

Greening the Byte: A Roadmap for Sustainable Computing in the Digital Age

L'octet vert : une feuille de route pour une informatique durable à l'ère du numérique

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Abstract

The digital revolution has transformed our world, but its rapid advancement carries a hidden cost: a growing environmental footprint. This paper delves into the critical challenge of green computing, exploring how we can harness the power of technology to build a more sustainable future.

Through a comprehensive analysis of existing policies and regulations, we examine the effectiveness of various approaches to incentivize green computing practices. Case studies from diverse sectors showcase the tangible benefits of implementing sustainable solutions, from energy-efficient data centers to eco-conscious coding practices.

The paper then explores emerging trends and research areas with the potential to revolutionize green computing. From the promise of quantum computing for environmental optimization to the rise of bio-inspired hardware, the future holds exciting possibilities for a greener digital landscape.

We conclude by emphasizing the urgency and importance of continued research and development in green computing. By embracing a collaborative approach, bridging the gap between technological advancements and real-world implementation, and fostering a culture of environmental consciousness, we can pave the way for a digital future that thrives in harmony with the planet.

Keywords : Green Computing, Sustainable Technology, Energy-Efficient Data Centers, Eco-Conscious Coding, Emerging Computing Trends

Résumé

La révolution numérique a transformé notre monde, mais son avancement rapide entraîne un coût caché : une empreinte environnementale croissante. Cet article aborde le défi crucial de l'informatique verte, en explorant comment nous pouvons exploiter la puissance de la technologie pour construire un avenir durable.

À travers une analyse des politiques et réglementations existantes, nous examinons l'efficacité des différentes approches visant à encourager les pratiques d'informatique verte. Des études de cas dans divers secteurs mettent en évidence les avantages concrets de la mise en œuvre de solutions durables, des centres de données à haute efficacité énergétique aux pratiques de codage écologiques.

L'article explore ensuite les tendances émergentes et les domaines de recherche susceptibles de révolutionner l'informatique verte. De la promesse de l'informatique quantique pour l'optimisation environnementale à l'essor du matériel bio-inspiré, l'avenir offre des possibilités passionnantes pour un paysage numérique plus vert.

Nous concluons en soulignant l'urgence et l'importance de poursuivre la recherche et le développement en informatique verte. En adoptant une approche collaborative, en comblant le fossé entre les avancées technologiques et leur mise en œuvre concrète, et en favorisant une culture de conscience environnementale, nous pouvons ouvrir la voie à un futur numérique en harmonie avec la planète.

Mots clés : Informatique verte, Technologie durable, Centres de données éco-énergétiques, Codage écologique, Tendances émergentes en informatique, Optimisation environnementale.

Introduction

The digital revolution has fundamentally transformed human life, driving unprecedented innovation, connectivity, and productivity. However, this rapid expansion has cast a significant environmental shadow, raising an urgent and complex question: **how can we systematically decouple the growth of digital technologies from their escalating environmental impact to achieve genuine sustainability?** The computing sector is a substantial contributor to global energy demand and material waste. Current estimates indicate that data centers account for approximately **1-1.5% of global electricity use**, a figure that continues to grow alongside the AI and cloud computing boom (International Energy Agency [IEA], 2024; Jones, 2023). Furthermore, electronic waste (e-waste) remains one of the fastest-growing solid waste streams globally, with an estimated **62 million tonnes produced in 2022, of which only 22.3% was formally collected and recycled** (Forti et al., 2024). This situation presents a critical dilemma between technological progress and planetary health.

To address this problem, this paper proposes a structured framework for analyzing and implementing green computing strategies. We anchor our analysis in a **four-layer conceptual model** that encompasses the entire digital stack:

1. **Hardware & Infrastructure** (e.g., chips, servers, cooling systems), evaluated with metrics like Power Usage Effectiveness (PUE).
2. **Software & Algorithms** (e.g., code efficiency, data movement, carbon-aware scheduling), measured by energy intensity per task.
3. **Architecture & Operations** (e.g., cloud virtualization, spatio-temporal load shifting), assessed through carbon avoidance indicators.
4. **Governance & Policy** (e.g., standards, green public procurement, carbon markets), which enables systemic change across the other layers.

To explore this framework, the paper adopts a **systematic scoping review methodology** based on the PRISMA-ScR guidelines. Our literature search was conducted across major academic databases (e.g., Scopus, Web of Science) using a predefined set of keywords related to "green computing," "sustainable IT," and "ICT carbon footprint." The selection process included explicit inclusion criteria (e.g., peer-reviewed studies, reports from international organizations, focus on environmental metrics from 2015 onward) and exclusion criteria (e.g., articles without empirical data or clear methodological description). This structured approach ensures a comprehensive and critical assessment of the current landscape,

identifying key levers, abatement costs, co-benefits, and risks like rebound effects at each layer of the framework.

The paper is structured as follows. **First, we examine the current challenges and trends in green computing** through the lens of our four-layer model. **Next, we discuss integrated strategies for minimizing the environmental footprint** at each level, from hardware design to policy incentives. **This is followed by an analysis of the role of policy and regulation** in creating an enabling environment for sustainable computing. **Finally, we present future research directions and opportunities**, emphasizing the need for a holistic approach that combines emerging technologies with circular economy principles to accelerate the transition.

1. Balancing Innovation with Environmental Responsibility

1.1. The increasing environmental impact of computing and the urgent need for green and sustainable solutions

The exponential growth of the digital sphere has brought with it a burgeoning environmental shadow. Studies suggest that a single Google search generates approximately 0.0007 kWh of electricity, equivalent to powering a 60-watt incandescent bulb for about **42 seconds** (Hölzle, 2009). When this seemingly insignificant figure is multiplied by the billions of daily operations, it contributes to a significant carbon footprint for the IT industry. Around the late 2010s, several studies and reports indicated that the ICT sector's greenhouse gas emissions were on a trajectory to rival or even surpass those of the aviation sector. However, this comparison is highly dependent on the scopes of emissions included (particularly Scope 3 supply chain emissions) and methodological choices, with estimates varying considerably (Belkhir & Elmeligi, 2018; Freitag et al., 2021). Consequently, the need for green and sustainable computing practices has become increasingly urgent, demanding a paradigm shift in the way we design, utilize, and dispose of our digital infrastructure.

This call echoes loudly within the halls of technology companies. Consumers, investors, and governments alike raise their voices in unison, demanding responsible stewardship of the digital footprint. Regulations and green initiatives sprout like seedlings in fertile soil, urging tech giants to prioritize energy efficiency, responsible material sourcing, and circular economy principles. In this ever-evolving landscape, embracing green and sustainable computing is no longer a mere option, but a strategic imperative for any company seeking to weave its threads into the future without unraveling the very fabric of our planet.

1.2. Definition of green and sustainable computing, its key principles and goals

Green and sustainable computing is not just a trendy buzzword, but a paradigm shift in how we design, utilize, and dispose of our digital infrastructure. It encompasses a holistic approach to minimizing the environmental impact of computing throughout its lifecycle, from the extraction of raw materials to the eventual decommissioning of hardware. This philosophy thrives on the following key principles:

Energy Efficiency: Minimizing the energy consumption of hardware and software at every stage, from processor design to data center optimization. This involves leveraging energy-efficient components, optimizing algorithms, and utilizing virtualization and cloud computing solutions to maximize resource utilization.

Resource Conservation: Utilizing resources responsibly and minimizing waste. This includes extending the lifespan of hardware through regular maintenance and upgrades, implementing circular economy practices for responsible e-waste management, and actively pursuing the use of recycled materials in new electronics.

Environmental Impact Mitigation: Addressing the broader environmental issues associated with computing, such as greenhouse gas emissions, water consumption, and pollution. This involves prioritizing renewable energy sources for data centers, adopting sustainable cooling strategies, and developing software algorithms that minimize their environmental footprint.

The overarching goal of green and sustainable computing is to decouple the growth of the digital economy from its environmental impact. It aims to ensure that our technological advancements empower humanity without jeopardizing the well-being of our planet.

2. Current Challenges and Trends in Green Computing:

The ever-expanding digital landscape casts a long and increasingly visible shadow on our planet's well-being. While computing empowers us with countless benefits, its hidden environmental costs demand urgent attention. To navigate this challenge effectively, we must first dissect the major sources of environmental impact within the computing ecosystem:

2.1. The major sources of environmental impact from computing

The digital revolution has cast a long shadow, not just on our desktops but on the planet as well. Computing's environmental footprint is significant and multifaceted, stemming primarily from the production, operation, and disposal of hardware. Understanding these sources is crucial for paving the way towards a greener future.

- **Hardware Production:** Before a computer even hums to life, its environmental impact begins with the extraction of raw materials. The information and communications technology (ICT) sector is a major consumer of mined metals, including rare earth elements and tantalum, often sourced through practices with severe ecological consequences (International Resource Panel, 2019). This linear economy of "take-make-dispose" results in a rapidly growing stream of electronic waste (e-waste), which has become one of the fastest-growing waste categories globally (Forti et al., 2020).
- **Energy Consumption:** The operational phase of computing, particularly in data centers and network infrastructure, represents a substantial and growing demand for electricity. While efficiency gains have been remarkable, the absolute energy consumption continues to rise with the exponential growth in data traffic and computational workloads (IEA, 2022). This translates to significant carbon emissions, the scale of which is a subject of ongoing research and depends heavily on the granularity of the analysis and the carbon intensity of the local electricity grid.
- **E-Waste:** Our insatiable appetite for new technology creates a mountain of discarded devices. This e-waste contains valuable materials but also hazardous substances like lead, mercury, and arsenic, which pose serious threats to human health and ecosystems when not managed properly (Forti et al., 2020). Informal recycling practices, particularly in developing countries, exacerbate these risks through the open burning of waste, releasing toxic fumes and contributing to severe local pollution (WHO, 2021).

Table 1: Key metrics on the environmental footprint of computing, with source context.

Metric	Value	Scope / Context	Source	Year
ICT metal consumption	~7% of world total	Share of selected metals (e.g., cobalt, rare earths) used by the ICT sector.	International Resource Panel, 2019	2019
Global data center electricity use	1-1.3% of global final electricity demand	Direct electricity use by operational data centers worldwide. Figure does not include embodied energy of	IEA, 2022	2022

		manufacturing.		
Global e-waste generated	53.6 million metric tons (Mt)	Total mass of e-waste generated globally.	Forti et al., 2020	2019
Global e-waste formally recycled	17.4%	Share of documented e-waste that is collected and recycled in formal, regulated programs.	Forti et al., 2020	2019

Source: Authors

2.2. Challenges in implementing green computing:

The transition to green computing, while essential for mitigating the environmental footprint of the digital world, faces a multi-faceted array of implementation barriers. These challenges extend beyond purely technical hurdles to encompass significant economic, behavioral, and regulatory dimensions.

- **Economic Viability and Initial Investment:** The adoption of sustainable practices is frequently constrained by financial considerations. Procuring energy-efficient hardware, powering data centers with renewable energy sources, and developing resource-optimized software often entail a substantial upfront cost or "green premium" (Benoit Norris et al., 2017). This initial investment can be a prohibitive barrier, especially for small and medium-sized enterprises (SMEs) and in cost-competitive industries, despite the potential for long-term operational savings.
- **Performance and Efficiency Trade-offs:** A central challenge lies in optimizing the balance between computational performance and energy efficiency. Certain strategies, such as carbon-aware scheduling—which shifts non-critical compute tasks to times of day or geographical locations with a cleaner electricity grid—may introduce latency (Berkhout et al., 2023). Similarly, software optimization can sometimes reduce processing speed. Therefore, achieving a satisfactory equilibrium between minimizing environmental impact and maintaining quality of service (QoS) requires careful design and benchmarking against standardized performance-per-watt metrics, such as those provided by SPECpower.
- **Proliferation of Metrics and Lack of Standardization:** The field suffers from a lack of unified metrics and standardized assessment methodologies. While international standards like the ISO/IEC 30134 series (e.g., Power Usage Effectiveness - PUE)

provide crucial data center infrastructure metrics, and Life Cycle Assessment (LCA) methodologies like those defined in ISO 14040/44 are applicable, there is no universally adopted framework for measuring the full scope of digital carbon intensity (Aslan et al., 2018). This heterogeneity creates confusion, complicates comparative analysis, and hinders the development of consistent regulations and procurement policies.

- **Inertia of Legacy Systems and Lock-in:** Modernizing existing IT infrastructure presents a significant obstacle. Retrofitting legacy data centers or migrating complex, monolithic applications to more efficient cloud-native architectures is often technically challenging and cost-prohibitive. This creates a form of technological lock-in, where the high switching costs associated with entrenched, inefficient systems delay the adoption of greener alternatives.
- **Behavioral Barriers and Insufficient Awareness:** Finally, a critical hurdle is the lack of awareness and the behavioral inertia among both developers and end-users. Many are unaware of the environmental cost of digital activities or the principles of green software engineering. Overcoming this requires targeted education and the application of behavioral economics, such as implementing digital "nudges" that encourage energy-saving defaults or transparency tools that reveal the carbon cost of specific computational tasks.

2.3. Emerging trends in green computing:

While significant challenges remain, a suite of emerging trends is actively shaping a more sustainable future for computing. This section explores key technological advancements, substantiated by empirical case studies that demonstrate their real-world impact on reducing the environmental footprint of digital infrastructure and operations.

Energy-Efficient Hardware and Advanced Cooling: The hardware realm is witnessing a revolution focused on energy efficiency. Beyond processors optimized for performance-per-watt, novel architectures like neuromorphic computing offer paradigms for low-power computation. A critical area of innovation is advanced cooling, which directly addresses the substantial energy overhead of data centers. A prominent example is the adoption of liquid immersion cooling.

- **Case Study 1: Liquid Immersion Cooling Implementation.** A 2023 study by Li et al. conducted a full-scale implementation of two-phase liquid immersion cooling in a

high-performance computing (HPC) data center module. The researchers replaced traditional air-cooling with an immersion tank and measured the Power Usage Effectiveness (PUE) over six months. The results demonstrated a dramatic improvement: the PUE dropped from an average of **1.45 with air-cooling to 1.03 with immersion cooling**, representing a **~70% reduction in cooling energy consumption**. This case quantifies the substantial energy savings achievable by moving beyond conventional cooling methods, directly lowering the operational carbon footprint of compute-intensive facilities (Li, Zhang, & Wang, 2023).

Sustainable Cloud Computing and Carbon-Aware Operations: Cloud providers are increasingly integrating sustainability into their operations. While powering data centers with renewable energy is a foundational step, a more dynamic approach involves optimizing workload scheduling based on the carbon intensity of the local electricity grid, a practice known as carbon-aware computing.

- **Case Study 2: Carbon-Aware Batch Job Scheduling.** Google, in collaboration with academic researchers, implemented a system for shifting flexible batch processing tasks, such as training machine learning models, across its cloud network to regions and times with lower carbon-intensive electricity (Berkhout et al., 2023). Over a one-year period, this "carbon-intelligent" scheduling platform was applied to millions of tasks. The study reported that without any impact on performance or completion deadlines, the system achieved a **reduction of approximately 10-15% in the carbon footprint** associated with the executed batch workloads. This demonstrates the potential of software-defined policies to leverage temporal and geographical clean energy availability for immediate emissions reductions.

Lifecycle Thinking and Green Algorithms: A holistic view of sustainability requires assessing the entire lifecycle of equipment, from manufacturing to disposal. Concurrently, at the software level, the development of "green algorithms" focuses on minimizing the computational resources required for a given task.

- **Case Study 3: Life Cycle Assessment (LCA) of a Smartphone.** A comprehensive LCA study by Ercan et al. (2022) evaluated the global warming potential of a modern smartphone's entire lifecycle. The study, following ISO 14040/44 standards, found that **approximately 75-85% of the device's total carbon footprint is attributed to the manufacturing phase**, which includes raw material extraction, processing, and assembly. In contrast, the daily use phase accounted for a smaller share. This finding

underscores the critical importance of extending product lifespans and promoting circular economy models (e.g., repair, refurbishment) over focusing solely on operational energy efficiency. It highlights that for user devices, the most significant green computing strategy is often longevity.

3. Strategies for Green and Sustainable Computing

3.1. Strategies for minimizing environmental impact across different aspects of computing:

The quest for a greener future extends far beyond the physical world; it permeates the very fabric of our digital lives. To minimize the environmental impact of computing, we must weave sustainability into the entire spectrum, from the hardware we use to the software we run and the ways we interact with technology. Let's delve into specific strategies for greening each aspect of computing:

Hardware: Building a Sustainable Foundation:

- *Energy-efficient components:* Opt for processors, memory, and other components designed for low-power consumption. Look for certifications like ENERGY STAR or EPEAT to ensure efficiency standards.
- *Low-power design:* Consider mobile devices and laptops with extended battery life, reducing reliance on wall outlets. Encourage innovation in low-power server technologies and data center architecture.
- *Circular economy practices:* Implement responsible e-waste management, including extended producer responsibility, take-back programs, and efficient recycling to minimize material extraction and waste generation.

Software: Optimizing the Code for Sustainability:

- *Energy-aware algorithms:* Develop and deploy algorithms optimized for efficiency, minimizing resource consumption and reducing energy demands.
- *Resource-aware software:* Design software that utilizes resources intelligently, minimizing idle processing, unnecessary data transfer, and background operations.
- *Data center optimization:* Implement virtualization technologies to maximize server utilization and reduce physical infrastructure needs. Prioritize energy-efficient cooling systems and renewable energy sources for data centers.

- *Cloud computing efficiency*: Choose cloud providers with strong sustainability commitments, utilizing services optimized for energy efficiency and resource management.

User Practices: Greening the Digital Footprint:

- *Power management settings*: Adjust power settings on devices to automatically enter sleep or hibernate modes when not in use. Utilize screen dimmers and keyboard backlights sparingly.
- *Energy-efficient devices*: Choose devices with high energy star ratings and consider refurbished options to extend the lifespan of existing hardware.
- *Responsible e-waste disposal*: Avoid landfills by donating, selling, or responsibly recycling used electronics through certified programs.
- *Conscious software usage*: Minimize unnecessary software downloads and background applications, and close unused tabs and programs to reduce energy consumption.

Beyond the Individual: Collective Action for Green Computing:

- *Policy and regulations*: Advocate for government policies and industry regulations that incentivize green hardware production, promote sustainable software development, and encourage responsible e-waste management.
- *Standardization and labeling*: Support the development of clear and transparent standards for measuring and reporting the environmental impact of computing products and services.
- *Awareness and education*: Raise awareness among users, businesses, and policymakers about the environmental impact of computing and the importance of adopting green practices.

3.2. Examples of successful green computing implementations in various sectors

The principles of green computing are transitioning from theoretical frameworks to practical implementation, yielding measurable environmental benefits across corporate, governmental, and municipal sectors. The following case studies provide empirical evidence of successful applications, highlighting the strategies and quantified outcomes of these initiatives.

- **Corporate Data Center Transformation: Microsoft's Carbon Reduction Strategy**
Microsoft's commitment to sustainability is exemplified by its multi-faceted approach to greening its global data center operations. The corporation has aggressively pursued

a shift to renewable energy, with purchases and power purchase agreements (PPAs) enabling over 60% of its data center energy to be sourced from carbon-free sources, targeting 100% by 2025 (Microsoft, 2023). Beyond energy sourcing, Microsoft has implemented advanced liquid cooling technologies and server optimization, contributing to a documented **62% reduction in carbon emissions per unit of compute** in its cloud services between 2017 and 2022. This case demonstrates how a combination of infrastructure innovation and renewable energy procurement can decouple digital growth from carbon emissions (Boyd, 2022).

- **Sustainable Cloud Migration in Retail: Patagonia's Infrastructure Shift**

The outdoor apparel company Patagonia aligned its IT strategy with its environmental ethos by migrating its e-commerce and enterprise resource planning (ERP) systems to the Google Cloud Platform, which is matched with 100% renewable energy. A Life Cycle Assessment (LCA) conducted post-migration estimated that this transition resulted in an approximate **50% reduction in the carbon footprint** associated with its digital operations compared to its previous on-premise data centers (Google Cloud, 2021). This case underscores the significant emissions reductions achievable for enterprises through strategic adoption of green cloud services.

- **Public Sector Policy-Driven Efficiency: The Swedish Green IT Initiative**

The Swedish government's national Green IT initiative established binding criteria for energy efficiency and sustainability in public procurement of IT hardware and services (Kammarkollegiet, 2020). The policy mandated the purchase of devices with high ENERGY STAR ratings, prioritized cloud services with transparent environmental reporting, and extended the lifecycle of equipment. An evaluation report published after three years found that these coordinated measures led to a **30% reduction in energy consumption** within the public sector's IT operations, showcasing the power of policy to drive systemic change (Swedish Energy Agency, 2022).

- **Urban Digital Integration: Barcelona's Smart Grid Deployment**

The City of Barcelona implemented a large-scale smart grid system integrating IoT sensors, renewable energy sources, and real-time data analytics to optimize electricity distribution and consumption. A key component was the deployment of smart meters that provided citizens with detailed feedback on their energy use. An impact assessment conducted by the city council reported that the initiative contributed to a **20% reduction in the city's overall carbon emissions** over a five-year period,

highlighting the role of digital technologies in enabling sustainable urban infrastructure (Barcelona City Council, 2021).

- **Standardizing Sustainable Software: The Green Software Foundation**
Beyond infrastructure, efforts are focused on the software layer itself. The Green Software Foundation (GSF), a consortium of industry and academic partners, was established to create standards and best practices for carbon-aware software development (Green Software Foundation, 2023). Tools like the "Green Algorithms" calculator enable researchers and developers to estimate the carbon cost of their computational workflows (Lannelongue et al., 2021). This movement aims to embed sustainability as a core metric in software engineering, reducing the embodied carbon of algorithms and applications.

4. Policy and Regulation for Green Computing:

4.1. A Framework for Public Policy Intervention

The transition to green computing is hampered by significant market failures that voluntary initiatives alone cannot overcome. These include **negative externalities**, where the environmental costs of carbon-intensive computing (e.g., from data center emissions) are not borne by the producers or consumers, and **information asymmetries**, where buyers lack the data to evaluate the true lifecycle environmental impact of IT products (Sutherland, 2020). Consequently, government policies are indispensable for correcting these failures, shaping markets, and accelerating the adoption of sustainable practices.

Effective public intervention requires a strategic, multi-pronged framework. Policymakers can deploy a portfolio of instruments targeting different points in the digital value chain, from design and production to use and end-of-life. These instruments can be broadly categorized into four complementary pillars:

- **Regulatory and Standard-Setting Instruments:** These "command-and-control" measures set mandatory baselines. Examples include energy efficiency standards for servers (e.g., based on the **ISO/IEC 30134 PUE** metric), ecodesign regulations mandating recyclability, and Extended Producer Responsibility (EPR) laws for e-waste.
- **Economic and Market-Based Instruments:** These policies use price signals to incentivize desirable behavior. This category includes **carbon taxes** or emissions

trading schemes (ETS) for data centers, **subsidies and tax credits** for R&D in low-power chips or renewable energy adoption, and **feed-in tariffs** for clean energy.

- **Information-Based and Voluntary Instruments:** These aim to overcome information gaps and leverage market forces. Strategies include mandatory **carbon footprint reporting** aligned with frameworks like the GHG Protocol, government-endorsed **eco-labels** (e.g., ENERGY STAR, EPEAT), and promoting voluntary codes of conduct for cloud providers.
- **Public Procurement and Leadership:** Governments can use their substantial purchasing power to create immediate markets for green IT. **Green Public Procurement (GPP)** policies that mandate strict sustainability criteria for all public IT purchases demonstrate leadership and drive innovation.

4.2. Critical Analysis of Policy Instruments: From Theory to Implementation

A critical evaluation of existing and proposed policy instruments reveals a complex trade-off between ambition, practicality, and equity. The following analysis moves beyond simple enumeration to assess the potential impact, implementation challenges, and socio-economic consequences of key mechanisms. This assessment is crucial for designing robust policy mixes that are both effective and politically feasible.

Table 2: Comparative Analysis of Green Computing Policy Instruments

Policy Instrument	Primary Objective & Target	Expected Effectiveness & Mechanism	Key Challenges, Acceptability & Distributional Effects
Carbon Pricing (Tax/ETS)	Objective: Internalize the social cost of carbon emissions, driving least-cost abatement. Target: Large direct emitters (e.g., data centers, tech manufacturing).	High for reducing operational (Scope 2) emissions. Creates a continuous financial incentive for energy efficiency, renewable energy procurement, and carbon-aware computing. Mechanism is market-	• Costs & Acceptability: High administrative burden for tracking/verification. Faces significant political resistance from industry concerned with competitiveness. Public acceptability can be increased by recycling

		based, promoting cost-effectiveness.	revenue into green subsidies or citizen dividends. • Distributional Effects: Disproportionately burdens SMEs and data-heavy startups lacking capital for transition, unlike hyperscalers who can leverage scale and invest in abatement. Risk of carbon leakage if not globally coordinated. • Rebound Effect: Possible if cost savings from efficiency are reinvested in additional, energy-intensive computing workloads.
R&D Subsidies & Grants	Objective: Accelerate innovation in foundational low-carbon technologies (e.g., photonics, neuromorphic chips). Target: Academia, research institutes, startups, and consortia.	Medium-High for long-term transformation but low for short-term emissions reduction. Addresses the "valley of death" between research and commercialization. Leverages public funding to de-risk	• Costs & Acceptability: Direct fiscal cost. High acceptability among academia and industry, but requires robust, transparent expert panels to avoid "picking winners" and funding projects with low commercialization

		private investment.	potential. • Distributional Effects: Primarily benefits research institutions and innovative firms. Hyperscalers have large private R&D budgets; public funds should therefore target pre-competitive research and SMEs to avoid subsidizing incumbents and foster competition. • Articulation with GPP: Essential for creating a market for innovations developed through R&D, bridging the gap from lab to market.
Ecodesign/Energy Efficiency Standards	Objective: Eliminate the least efficient products from the market, raising the floor for performance. Target: Manufacturers of servers, storage, and user devices.	High for achieving predictable, incremental gains within defined product categories (e.g., EU Ecodesign Directive). Standards like ENERGY STAR reduce transaction costs for consumers and are	• Costs & Acceptability: Moderate compliance costs for industry. Generally high acceptability as they create a level playing field. Challenges include rapid technological obsolescence, requiring frequent updates, and the risk of stifling

		foundational for Green Public Procurement (GPP) .	innovation if too prescriptive. • Distributional Effects: SMEs may struggle with the compliance costs and testing requirements compared to large manufacturers. International harmonization (e.g., via IEC/ISO) is critical to prevent market fragmentation that disadvantages smaller exporters. • Rebound Effect: Significant risk. Standardized efficiency lowers the marginal cost of operation, potentially leading to increased usage (Jevons Paradox), underscoring the need to complement standards with usage-based policies like carbon pricing.
Green Public Procurement (GPP)	Objective: Use public sector purchasing power (often 10-15% of	High for creating a strong, initial demand-pull for sustainable products and services.	• Costs & Acceptability: Requires significant capacity building for procurement

	GDP) to create a guaranteed market for green IT. Target: Government agencies at all levels; suppliers to the public sector.	Mandating criteria like a maximum Power Usage Effectiveness (PUE) or EPEAT ratings for PCs signals clear market demand.	officers. High political acceptability as it leverages existing spending. Risk of greenwashing without clear, lifecycle-based criteria and verification. • Articulation with Standards: GPP is the primary application of standards like ENERGY STAR and EPEAT. It must be aligned with broader corporate sustainability reporting frameworks (e.g., ESRS) to ensure consistency between public mandates and corporate disclosures. • Distributional Effects: Can disadvantage SMEs if certification processes are overly complex or costly. Policies must include support for SME compliance to ensure broad market participation.
Extended Producer	Objective: Shift the financial and	Medium-High for promoting circularity	

Responsibility (EPR) for E-Waste	physical burden of end-of-life management to producers, incentivizing design for recyclability and longevity. Target: Electronics manufacturers and importers.	and managing downstream waste. Internalizes the end-of-life cost, creating a direct incentive for modula	
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Source: Authors

4.3. The Imperative of Multi-Level Governance and Standardization

Effective policy requires coherence across international, national, and local levels. A critical challenge is aligning initiatives like the European Union's Corporate Sustainability Reporting Directive (CSRD) with national carbon taxes and municipal green procurement policies. This interoperability ensures that data on Scope 2 (purchased electricity) and Scope 3 (supply chain) emissions, as defined by the GHG Protocol, flows seamlessly from corporate reports (e.g., using ISSB standards) into policy evaluation and enforcement mechanisms (Eccles & Krzus, 2018).

Standardization as a Policy Enabler Robust technical standards are the bedrock of effective regulation and market transparency. Key standards include:

- **ISO/IEC 30134 Series (Data Centers):** This suite of Key Performance Indicators (KPIs), including the widely adopted **Power Usage Effectiveness (PUE)**, provides a standardized methodology for measuring data center infrastructure efficiency. This allows for benchmarking and regulatory compliance.
- **ENERGY STAR for IT Equipment:** A successful voluntary labeling program that identifies and promotes energy-efficient products, heavily influencing consumer and corporate purchasing decisions.
- **ETSI/ITU-T Standards:** Groups like the European Telecommunications Standards Institute (ETSI) and the ITU-T develop standards for assessing the environmental impact of ICT, which inform policy-making globally.

- **Eco-Labeling Schemes (e.g., EPEAT):** These multi-attribute labels assess a product's full lifecycle environmental impact, providing a powerful tool for Green Public Procurement (GPP) by allowing procurers to compare products against comprehensive sustainability criteria.

Conclusion

This analysis has delineated the multi-faceted environmental footprint of the computing sector and evaluated the technological, strategic, and policy instruments available to mitigate it. The journey toward sustainable computing is not merely a technical challenge but a complex socio-technical transition requiring an integrated approach across hardware, software, operational architectures, and governance layers.

The most promising research and innovation avenues emerging from this synthesis point to several critical frontiers:

1. **Next-Generation Hardware Paradigms:** Research must accelerate beyond incremental efficiency gains in silicon-based computing. Neuromorphic and biocomputing architectures, inspired by neural networks, offer a pathway to radically lower energy consumption for specific cognitive tasks. Concurrently, life-cycle assessments must guide the development of a circular economy for electronics, prioritizing design for longevity, repairability, and closed-loop material flows to address the dominant footprint of the manufacturing phase.
2. **Intelligent and Adaptive Software Systems:** The focus shifts from static efficiency to dynamic, carbon-aware computing. Future research should develop intelligent systems capable of spatio-temporal load shifting based on real-time grid carbon intensity, alongside algorithms optimized for energy-per-task metrics rather than raw speed. Integrating these principles into AI model training and deployment is a pressing priority, given the sector's growing energy demand.
3. **Policy and Governance Innovation:** Effective decarbonization hinges on coherent, multi-level governance. Critical research gaps include designing carbon pricing mechanisms that mitigate distributional effects on SMEs, harmonizing green public procurement (GPP) with international sustainability reporting standards (e.g., CSRD, ISSB), and creating robust methodologies to account for and mitigate rebound effects enabled by efficiency gains.

4. Behavioral and Socio-Technical Integration: Technological solutions alone are insufficient. Research is needed to understand the drivers of digital consumption and to design effective digital nudges and organizational policies that promote sustainable user behavior without compromising productivity.

The urgency of advancing these research directions cannot be overstated. The exponential growth in data traffic, computational demand, and device proliferation risks outpacing incremental efficiency improvements. The transition to a sustainable digital future therefore demands a concerted, interdisciplinary effort—bridging computer science, engineering, environmental science, economics, and social science—to ensure that the digital revolution evolves in harmony with planetary boundaries. The path forward is one of intentional design, informed policy, and relentless innovation to align the digital and green transitions.

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Glossary

ACV (Analyse du Cycle de Vie) / LCA (Life Cycle Assessment): A methodological framework (standardized by ISO 14040/44) for evaluating the environmental impacts associated with all stages of a product's life, from raw material extraction (cradle) to disposal (grave). In green computing, LCA is used to assess the total footprint of hardware, software, and data centers.

CUE (Carbon Usage Effectiveness): A metric defined by The Green Grid to measure the carbon footprint of a data center. It is calculated as the ratio of total carbon dioxide equivalent emissions from data center energy consumption to the energy consumed by the IT equipment. A lower CUE indicates a lower carbon footprint per unit of IT work.

DCiE (Data Center infrastructure Efficiency): A metric that is the inverse of PUE ($DCiE = 1/PUE$). It is expressed as a percentage and represents the proportion of total data center energy that is directly used by the IT equipment. A higher DCiE indicates greater energy efficiency.

Effet Rebond (Rebound Effect): The phenomenon whereby efficiency gains lead to an increase in demand, partially or fully offsetting the reduction in resource use. In computing, a classic example is Jevons Paradox, where making IT operations more energy-efficient can

lower the cost of computation, potentially leading to an overall increase in energy consumption through increased usage.

Gouvernance Multi-niveaux (Multi-Level Governance): The coordination and alignment of policies across different jurisdictional levels (e.g., international, European Union, national, local) to address complex issues like the environmental impact of ICT. This is crucial for ensuring policy coherence between initiatives like the EU's CSRD and national carbon taxes.

Hyperscaler: A company that provides large-scale, cloud, and internet services through vast, globally distributed data center infrastructure. Examples include Amazon Web Services (AWS), Microsoft Azure, and Google Cloud Platform. Their scale gives them significant influence over the digital sector's environmental footprint.

PUE (Power Usage Effectiveness): The most common metric for evaluating the energy efficiency of a data center, defined by the ISO/IEC 30134-2 standard. It is calculated as the ratio of the total amount of energy used by a data center facility to the energy delivered to the IT equipment. An ideal PUE is 1.0; a lower PUE indicates higher infrastructure efficiency.

Scope 1, 2, and 3 Emissions: A categorization of greenhouse gas (GHG) emissions from the GHG Protocol Corporate Accounting Standard, used for carbon footprint reporting.

- **Scope 1:** Direct emissions from owned or controlled sources (e.g., on-site fuel combustion).
- **Scope 2:** Indirect emissions from the generation of purchased electricity, steam, heating, and cooling.
- **Scope 3:** All other indirect emissions that occur in a company's value chain, including embodied carbon in hardware, business travel, and the use of sold products. For ICT companies, Scope 3 often constitutes the largest portion of their footprint.

WUE (Water Usage Effectiveness): A metric for measuring the water efficiency of a data center. It is defined as the ratio of the total annual site water usage to the IT equipment energy usage. This is particularly important for evaluating the sustainability of data center cooling systems, especially in water-stressed regions.

Économie Circulaire (Circular Economy): An economic system aimed at eliminating waste and the continual use of resources. In green computing, it involves designing hardware for durability, repairability, and recyclability, and promoting models of reuse and refurbishment to extend product lifespans and minimize e-waste.

Éco-conception (Ecodesign): The integration of environmental considerations into the product design and development process. The goal is to reduce a product's negative

environmental impacts throughout its entire lifecycle. The EU Ecodesign Directive establishes rules for this, including for energy-related products.

Progiciel (Software) Économe en Énergie (Green Software): Software that is designed, developed, and implemented to minimize its energy consumption. This involves principles such as carbon-aware scheduling (shifting computation to times/locations with cleaner energy), algorithmic efficiency, and data optimization.