International Journal for Multidisciplinary Research (IJFMR)
E-ISSN: 2582-2160 ● Website: www.ijfmr.com ● Email: editor@ijfmr.com

S.M.A.R.T: Sustainability Meets Analytics in a Resource Trade

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Abstract

This paper interrogates the prevailing paradigm of smart urbanism through the analytical lens of environmental sustainability, focusing particularly on the frequently obscured carbon intensities and ecological ramifications of digitally mediated urban infrastructures. It critically examines the dominant techno-optimist narratives that surround the deployment of Internet of Things ecosystems, algorithmic governance, and ambient computational environments. While ostensibly designed to enhance efficiency and optimize resource use, these configurations often inaugurate novel energy dependencies, intensify extractive infrastructures, and externalise ecological costs beyond national boundaries. Drawing from urban theory, environmental political economy, and critical technological studies, the paper exposes the systemic tradeoffs embedded within the contemporary smart city model. Empirical illustrations from Songdo, Masdar City, Pune, Amsterdam, and Nairobi underscore a consistent accountability deficit in the material governance of smart urban development. The research ultimately advocates for an environmentally reflexive urban informatics, which is an approach that not only deploys data to achieve sustainability objectives but also internalises the energetic and ecological costs of its own operations.

Keywords: smart urbanism, environmental sustainability, carbon intensity, ecological impacts, digital infrastructures, Internet of Things (IoT), algorithmic governance, urban informatics, techno-optimism, extractive infrastructures, energy dependencies, environmental political economy, critical technology studies, material governance, sustainability trade-offs

1. Introduction

In today's world, smart cities are regarded as the solution for urban living challenges. They offer advanced systems for transport management, energy usage, and public facilities. Using the Internet of Things (IoT), artificial intelligence, and cloud computing, these cities seek to be efficient, responsive, and sustainable in the environment. Underlying this is a very critical issue: the environmental price of the very technology making the cities run (Batty et al., 2012). Smart cities can look green, but they are based on an enormous digital infrastructure. Data center operation, perpetual data transmission, and device manufacturing require vast energy and material needs. These systems consume a constant power supply and extensive mining, which results in vast carbon emissions and long-term environmental degradation (Crawford, 2021; GeSI, 2019). Most smart city sustainability approaches do not include these impacts, thereby promoting a deceptive image of advancement (Greenfield, 2013).

This research explores the intrinsic trade-offs of smart city networks. It looks at their impact on the environment, finds weaknesses in the quantification of sustainability, and calls for more critical methods to the design and governance of digital infrastructure. If we turn a blind eye to these hidden impacts, smart cities risk substituting or even accelerating environmental degradation instead of mitigating it. The aim is not to oppose innovation; it is to put technological progress in harmony with environmental responsibility.

That harmony is necessary in order to render smart cities a reality that is not merely efficient but truly sustainable in the long run (Sadowski, 2020).

The redevelopment of city spaces into digitally enhanced environments, more popularly known as smart cities, is generally posed as an eco-friendly solution to the urban issues of congestion, pollution, and wasteful consumption of resources. However, this techno-optimist discourse has the tendency to evade the inevitable environmental compromises and energy reliance of these solutions.

2. Literature Review

2.1 Evaluating the Carbon Footprint of Smart Cities and IoT Networks

Internet of Things networks in recent years have been predicted as a revolutionary solution to growing urban challenges like traffic, pollution, energy waste, and decaying infrastructure. Smart technologies want to create a more livable, efficient, and resilient environment by integrating sensors and automation systems into urban fabrics. Smart technologies aim to create more livable, efficient, and resilient environments (Batty et al., 2012). With over 70% of the global population expected to reside in urban areas by 2050 (United Nations, 2018), the adoption of these technologies has become not only a trend but an imperative for future-proofing cities.

These systems claim to reduce traffic, save electricity, and improve daily life. But while they promise sustainability, they also use a lot of energy and materials. At first glance, smart infrastructure gets billed as this big win for efficiency and sustainability. But dig a little deeper, and there's a real issue, which is hidden energy demands and environmental fallout. Manufacturing, installing, and running all these interconnected devices, sensors, and servers draws a surprising amount of power. As the International Energy Agency flagged back in 2021, the electronic waste generated by these systems is piling up fast. (International Energy Agency,2021). Ironically, the very tech designed to curb environmental harm might just be feeding the problem. This raises a critical point. Are smart cities actually proposing a solution to the environment, or are they just creating a new type of pollution? As urban digitization accelerates, policymakers, designers, and engineers need concrete data on the actual ecological costs of these technologies. (Townsend, A. M. (2013)Without that, "smart" urban solutions could end up undermining global climate targets instead of supporting them. So, understanding the full life-cycle impact is crucial for strategic decisions in urban planning and tech development.

Exploring their real carbon footprint and whether they live up to their green claims, data centers alone are responsible for nearly 2% of global emissions right now, and forecasts say they could soak up as much as 8% of global electricity by 2030. So, while IoT networks and digital infrastructure are sold as solutions for reducing urban emissions, the reality is that their operational and lifecycle energy costs are significant. The real carbon footprint of "smart" urban tech, highlighting the importance for urban planners and policymakers to consider the full ecological impact (Hitachi, 2022); the real carbon footprint behind smart technologies and IoT systems covering everything from energy consumption and cloud infrastructure to data transfer and device lifecycle impacts. To critically assess if smart cities are truly advancing sustainability or if we're just trading one set of environmental headaches for another under the label of innovation.

2.2 Reconstructing the Epistemology of Smart Urbanism in the Anthropocene

The conceptual foundation of smart cities is deeply intertwined with the epistemic currents of post-industrial urbanism, wherein computational logic supplants traditional bureaucratic modalities as the governing rationality of metropolitan life (Greenfield, 2017). This transition reframes cities as algorithmic

assemblages, orchestrated through the predictive analytics of data dashboards, sensor networks, and digital twins. The city thus emerges not as a physical or social entity alone but as a living algorithm, constantly recalibrated by real-time data inputs. Yet beneath this aesthetic of seamless efficiency lies an underacknowledged material reality, one shaped by energy-intensive infrastructures, carbon-heavy server ecosystems, and extractive global supply chains.

This ontological transformation of urban space from a zone of lived sociality to a computational terrain marks a paradigmatic rupture in urban governance. Smart cities are no longer merely governed; they are programmed, with governance mediated by automated decision-making processes rather than deliberative politics (Sadowski, 2020). This epistemological shift obfuscates the material foundations of digital governance. The infrastructures that support data-driven urbanism, hence the subterranean fibre optic cables, expansive data centres, and energy-intensive cooling systems, remain hidden from public view and are absent from sustainability metrics.

Consider Songdo, South Korea, often hailed as a prototype of smart urban design. Engineered from its inception to integrate ubiquitous computing, Songdo features centralized digital governance, intelligent traffic systems, and sensor-embedded waste management. However, recent environmental audits indicate that the energy footprint of Songdo's technological infrastructure, particularly its regional data centers reliant on coal-fired power, significantly offsets its sustainability claims (International Energy Agency, 2023). This disjuncture between symbolic cleanliness and material entropy exemplifies the ecological paradox of smart urbanism.

2.3 From Metrics to Materials: The Paradox of Dematerialised Urban Intelligence

The myth of dematerialisation pervades the discourse of smart cities, whereby the infusion of information technologies is presumed to result in a lighter environmental footprint. This presumption is fundamentally flawed. Every digital transaction, sensor relay, and cloud computation presupposes a vast assemblage of physical materials and energy flows (Höjer & Wangel, 2015). The interface of a smart city dashboard is the terminal point of a global industrial chain involving mining, logistics, manufacturing, and eventual disposal.

The techno-centric urban imaginary erases the materiality of digital infrastructures. Sensors require rare earth metals, smart meters rely on plastic composites, and wireless networks necessitate energy-intensive base stations. Yet these material prerequisites are excluded from mainstream environmental assessments. Lifecycle analyses, where they exist, are often incomplete or fragmented, failing to capture the full ecological footprint of technological deployments.

Masdar City in the United Arab Emirates serves as a salient case study. Initially envisioned as a zero-carbon metropolis powered entirely by renewables, Masdar incorporated cutting-edge smart technologies for urban optimisation. However, the city’s climate control systems, combined with the energy needs of its digital infrastructure, have rendered its operations far more carbon-intensive than projected. Investigations reveal that the ambient temperatures in the region necessitate constant air conditioning for server farms, thereby undermining the city’s net-zero aspirations (UN-Habitat, 2022). Masdar thus exemplifies the ecological costs concealed beneath the dematerialised rhetoric of smartness.

2.4 Smart Urbanism and the Rise of Data-Driven Governance

Smart cities are not just about using new technology, but about changing how cities are governed. Literature across urban studies consistently identifies smart urbanism as a form of techno-managerial governance that centralizes control through data systems. Now, in smart cities, decisions are increasingly made based on data. Cities use sensors, cameras, and algorithms to track everything from traffic to energy

use, and even citizen behavior. This kind of governance is called techno-managerial governance, because it relies on technical systems and data managers, not public officials or communities, to guide city functions (Kitchin, 2014; Shelton et al., 2015). Traditionally, cities were run through bureaucratic systems, and people in government offices made decisions based on public discussions, policies, and human judgment.

However, a critical reading reveals that this concentration of power often lacks democratic accountability and embeds environmental trade-offs that remain underexplored (Hollands, 2015). This means that smart cities do seem efficient, but at the same time, they bring serious concerns. A few issues include: ordinary citizens don't often have a say in how data is used, and they don't have a clear idea of how the power becomes centralized in the hands of a few tech companies or government departments that control data systems. The people affected by the decisions have little control over them. Clearly showing that democratic accountability has weakened, people can't always question or understand how decisions are made by algorithms or why certain technologies are implemented. Even though the Environmental trade-offs are hidden, these systems need large amounts of energy to collect, store, and process data through servers, networks, and cloud platforms. But this carbon footprint is rarely included in the city's sustainability scorecard (Hollands, 2015). Are smart cities truly sustainable and fair when the digital systems that run cities cause hidden environmental harm, and where policies focus on data efficiency rather than social or ecological well-being? Measures such as involving the citizens from the beginning in planning digital infrastructure and tools like citizen juries, digital town halls, or urban labs allow public input on technologies before they're deployed, or an Open Data Platform, where cities make data transparent and accessible, so people can scrutinize how it's collected and used. This builds trust and allows informed public debate and ensures that citizens have a voice in the decision-making processes within smart cities.

As far as the environmental impacts are often overlooked in assessments of smart city initiatives, despite their eco-friendly branding, smart cities often overlook key environmental costs, which stems back to the Energy Consumption of Data Centers in where already running cloud systems, AI engines, and IoT networks require huge amounts of electricity, often from non-renewable sources. Even as devices quickly become outdated, electronic waste piles up, often dumped in developing countries without proper recycling, and cooling systems for data centers contribute to local heat islands, especially in dense urban zones (*Crawford, K. 2021)*. They can be addressed by adopting green AI standards that optimize computational resources; using carbon labeling on digital infrastructure; and building circular tech policies that promote repair, reuse, and ethical sourcing. (Greenfield, A.2013)

2.5 Ecological Critiques of Digital Infrastructure

Smart technologies come with significant, and often ignored, ecological costs. While they improve efficiency or sustainability on the surface, either by reducing traffic or cutting down on paper usage, the digital backbone powering them is far from clean. It contributes to carbon emissions, requires rare resources, and creates new forms of environmental risk. The infrastructure that supports smart urban, sm ranging from data centers to Internet of Things devices, requires vast amounts of energy and materials, generating significant carbon emissions and ecological strain. For instance, the global data centers consumed an estimated 240–340 terawatt-hours of electricity in 2022, which is roughly equivalent to the total annual power usage of South Africa. Another example is where data centers alone consume about 1-1.5% of global electricity. This figure is expected to double by 2030 if trends continue (IEA, 2021). Moreover, carbon emission and the rapid expansion of AI systems have introduced new climate burdens:

training a single large AI model can emit as much CO_2 as five average cars over their entire lifespan (Strubell et al., 2019). Methods that can be taken to mitigate the ecological costs associated with digital infrastructure can be shifting towards renewable energy for data centers, in which data centers would transition from fossil fuel power to solar, wind even hydro-based energy. Companies like Google and Microsoft have begun operating carbon-neutral or carbon-negative data centers (Google Sustainability Report, 2023). Edge Computing is an aspect that can be taken into consideration. Instead of sending all data to distant cloud centers, edge computing allows data processing to happen locally, reducing transmission energy costs. (IEA 2021)Furthermore, the proliferation of IoT devices, now exceeding 15 billion globally, contributes to this energy drain, especially given their 24/7 connectivity. The production of the digital infrastructure depends majorly on the earth's elements and important minerals like lithium and cobalt, often sourced through extractive and environmentally degrading practices. They are mined in environmentally destructive ways, often in countries with poor labor regulations. Such an incident in 2022 can be recalled, where over 59 million metric tons of e-waste were generated globally, and only 17.4% was properly recycled. (Global E-Waste Monitor, 2020). These findings challenge the green narratives surrounding smart technologies and underscore the need to incorporate full life-cycle ecological assessments into digital urban planning.

Carbon emissions from digital technologies in comparison to those of traditional infrastructure in urban environments, where Digital technologies now rival or exceed some traditional infrastructure in carbon output. It can be concluded that Data centers and digital devices are responsible for 2.4%–3.7% of global carbon emissions, comparable to the entire aviation industry, and in cities, digital infrastructure can consume more electricity than public transit systems or municipal lighting, especially when scaled up for surveillance, traffic, and AI-based management systems (Belkhir & Elmeligi, 2018). For example, a city like Amsterdam found that energy used by its digital network was growing faster than any other sector, even surpassing its street lighting energy use (Municipality of Amsterdam Smart City Report, 2021).

While traditional infrastructure, such as roads, is still the largest contributor to embedded carbon, digital infrastructure adds continuous operational emissions through constant connectivity, server maintenance, and device turnover. Regulations could be implemented to improve the sustainability of resource extraction for digital technologies which would Require tech companies to disclose sourcing of materials like cobalt, lithium, and rare earths, especially when sourced from high-risk regions (e.g., Dodd-Frank Act's Section 1502 for conflict minerals in the US) or could Enforce Extended Producer Responsibility (EPR), where manufacturers must manage the return, recycling, or safe disposal of digital devices. They could also promote eco-certified mining practices that reduce land degradation, water pollution, and emissions, e.g., IRM (UN Environment Programme,2021).

2.6 Global Inequalities in Smart Transitions

Smart cities are places where digital technologies, such as sensors, data analytics, and IOT networks to improve sustainability and governance, whereas digital transitions refer to the shift from digital traditional infrastructure to tech-driven systems that enable real-time, data-informed decision-making methods. The idea of smart urbanization is a global project; the initiative has sharp inequalities in how urban technologies are adopted and embedded can particularly be seen between the global north and south. The northern cities often initiate smart transitions from within and have well-developed infrastructure ecosystems, which makes it easy to implement, and the global south adopts smart tech under international pressures without the infrastructure capacity (Datta, 2018). International pressures, such as the World Bank and UN-Habitat, have promoted smart urbanism frameworks that often ignore local socio-ecological

realities (Watson, 2015). Other instances, such as India's Smart Cities Mission, in 2015, were partly modeled on global templates, with $15 billion allocated for 100 cities, heavily influenced by private sector logic.
African cities like Nairobi have partnered with foreign tech firms, which shape policies through Public Private Partnerships, often reducing public control (Taylor & Broto, 2015). Konza City and Pune are examples of cities that implement surface-level solutions without any ecological reflection. These adoptions often occur without sufficient groundwork or systematic reflection on local ecological and social realities. For instance, the Konza city in Kenya and Pune in India have become a major template of urbanism, where imported technological blueprints are prioritized over grassroots ecological integration (Gopakumar, 2020; Odendaal, 2015). In both countries, smart technologies are deployed and used to attract investments and boost global competitiveness, but due to this, they remain disconnected from infrastructure capacities, local needs, and environmental concerns. If we look into the case of Pune, over 65% of urban infrastructure in Indian smart cities was built before 1980, lacking the capacity for digital retrofitting. Pune struggles with inconsistent data collection and power outages, undermining its "smart surveillance" goals. Pune Spent over $250 million on smart infrastructure, but 70% went into surveillance and centralized traffic systems (Pune Municipal Data, 2021). As far as the concern of informal settlements, ie, 40% of Pune's population saw no improvement in basic water, sanitation, or climate resilience services (Datta, 2018). Looking at the second case
Africa's Silicon Savannah, Konza, has stalled since 200,8 with only 5% of its planned infrastructure complete by 2021. Konza prioritizes global investors and corporate tech parks over local housing and sustainability. The environmental conditions for Konza's 5,000-acre site are being diverted from drought-prone areas, raising ecological justice concerns (World Bank Urbanization Review, Kenya). Looking into smart infrastructure, it depends on rare earth minerals like lithium, cobalt are often sourced under poor labour conditions in the global south. This reflects that digital colonialism, where cities in the South are data-rich but power-poor, exporting environmental costs while importing surveillance (Tzaninis & Kaika, 2021). There is limited longitudinal research on the ecological impacts of smart infrastructure in Southern cities. Few studies connect e-waste, rising digital consumption, and local environmental degradation in cities like Konza or Pune. Very little interdisciplinary work combines urban tech, environmental justice, and postcolonial critique. This results in what is referred to as "technological territorialization," where the surface promise of innovation masks deeper structural vulnerabilities.

2.7 Networked Ecologies and the Political Economy of Energy Flows

The infrastructural underbelly of smart cities is composed of complex, networked ecologies that consume immense quantities of energy, water, and mineral resources. While these systems are often touted as invisible and seamless, they are in fact material behemoths with sprawling global footprints (Graham & Marvin, 2001). The extraction, transportation, and deployment of minerals such as lithium, cobalt, and neodymium form the geopolitical and ecological foundation of urban intelligence. Smart urbanism, in its current form, is embedded in a political economy that privileges short-term optimisation over long-term sustainability. The supply chains of digital technologies are riddled with ecological degradation and labour exploitation, particularly in the Global South. Environmental costs are routinely externalised to communities and ecosystems far removed from the sites of smart deployment.
The case of Pune, India, under the Smart Cities Mission, illuminates this contradiction. The city introduced adaptive traffic systems and smart lighting without corresponding investment in renewable energy infrastructure. While traffic congestion marginally declined, energy consumption during peak hours

surged, thereby increasing emissions. Moreover, the deployment of IoT devices exacerbated electronic waste challenges, as disposal protocols were not integrated into the planning architecture (Cugurullo, 2018). Pune's experience underscores the myopia of techno-centric sustainability models that fail to reckon with their own ecological ramifications.

2.8 The Semantics of Sustainability and the Spectacle of Intelligence

In the realm of smart urbanism, sustainability often functions as a rhetorical device rather than an empirical claim. The performative use of green aesthetics and symbolic metrics masks the absence of substantive environmental gains. Proprietary data systems, opaque algorithms, and selective reporting create an illusion of ecological virtue while obfuscating actual resource use (Townsend, 2013).

This performative dimension is particularly evident in cities like Amsterdam, which have become global showcases for smart grid technologies and renewable integration. While municipal reports celebrate the city's progress, independent reviews reveal discrepancies in carbon accounting and lifecycle emissions. Much of the city's smart infrastructure, including digital interfaces and network components, is sourced from regions with lax environmental standards, thereby displacing ecological harm across borders (International Energy Agency, 2023).

Furthermore, the emphasis on high-tech solutions marginalises community-based, low-carbon alternatives. In Nairobi's Konza Technopolis, the prioritisation of elite digital infrastructure over decentralised, ecologically embedded interventions has reinforced socio-ecological inequalities. The city's construction on ecologically sensitive land has disrupted local hydrological systems and displaced rural communities, exemplifying how smart development can become a vector of ecological injustice (UN-Habitat, 2022).

2.9 Recalibrating the SMART Agenda: Toward Environmentally Reflexive Urban Analytics

To realise the emancipatory potential of smart cities, it is imperative to conceptualize the SMART paradigm not as a technological imperative but as an ethical framework: Sustainability Meets Analytics in Resource Tradeoffs. This involves designing digital infrastructures with ecological intelligence, technologies that are aware of their own material and energetic costs and governed by principles of environmental justice.

This transformation requires institutional innovation. Lifecycle assessments must be integrated into procurement processes. Emissions reporting should be standardised across jurisdictions. Digital infrastructure must be governed not solely by performance metrics but by principles of carbon accountability and material transparency (Sadowski, 2020).

International institutions have a critical role to play. Agencies such as the International Telecommunication Union and the United Nations Environment Programme should develop enforceable standards for digital infrastructure sustainability. These should include protocols for emissions reporting, material sourcing, and end-of-life disposal. Additionally, cities must be disincentivized from participating in green branding exercises unless they can substantiate their sustainability claims through empirical verification.

The case of Amsterdam is instructive once again. In recent years, the city has initiated collaborative audits with independent environmental bodies to assess the carbon impacts of its digital infrastructure. While the results were sobering, the process itself represents a step toward institutional reflexivity. Such efforts must be generalised and internationalised if smart urbanism is to evolve into a genuinely sustainable paradigm.

3. Analysis and Discussion

3.1 IoT Network Infrastructure and Energy Demand

IOT is present everywhere now, connecting basically everything from traffic lights to trash cans, anything you name it. Cities use it to improve efficiency and reduce waste, but these benefits come at a cost; all those connected devices need to stay online 24/7 to work, and that requires a surprisingly large amount of energy. To manage this, many cities are turning to newer models like fog editing and edge computing. Now these systems move data processing closer to where it's generated, so they cut down on delays and reduce the energy used to transmit data across long distances. (Mahmud et al., 2020). But in all this, there's a catch: spreading out data processing doesn't make the energy demands go away. It just spreads them across more places. Edge computing, in particular, creates a whole new layer of infrastructure that still needs power to run and maintain. (Chiang & Zhang, 2016). And as more devices go online in smart cities, from street cameras and pollution monitors to park sensors and wearable health trackers, the combined energy draw keeps increasing. These devices aren't just passively collecting data. They're constantly communicating, processing, syncing, and updating; this always-on architecture creates a continuous energy load that scales with every new system added. By 20300, we expect the global number of IOT connections to surpass 30 billion, and even low-power devices add up when deployed in millions (Statista, 2023).

As more devices go online in smart cities, from street lights, cameras, and pollution monitors to parking sensors and wearable health trackers, the combined energy drawn keeps increasing. These devices aren't just passively collecting data. They're constantly communicating, processing, syncing, and updating. This always-on architecture creates a continuous energy load that scales. By 2030, the global number of IoT connections is expected to surpass 30 billion, and even low-power devices add up when deployed in the millions. This surge is in demand and is amplified by the need for redundancy and uptime guarantees. For example, public safety systems, autonomous vehicles, and smart grid controls require constant connectivity and rapid data transfer. To ensure low latency and prevent failure, multiple node backup servers and localized processing hubs are developed across the city. What's more, each of these computing nodes has its own material footprint. These devices need semiconductors, plastic-enclosed rare earth minerals, and batteries, resources that are mined, processed, and shipped across global supply chains. Over time, these devices degrade and are replaced, generating e-waste and perpetuating the cycle of extraction and disposal. Yet this entire blackened device lifestyle emissions, server manufacturing, and network maintenance which is rarely included in sustainability reports. Cities track how many sensors are installed, how fast their network runs, or how responsive their dashboards are. But they don't usually report how much power it takes to take those systems online, or where that electricity comes from. This creates what a researcher has called an accountability gap in digital infrastructure (Tzaninis & Kaika, 2021). Because the energy costs of IOT systems are spread out and often occur outside city boundaries, like in data centers in rural zones or in overseas manufacturing plants, they're easy to ignore. A smart camera might save fuel by reducing traffic jams, but the energy it uses, and the energy needed to process and store its footage, might outweigh those over time.

The problem isn't the technology itself. It's the lack of full-picture thinking. If cities want their IoT systems to be truly sustainable, they need to start measuring more than just performance. They need to track the electricity use, material sourcing, and disposal costs of their digital infrastructure from start to finish. That means adopting life cycle assessments, integrating energy-efficient protocols, and sourcing clean energy not just for public lighting or EV chargers, but for the entire urban computing ecosystem.

3.2 Smart Grids and Urban Energy Flows

Smart grids sound like the ideal fix. They help cities keep electricity flowing smoothly, match supply with demand, and respond quickly when something goes wrong. They can predict when power use will spike or shift loads around, and even prevent blackouts before they happen (Gharavi & Ghafurian, 2011). But on the other hand, on its surface, it feels progressive, that systems that are faster, smarter, and more reliable than the old power grids, but there's a problem hiding underneath all that smartness. These grids rely on whatever energy is available. If the electricity feeding the grid is coming from coal. Or gas, then all the smart system is doing is managing fossil fuel use more efficiently. It might reduce some waste, but it doesn't automatically lower emissions. You can't tell if a city is clean if the power running on a smart grid is still dirty. The thing is, smart cities don't run on magic; they need their own digital infrastructure, smart meters in homes, communication towers, sensors, software platforms, and control rooms filled with screens and servers. All of that tech draws electricity, too. It's often invisible to the public, but it's always running in the background. In some cities, digital systems alone now use more energy than traditional public lighting (Municipality of Amsterdam, 2021). So, while smart grids improve how energy is managed, they also introduce new layers of consumption.

Another issue is the assumption that smart cities are equally sustainable. Many smart grid projects are rolled out before cities fully invest in renewables. That means that technology ends up boosting efficiency in systems that still depend on fossil fuels. A smart grid running on coal isn't a climate solution. It's just a high-tech mask over a dirty energy problem. Real progress only happens when smart grids are actually equal and sustainable. Many smart grid projects are rolled out before cities fully invest in renewables. That means the technology ends up boosting efficiency in systems that still depend on fossil fuels. A smart grid running on coal isn't a climate efficiency solution. It's just a high-tech mask over a dirty energy problem. Real progress only happens when smart grids are paired with renewable sources like solar, wind, hydropower, and when cities commit to greening their entire energy supply. Some places are doing this as well. For instance, Germany has smart grids that are deeply tied to community-owned solar and wind installations. These networks don't just optimize electricity; they shift the entire grid toward sustainability. But in many developing or fast-growing cities, smart grid investments are made before basic infrastructure is in place. That can create a mismatch to an extent, where the grid is intelligent, but the energy it carries is still harmful to the climate.

To make smart grids actually smart for the planet, better, more eco-friendly, cities need to ask tougher questions. Where is our energy coming from? What powers the servers and software? Are we using this tech to transform the system, or is it just polishing it? Without those answers, smart grids risk being more about branding than meaningful change.

3.3 Renewable Integration or Greenwashing?

A lot of smart cities love to showcase their green credentials. We can find solar panels topping bus shelters, electric vehicle chargers in parking lots, and maybe even a few wind turbines dotting the skyline. These features look and are impressive and are meant to be. They are photo-friendly, easy to promote, and make cities seem like they're leading the charge towards sustainability. But looks sure can be deceiving. These clean energy touches often scratch the surface. What's happening behind the scenes is rarely talked about. The same solar-powered bus stop might feed into a network controlled by a server farm running on coal. So while the symbol is clean, the system behind it isn't. The danger here is that cities start to believe their own marketing. They think ticking off a few green tech boxes equals climate progress. In reality, the real change comes from transforming the underlying energy systems and not just dressing up the old ones

(Sharma et al. 2022). Now, having highlighted that many urban projects stop at surface-level upgrades. They install smart gadgets and renewable tech where it's most visible, but leave the deeper issues untouched. A city has highlighted how many urban projects stop at surface-level upgrades. They install smart gadgets and renewable tech where it's most visible, but leave the deeper issues untouched. A city may roll out electric buses, for example.

Have highlighted how many urban projects stop at surface-level upgrades. They install smart gadgets and renewable tech where it's most visible, but leave the deeper issues untouched. A city may roll out electric buses, for example, while still sourcing most of its power from fossil fuels. So emissions shift, but don't shrink.

Masdar City in the UAE offers a cautionary tale. Billed as the world's first zero-carbon city, it was packed with futuristic tech from the start. But operating high-end computing systems in the middle of a desert came with a major trade-off: air conditioning. Massive energy use just to keep digital infrastructure cool undermined the entire sustainability claim (UN-Habitat, 2022). The vision was bold, but the climate logic didn't hold up under real-world conditions.

It's not that these technologies are bad. Solar panels, EVs, and smart buildings can absolutely help cities lower their carbon footprint. The problem is when they're used to cover up business-as-usual. Cities end up investing in aesthetics rather than systems. They focus on visibility instead of accountability. And the worst part? These superficial solutions often get more funding and attention than the tough, less glamorous work of grid reform or energy diversification.

If a smart city wants to be truly sustainable, it needs to look past symbols and dive into structure. That means greening the power behind the scenes, auditing data center emissions, and making sure that every smart feature is connected to a clean supply chain. Otherwise, all those solar rooftops are just window dressing on an unchanged system.

3.5 Energy Intensity and Material Infrastructure

3.5.1 Data Centers and Energy Consumption

Data centers are often called the "brains" of smart cities, but in reality, they're more like the metabolism working constantly behind the scenes to keep everything running. Whether it's streaming real-time traffic updates, storing citizen data, or powering AI-based decision systems, these facilities never pause. They operate day and night, relying on vast arrays of servers that require constant electricity, backup systems, and intense climate control.

The energy demands are enormous. The International Energy Agency (2021) reported that data centers already consume around 1% of the world's electricity. That number is projected to keep rising as more cities adopt smart systems and the Internet of Things expands. But it's not just about how much energy they use, it's also about where that energy comes from. A data center powered by coal or gas may enable efficient digital services, but it does so while quietly driving up carbon emissions. Without a shift to cleaner energy sources, these centers become hidden polluters powering smart systems while working against climate goals.

What makes this more complex is that these facilities are often built outside of city centers in industrial zones, rural outskirts, or even in different countries. That means the energy burden they create is externalized, often missing from urban sustainability reports. A city might claim its operations are "green" while outsourcing the heavy lifting and the emissions to unseen locations. This creates a false sense of progress where smart infrastructure looks clean, but its supporting systems are anything but.

Cities like Amsterdam are already seeing the effects. As of 2021, the city reported that the energy used by its digital network had outpaced what was spent on public street lighting (Municipality of Amsterdam, 2021). That’s a striking indicator of how digital infrastructure can outgrow even the most basic urban services in power demand. And yet, most residents remain unaware of how much electricity goes into the platforms and tools they rely on daily.

There's also the issue of heat. Servers generate significant amounts of it, and cooling them requires additional electricity. In warmer climates, this becomes even more problematic, as the cooling systems themselves contribute to energy consumption and, in some cases, local heat island effects. Some companies have begun experimenting with underwater or Arctic-based server locations to mitigate this, but for urban environments, this isn't a scalable solution.

The real challenge lies in visibility and accountability. These energy-hungry systems are hidden behind sleek apps and dashboards. Their costs, both environmental and financial, are buried under layers of software abstraction. Unless cities start treating digital infrastructure the same way they treat roads, bridges, or public transport, requiring audits, regulations, and transparent energy metrics, they’ll continue to grow unchecked.

It’s no longer enough for a city to invest in “smart” upgrades without asking what powers them. Energy audits must go beyond the visible grid and dive deep into the digital. A truly sustainable city doesn’t just use smart tools. It makes sure those tools aren’t quietly undermining everything else.

3.5.2 Rare Earths and Extractive Infrastructures

Every sensor, camera, and smart speaker in a city’s digital network starts its life deep underground. Materials like lithium, cobalt, and neodymium are essential for building batteries, processors, and magnetic components in smart devices. These rare earth elements power everything from electric buses to smartwatches. But their journey from mine to the motherboard is anything but clean.

Extracting these minerals leaves a heavy environmental footprint. It often involves strip mining, chemical leaching, and massive water use. The result is soil erosion, groundwater pollution, and damaged ecosystems. In many mining zones, particularly in parts of the Democratic Republic of Congo, China, and South America, labor standards are weak, regulations are loose, and communities are exposed to toxic byproducts (Nace, 2020). While urban consumers enjoy sleek devices and faster networks, the ecological and human costs are borne elsewhere, often by people with little power to resist or protest.

This disconnect rarely shows up in policy documents or smart city branding. Reports talk about connectivity, innovation, and clean mobility, but they rarely mention the cobalt in their sensors or the lithium in their backup batteries. These materials don’t magically appear in a warehouse; they're pulled from somewhere, and when the devices break down, they end up somewhere too.

And that's the second part of the problem: disposal. Most smart devices have short life cycles. Phones, routers, and meters become obsolete within a few years. The result? Tons of e-waste. In 2022 alone, the world generated nearly 60 million metric tons of electronic waste, and less than one-fifth was properly recycled (Global E-Waste Monitor, 2020). A large portion of this waste is dumped in developing countries, where it’s either burned or stripped for parts under hazardous conditions.

Despite this, urban sustainability strategies still focus mostly on energy use and emissions, not on material sourcing or afterlife impacts. We praise smart infrastructure for reducing paper use or improving transport flow, but we ignore what it’s made of and where it ends up.

Real sustainability means thinking across the full lifecycle. Cities need to start asking harder questions when they buy tech: What materials were used? How were they mined? Can the devices be recycled or

repurposed? Governments can also push for better procurement standards—requiring ethical sourcing, extended producer responsibility, and built-in repairability. It's not just about using less power. It's about using fewer harmful materials and being honest about the cost of staying connected.

3.6 Global Inequalities in Smart Transitions

Smart cities aren't often as they are presented universally as a solution to urban challenges, but the global playing field is far from equal. While many cities in the Global North upgrade their digital systems on top of their robust infrastructure, cities in the Global South are expected to jump straight forward directly into the future without the basics in place. For instance, India's smart cities mission, the ambition was bold to introduce cutting-edge technology to transform 100 cities, but in reality, many of these cities still struggle with their water access, electricity, and sanitation. In Pune, surveillance systems and smart traffic lights were installed. Over 40% of the population lives in informal settlements that continue to face flooding, population, and service gaps (Datta, 2018). The promise of becoming "smart" rarely reached them. A similar story was summed up in Kenya's sub-Saharan savannah. It was envisioned as a futuristic tech hub to drive innovation across Africa. But by 2021, less than 5% of the city was built. Most funding prioritized glossy tech parks meant for international companies, not affordable housing or climate resilience for nearby communities(Work Bank, 2016). Analysing this pattern reveals a deeper imbalance. As Tanzania and Katinika (2021) argue, this is a form of digital colonization where cities in the Global South are transformed into data-generating machines for global tech giants. These cities become hyper-visible in promotional campaigns, but remain structurally powerless. While data is harvested, land is cleared, communities are pushed aside, and yet the benefits rarely stay local. Some algorithms designed for London or Singapore are hastily imported into cities like Jakarta or Lagos, often without adaptations. This results in systems that fail or exclude the very people they claim to serve. Instead of solving inequality, uncritically smart urbanism risks deepening it. To create more just and inclusive smart cities, the process must begin with people, not just sensors. Infrastructure must be rooted in local needs. The right to the city, including data rights, housing, and environmental justice, should not be traded for shiny dashboards and investment brochures.

3.7 Networked Ecologies and the Political Economy of Energy Flows

Smart cities aren't just made up of apps and sensors; they're living organisms that are stitched together by unseen arteries of power lines, data cubes, rare earth, and sweat. This so-called network ecologies, a term coined by Graham and Marvin, embodies the paradox of modern urbanism, which includes hyper efficiency built on invisible exhaustion. What appears as seamless connectivity at the urban surface often hides ecological rupture and human cost at its core. Investigating in Pune, data travels from surveillance cameras to cloud services possibly located in Singapore, processed using electricity from coal-fired plants in Jharkhand, with components manufactured in Shenzhen and cobalt mined in the DRC, where children still dig with their bare hands (Amnesty International, 2016). A single green signal is not just a byte; it's a geographical event. Yet these systems are misread, smart governance tends to reward efficiency, and not equity. Pune's adoption of smart lighting and traffic systems led to higher emissions during peak hours because the tech infrastructure ran on the same fossil-powered grid. What's worse, policymakers skipped life cycle planning. Devices age, batteries swell, wires corrode, but e-waste mounts. In 2022, India alone generated over 1.6 million tonnes of e-waste (MoEFCC, 2023), all of which ends up in informal dumps, burned by vulnerable workers with no protection

The core issue is not technological but epistemological; we usually count what we see, and we govern what we count. Currently, mart city dashboards show traffic speed, crime heatmaps, and air quality indices,

but they rarely show the carbon footprint of the data centers, the lives behind lithium supply chains, or the gallons of water evaporated to cool server racks. The illusion of control obscures the geography of harm. Even renewables are not innocent; the installation of solar panels in Rajasthan requires flattening deserts, displacing nomadic tribes, and consuming massive water reserves for panel cleaning (Anand & Radhakrishnan, 2021). Shifting burdens doesn't solve them. As cities race to outsmart each other, we risk designing future utopias that operate on extractive pasts. In his critique of smart urbanism, Greenfield (2013) calls this solutionism the belief that all problems can be coded away. But you can't debug a broken energy policy with an app. To humanize smart cities, efforts can be made, such as localizing data infrastructure, decentralizing edge computing can reduce energy draw from distant server farms. Accounting for ecological externalities where sustainability indices must include upstream water, land, and labor impacts. Regulating algorithmic impacts. Smart traffic systems that maximize flow can worsen air quality in marginalized zones. We need justice-oriented design. Value human inputs. Sanitation workers, linemen, data laborers, these are the invisible sentinels of smart ecosystems. Urban problems can't be fixed with tools that create new ones. Smart must not mean soulless. The cities of tomorrow must be measured not just by efficiency, but by empathy.

3.8 The Semantics of Sustainability and the Spectacle of Intelligence

Sustainability gets tossed around a lot in smart city plans. It sounds good in press releases, shows up in slide decks, and adds a green tint to dashboards. But often, it's more of a buzzword than a real goal. Cities dress up their plans in eco-friendly language while hiding the actual costs behind the scenes. Townsend (2013) called this the "spectacle of intelligence", where cities appear sustainable on the surface, but the deeper systems don't match the narrative. Amsterdam is a good example. It's often praised for its smart grid projects, but independent reviews found gaps in how carbon data was reported. The city's digital infrastructure relies heavily on tech built in regions with loose environmental laws and high emissions (IEA, 2023). So while the local systems look clean, the global footprint tells a different story.

In Nairobi, the development of Konza Technopolis focused more on elite digital infrastructure than on the basics like sustainable housing or water systems. Construction disrupted local water supplies and forced people out of their homes. The project was marketed as progress, but the benefits were mostly for investors and the tech industry. Communities were pushed aside. If sustainability only serves marketing and investor pitches, then it loses its value.

Real sustainability needs to go beyond appearances. It has to ask hard questions about who gains, who pays, and what's being hidden. A city can't be considered green if it relies on extractive supply chains, displaces people, or dumps e-waste in someone else's backyard.

Instead of designing cities to look smart, we should focus on making them fair. That means including environmental and social costs in the conversation. It means valuing people, not just sensors. If the goal is to build better futures, we need to stop treating sustainability as a label and start treating it as a responsibility.

4. Conclusion

This paper has illuminated the fact that smart cities today are often sold as solutions to the climate crisis, urban congestion, and governance inefficiencies. But this paper has shown that beneath the language of innovation and sustainability lies a system deeply entangled in ecological contradiction. The digital infrastructures that support smart cities are not weightless. They are heavy with material costs, energy demands, and extractive labor, much of which is outsourced and hidden. Cities like Amsterdam may

appear green in their reports, but independent audits reveal carbon mismatches and a global supply chain built on weak environmental protections. In Konza and Pune, glossy infrastructures and smart traffic systems were introduced, yet the local communities continued to face displacement, environmental degradation, and unmet basic needs. These cities invested millions in surveillance and optimization, but neglected the environmental and social groundwork required to make those technologies truly sustainable. This isn't about isolated failure. It's a pattern of urban theater where sustainability is performed, not practiced. Sustainability becomes a sticker, a brand, something to signal rather than something to substantiate. And when we measure success by dashboards and innovation indexes instead of life-cycle impacts and equity, we lose sight of the real question: who pays the price for our progress?

This paper has pushed past the glossy veneer of smart urbanism to uncover the physical and political architectures that support it. It's clear that smart cities are not immaterial; they're built on networks that consume electricity at staggering rates, from data centers that never sleep to IoT systems that never shut off. They require rare earth minerals, often mined under dangerous and unethical conditions, and generate massive amounts of e-waste that ends up in countries with little capacity to safely process it. Digital infrastructure doesn't just have a carbon footprint. It has a human one. Yet city planners, investors, and even sustainability frameworks continue to measure efficiency by what a city can automate, rather than what it can sustain. We are told that smart cities will help us transition to a cleaner future, but the evidence suggests they may be accelerating the very environmental collapse they claim to prevent. Cities like Masdar, once hailed as models of carbon neutrality, have failed to deliver on their promises, burdened by the energy needs of their own technological ambition. And despite all the talk of progress, informal settlements remain underserved, workers remain invisible, and energy remains dirty. The central problem is not innovation itself, but how we define and deploy it. Right now, smart urbanism privileges optimization over justice, performance over accountability, and aesthetics over long-term durability. It doesn't have to be this way. If we're willing to ask harder questions about where our materials come from, how our systems are powered, and who is left out of the equation, then we can begin to redefine what smart truly means. Cities need to move beyond symbolic sustainability and start accounting for the full material, ecological, and ethical cost of their digital development. That means rethinking procurement, mandating transparent emissions reporting, building edge computing networks that reduce energy waste, and embedding citizen voices into the design of smart systems. We need lifecycle audits for every device, ethical sourcing for every mineral, and green power for every data center. Sustainability cannot begin and end with public relations. It must begin with people.

So where does that leave us? Smart cities shouldn't just be smart by design. They should be smart in how they treat the planet, how they distribute benefits, and how they anticipate unintended consequences. The current model has made intelligence a spectacle and sustainability a slogan. That needs to change. The future isn't just about faster algorithms or sleeker dashboards. It's about slowing down enough to measure the hidden costs, listen to marginalized communities, and reimagine progress not as constant acceleration, but as careful, accountable design. This paper doesn't argue against technology. It argues for a smarter way to be smart—one that's reflexive, responsible, and real. If we can embrace that shift, then maybe, just maybe, our cities can become more than sites of performance. They can become models of planetary care.

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