 7: ***Structural Risk Dimensions***

Risk Category	Mechanism	Environmental Consequence
Rebound Effect	Efficiency-induced demand growth	Net emission increase

Annual Methodological Archive Research Review
http://amresearchreview.com/index.php/Journal/about
Volume 4, Issue 3 (2026)

Online ISSN 3007-3197
Print ISSN 3007-3189

http://amresearchreview.com/index.php/Journal/about

Risk Category	Mechanism	Environmental Consequence
Carbon Leakage	Outsourced infrastructure	Hidden global emissions
Greenwashing	Selective reporting	Misleading sustainability claims
Digital Inequality	Infrastructure asymmetry	Unequal environmental burdens

5. Discussion

The findings have demonstrated that sustainable digital transformation is neither a technological project, but, in fact, an institutional, economic, and political project (Orlikowski and Scott, 2008; Vial, 2019). Digital infrastructures are not independent, they are embedded in regulatory frameworks, energy markets, world supply chains and corporate governance. Next, the strategic choices related to the infrastructure design, renewable energy agreements, carbon accounting policies, regulatory policies, monetary rewards, and organizational culture overpower environmental outcomes in general (Hilty and Aebischer, 2015; GeSI, 2015). Digital systems are not solely dependent on the effectiveness of technology but the governance systems where they are adopted.

It is a study consistent with recent studies that predict that digital technologies are sociotechnical systems which are sensitive to the accommodation of institutions (Orlikowski and Scott, 2008; Brenner and Hartl, 2021). Cloud computing may, among other things, reduce the energy intensity per unit of computation, but the overall environmental impact of cloud computing would be contingent on grid decarbonization trajectories in addition to hardware production lifecycle emissions (IEA, 2023; Belkhir and Elmeligi, 2018). Similarly, artificial intelligence has the potential to streamline the logistics, reduce material waste, and enhance renewable projections (Patterson et al., 2021), yet the training on the AI models can lead to a substantial volume of carbon emission without the need to be transparent and favorable to energy-saving design approaches (Strubell, Ganesh and McCallum, 2019).

The findings further reveal that the effect on the environment can be significantly

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Online ISSN 3007-3197
Print ISSN 3007-3189

http://amresearchreview.com/index.php/Journal/about

reduced with the implementation of digital technologies in the process of transition to renewable energy, material-circular management, and transparent reporting systems. In conjunction with renewable energy acquisitions, carbon attentive workload programs and intelligent grid frameworks match digital expansion and decarbonization paths (IEA, 2023). Circular digital strategies are modular hardware design, blockchain traceability, and extended producer responsibility to reduce material leakage and electronic waste (Bocken et al., 2016; OECD, 2016). Moreover, carbon dashboards and enterprise systems in accordance with the environmental responsibility enhance responsibility and executive control (Friede, Busch and Bassen, 2015; GHG Protocol, 2011).

However, in the absence of regulation, digital expansion may become a fast-increasing environmental strain. Another structural threat that is critical, but not to rule out, is the problem of rebound effects, which can lead to net emission growth due to the increase in the consumption of digital services, achieved through their low cost (Jevons, 1865; Hertwich, 2005). Carbon emission through geographic outsourcing of data centers would create a false impression of sustainability to the global community (Peters et al., 2011). There is also greenwashing where sustainability claims made go beyond the level which can be determined by investigating the real environmental performance (Delmas and Burbano, 2011). The simplicity of extractive hardware supply chains and reliance on rare earths also add to sustainability narratives, and the environmental impacts of such questions also affect it (UNEP, 2020).

This demonstrates that the future of digitalization in the environment is not the ability to possess technology but the governmental framework. These regulatory actions such as the carbon pricing, mandatory Scope 13 disclosure of emissions, and lifecycle reporting, mandatory renewable energy, as well as extended producer responsibility are essential in ensuring that the digital growth does not exceed the planetary limits (Rockström et al., 2009; Steffen et al., 2015; GHG Protocol, 2011). Without such institutional safeguards, the digital innovation may be a factor in the high-consumption curves of growth that cannot be maintained over the long term by ecological stability (Parriere et al., 2019).

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http://amresearchreview.com/index.php/Journal/about
Volume 4, Issue 3 (2026)

Online ISSN 3007-3197
Print ISSN 3007-3189

http://amresearchreview.com/index.php/Journal/about

Lastly, the sustainable digital transformation should be systematic which includes technological design, institutional change, financial responsibility and international environmental governance. Digital technologies are powerful amplifiers: these can accelerate the process of environmental degradation or result in radical decarbonization and changes of the circular economy. They will be oriented not on expertise calculated in isolation, but by harmoniousness of policies, strictness of regulatory measures and the ethical administrative initiative.

6. Conclusion

Sustainable digital transformation has been discussed in this paper as one of the nexus points at the intersection of technological change and environmental sustainability. Digitalization is neither sustainable nor harmful as the outcomes of digitalization on the environment depend on the system of governance, choices on infrastructure, energy systems and mechanisms of institutional responsibility (Hilty and Aebischer, 2015; Vial, 2019). Digital technologies are sociotechnical systems which are embedded in economic incentives and regulation settings in other words, their ecological impact is predetermined by policy-making and organization practice and not technical efficiency as such (Orlikowski and Scott, 2008).

As per the results, the digital transformation has the potential to result in a major reduction of the emission levels, resource efficiency, and additional environmental monitoring when linked strategically with renewable energy transitions, lifecycle transparency, and circuit material governance as well as standardized carbon accounting models (IEA, 2023; Bocken et al., 2016; GHG Protocol, 2011). Some examples of the digital infrastructure as the driver to decarbonization routes are carbon-aware computational scheduling, AI-based optimization, smart environmental systems, and digital traceability tools (Patterson et al., 2021; GeSI, 2015). This possibility is however conditional upon protection measures at the structure that addresses rebounding effects, carbon leakages, mine chain, and greenwashing (Jevons, 1865; Peters et al., 2011; Delmas and Burbano, 2011).

The concept of sustainable digital transformation as a process driven by the government and not a technological agenda is one of the key contributions made by

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Print ISSN 3007-3189
http://amresearchreview.com/index.php/Journal/about

the study. The way forward of the digitalization in the environmental context is regulatory coherence, cross- sector coordination, ESG integration, and planetary boundary alignment (Rockström et al., 2009; Steffen et al., 2015). Without systemic policy responses, such as mandatory reporting of emissions, renewable energy requirements, lifecycle reporting, and extended producer responsibility, the digital growth will assist in reinforcing high consumption economic paradigms, which has no ecological steadiness (Parrique et al., 2019).

In the future, research should take a step further to quantify lifecycle emission of new digital infrastructures, provide homogeneous algorithmic measures of carbon, and address equity issues of global decarbonization of digital strategies. The digital governance should be included in the climate policy framework by the policymakers and sustainability measurement should be in the heart of the design of the digital architecture by corporations. International institutions should not be fragmented in the process of coordination of standards and carbon outsourcing should also be avoided.

Lastly, digital transformation sustainability is not an operational change but a re-systematisation of how the digital innovation and the environmental constraints interact with one another. The possibilities of digital technologies to improve the ecological shift are enormous, but only in the conditions of responsible systems of governance and their design in compliance with planetary boundaries. Whether the process of digitalization will continue or not is not going to be considered the main issue of the future decades but whether it will be evolved in the frames which will ensure the technological progress as well as the environmental stability.

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