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The Circular Economy (CE) Rebound as a Paradox of Knowledge: Forecasting the Future of the CE–IoT Nexus through the Global E-Waste Crisis

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Abstract: There are widespread assumptions to the effect that the real-time data generated through the 5G-enabled Internet of Things (IoT) will improve material traceability and accelerate the global transition to a circular economy (CE), thereby helping to achieve the UN Sustainable Development Goals and carbon neutrality. Many industries, governments, and NGOs are supporting this vision by investing in related digital infrastructure (5G networks, servers, computer hardware, etc.). Conversely, recent literature has highlighted a paradoxical phenomenon known as the CE rebound, whereby sound CE activities end up offsetting environmental gain(s). This challenges the assumption that the new 5G-enabled IoT will be conducive to greater circularity while carrying its own environmental weight. Resorting to applied epistemology—a perspective seldom used in sustainability research—and the global e-waste crisis as an intense case in point, we question the confidence with which actors predict positive outcomes from the CE–IoT nexus. We argue that avoiding circularity rebounds cannot be construed as a matter of methodological development or, by extension, modeling sophistication through real-time data exploitation. Instead, circularity rebounds need to be recognized and theorized as a paradox of knowledge that also narrows sustainability research's horizons, despite AND because of the 5G-enabled IoT. As per this paradox, advanced digital technologies may well be compounding environmental issues at the same time as they illuminate them.

Keywords: circular economy (CE); 5G-enabled Internet of Things (IoT); CE–IoT nexus; advanced digital technologies; e-waste; rebound effects; paradox; applied epistemology; intensity sampling

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1. Introduction

The circular economy (CE) concept has benefited from widespread public visibility and political influence in the last decade to the extent that it now stands as a commonly shared premise of environmental sustainability among government officials, policy designers, environmental advocacy groups, and businesses. Broadly defined as an approach to decouple economic growth from natural resource extraction on variable scales [1,2], CE can also be construed as a transition pathway in and of itself (e.g., [3]) or as an increasingly popular goal of sustainability transitions research, as it rapidly—if loosely—translates into political discourse [4,5]. For the French philosopher and politician Luc Ferry, the CE concept injects a new momentum into the ecological movement: "If ecology does not want to be associated with an all-out decline in terms of amenities, comfort, time, purchasing power, but also freedom and well-being, it will have to stop being punitive, anti-liberal, diminishing and deadly to become "positive" in finally integrating the notion of circularity" [6].

Despite such favorable perspectives, the CE concept and its potential outcomes remain contested [7], and its implementation poses multiple social, economic, and technical challenges [8]. This explains, in part, why sustainability experts (professionals and researchers alike) often tie the future of CE to developments in digital technologies. Indeed, CE's operationalization (i.e., the concept's concrete translation and implementation through policies, strategic plans, programs, and economic actors' decision-making) is now increasingly perceived to rely on an acceleration of widespread digital systems and applications. Together, for example, the 5G-enabled Internet of Things (IoT) and associated devices/sensors in supply chains [9–11], edge cloud computing [11], Distributed Ledger Technology [12], and/or machine learning for big data analytics [13], are expected to enable and accelerate traceability and improve the governance of material flows. Whether in line with such expectations or in tension with them [8,14,15], different kinds of propositions have been made by researchers to help overcome CE's operationalization challenges: i.e., propositions spanning a broad range of disciplinary perspectives in engineering [2] and economics [16], but also in sociology [17], geography [18], or environmental policy studies [19]. For a sense of CE's conceptual breadth and diversity within and across disciplines, see [7].

In contrast with the disciplinary core of CE research, this conceptual article questions CE's operationalization challenges from an applied epistemological perspective. As per an influential definition by philosopher Larry Laudan: "Applied epistemology in general is the study of whether systems of investigation that purport to be seeking the truth are well engineered to lead to true beliefs about the world" [20] (p. 2). As such, applied epistemology "routinely examines [s] truth-seeking practices [. . .] to find out whether they are capable of delivering the goods they seek." [20] (p. 2) Recognizing the newfound hopes and beliefs of CE's operationalization brought on by the rise of so-called "intelligent assets" [1]—and perhaps most of all, by the rise of the 5G-enabled IoT and associated devices/sensors in supply chains, for tracking product and material flows–, we question whether big data analytics can realistically help fulfill CE's "green" promises. Treading in Zink & Geyer (2017)'s footsteps, we specifically ask whether conditions that are both *necessary AND sufficient* for the core of CE activities to avoid CE rebounds can ever be known: i.e., the phenomenon whereby circular systems or activities end up increasing or accelerating overall production, thereby eliminating partially or fully their expected environmental benefits [21].

To shed light on this issue, we explore very practical questions about "what [can] be known or reasonably believed" from the probabilistic system of investigation underpinning the bulk of CE research and practice [22] (p. 153). Our main argument is that full awareness of these conditions cannot ensue from increasing and optimizing the interface between CE and advanced digital technologies. As we move on to show, model uncertainty is bound to increase as modelers tap into the epistemic potential of artificial intelligence (AI) and big data analytics. No matter how intent modelers may be on improving systems-based approaches to environmental modeling (e.g., by hybridizing life-cycle assessment using agent-based modeling, network models, AI techniques. . . or a combination thereof) for sustainability purposes, the exploitation of real-time data provided by 5G-enabled IoTs exposes the field of sustainability research itself to rebound effects. The question therefore arises as to whether the knowledge we readily possess about material flows is actionable without further relying on "intelligent assets"; if it is, how can this knowledge be exploited to its full potential, despite being "incomplete" or "insufficient" [23,24]. For example, on the policy-making side, how might model uncertainty be conceived and exploited as knowledge instead of being construed as liability, ignorance, or failure [25,26]? Or, on the environmental modeling side, how might extant modeling approaches such as Life-Cycle Assessment (LCA) be epistemically recast so that the modeling community's core identity and epistemic values fit more tightly with its modeling practices [27,28]? Apart from a few potential exceptions (e.g., [29]), such an applied epistemological take on CE has earned no research attention thus far.

In this article, we set the stage for a new research agenda at the intersection between the paradox theory in Management & Organization Studies (MOS) and sustainability research. In Section 2, we offer brief literature and expose our main premises: by adapting Larry Laudan's legal epistemology and leveraging it, the CE–IoT nexus is cast as an "epistemic engine", urging us to ask whether its mechanics of knowledge production are "truth-conducive" [22]. We develop our main argument in Section 3: i.e., the circularity rebound phenomenon is theorized as a paradox of knowledge inherent to the CE–IoT nexus. A conceptual framework based on the paradox theory is also drawn to capture the deadlock in which the CE's operationalization is arguably caught. In Section 4, we illustrate the main argument by drawing from the ongoing electronic waste (e-waste) crisis, framing it as an intense case in point: that is, as a single case study whereby our phenomenon of interest (the circularity rebound) is intensely manifested [30], and thus exposed as a paradox of knowledge. Overall, this conceptual article challenges the eco-modernist take on CE's operationalization by questioning the effectiveness and enabling capacity of advanced digital technologies for methodological development and model sophistication.

2. Literature Review: The CE–IoT Nexus as an "Epistemic Engine"

As mentioned above, some of the CE's most promising operationalization pathways have been linked to the 5G-enabled IoT: that is, to the epistemic potential of Big Data and new data analytics in terms of material traceability, monitoring, and control. Tapping into Larry Laudan's scholarship in applied epistemology and paradox research in MOS, we expose the need to unpack some of the key assumptions and shortcomings of this perspective. Admittedly, our proposition may appear to feed into the false dichotomy between high- and low-tech operationalization pathways, which currently permeates CE discourses [7,8]. To the contrary, however, our premise is that the main challenge lies elsewhere and much deeper, in our own "trained incapacity" as sustainability researchers to see beyond data-driven, mathematical modeling and probabilistic analysis for purposes of sound knowledge production or scientific advice [23,31].

For example, let us consider the long-standing debate on whether and how LCA modeling can rein in subjective (value-laden) choices by further relying on data and mathematical modeling (e.g., [32–35]). In line with this last take on the debate, some sustainability researchers using LCA-based methodologies see value assumptions as a threat to scientific robustness and credibility. LCA guidelines and ISO standards also implicitly advise model developers to eliminate values from their models as much as possible [28,35,36]. Yet, as philosophers of science and social scientists have known and have been arguing for over three decades [36,37], "value-based judgments, based on situated knowledge, can actually enhance the rigor, accountability, and credibility of scientific assessments." ([28], p. 1410). In becoming more qualified as LCA experts, sustainability researchers are therefore prone to developing an implicit bias in favor of data-intensive models and metrics, which may appear more objective and complete than mixed (both qualitative and quantitative) modeling approaches (e.g., [38]): that is, they are likely to refrain from using value-based judgment even when it would enhance rigor [34].

In this last respect, any scientific training may culminate into what Gendron et al. coined as "epistemological short-sight" [23]: a phenomenon akin to what Hannah Arendt described as "thoughtlessness" [39,40]. It follows that sustainability researchers (e.g., many of which are engineering or natural sciences scholars) may come to lack theoretical judgment and/or imagination precisely as they rise and become proficient in their own discipline and/or field of enquiry [23]. Through this process of *epistemic acculturation* or "habitus incorporation", as Pierre Bourdieu would call it [41], one typically acquires "contributory expertise" at the expense of "interactional expertise" [42], thus becoming shortsighted, so to speak, and much less inclined or capable to explore alternate epistemologies or take part in interdisciplinary integration [43–45]. Through this process, CE research's prime and longstanding focus on problem-solving becomes exacerbated as if debates about problem definition had no epistemic value of their own or should come without political considerations [23,37]. Yet insofar as CE researchers aspire to formulate "socially robust" responses to the pressing environmental challenges of our time, knowledge and technology development at the CE–IoT nexus does need to account for such debates and political considerations [44,45].

Let us, therefore, consider the CE–IoT nexus as the "epistemic engine" it appears to be in the eye of many sustainability and CE researchers: that is, as a "a tool for ferreting out the truth from what will often initially be a confusing array of clues and indicators" [20] (p. 2), whereby material traceability is enabled, and the global transition to a CE made possible [46,47]. Let us propose a thought experiment rooted in the legal system as a metaphor for the CE–IoT nexus, instead of a more familiar form of analysis, to think about uncertainty, error, and validity in environmental models, the status of knowledge in environmental decision-making and the operationalization of the CE.

While the 5G-enabled IoT, Big Data and new data analytics are often construed by sustainability researchers as an epistemic boon, a more critical literature suggests that they should also be seen as an epistemic bane on at least two fronts:

(1) In terms of *error reduction,* i.e., avoiding counterproductive decisions (or "false verdicts") [20], data-driven sustainability science can increase the risk of spurious correlations and may, as such, threaten the very purpose of the CE–IoT nexus [48–50];
(2) In terms of *error distribution,* i.e., choosing the lesser evil when errors do occur (e.g., supporting "false acquittal" instead of "false convictions") [20], data-driven sustainability science finds itself in the awkward position of being both judge and jury as it tries to account for the environmental burden of its own sensing-and-measuring apparatus, namely at the CE–IoT nexus [51,52].

These two sets of issues are not new. Yet, as we argue in Section 3, they tend to be trivialized, and their underlying paradox is overlooked. As per the paradox definition, *error reduction* and *error reduction* are to be construed as "persistent contradictions between interdependent elements" [53] (p. 10). Such contradictions are persistent in the sense that they resist any sort of resolution: i.e., paradoxes are inherently insoluble. This is why a *paradox* cannot be understood as (or assimilated to) a *problem*, albeit a very complex or "wicked" one [54]. Because of this intractability, a paradoxical situation needs to be recognized and managed differently than a problematic one [54,55]. In fact, a paradox can become even more damaging when it remains implicit—that is, when it is blindly assimilated to a problem as if it was plainly amenable to resolution (e.g., [56]). So, rather than considering the CE–IoT nexus in terms of problem-solving, we propose to consider the dynamics underpinning its mode of knowledge production as paradoxical. Hence, new insight was gained from this study.

On the first front (*error reduction*), one must heed the fact that data-driven (as opposed to theory-driven) discovery increases the risk of assigning meaning to spurious correlations [49] and, as such, turns the CE–IoT nexus into both an epistemic boon and bane, all at once. As statisticians Xiao-Li Meng puts it, Big Data can hold statistical paradises for the heedful analyst, but it mostly holds fallacies for all those who carelessly turn to it for scientific breakthroughs based on the false premise that more data necessarily translates into less uncertainty, better models and better decisions [57]. More to the point, "without taking data quality into account, population inferences with Big Data are subject to a Big Data Paradox: the more the data, the surer we fool ourselves" [57] (p. 686). The same holds even more true for predictive analysis based on Big Data, whereby "[spurious correlations] appear only due to the size, not the nature [or quality], of data", [49] (p. 595). It appears that the future relevance of data-driven sustainability science—and hence the CE–IoT nexus—is closely tied to the future epistemological proficiency of sustainability researchers [23].

On the second front (*error distribution*), one must heed the paradox underlying the digital transformation of environmental modeling, so to speak (e.g., [58–60]). Epitomizing this trend, a strand of CE research is reasserting the centrality of methodological development based on advanced digital technologies to bridge knowledge gaps, reduce uncertainty, and push back epistemic frontiers. From this perspective, the time is ripe for a major leap in our collective capacity to monitor and govern material flows in an environmentally optimal way [59]. Thanks to the advent of fifth and sixth-generation (5G, 6G) wireless networks, the latency and capacity to connect devices worldwide are tremendously improved, thereby allowing the IoT to become a critical enabler of CE [61]. And thanks to recent advances in lithographic technology and semiconductor traceability, supply chains could now be tracked and managed down to the wafer level, as opposed to the packaged semiconductor unit/product (Micro-Electro-Mechanical systems) level [62]. A 5G-enabled IoT is therefore seen as a pragmatic way of fulfilling a long-awaited epistemic function by allowing digitized products, digital components and material flows to become fully traceable and the data collected to be transformed into real-time, global lifecycle inventories: in other words, allowing for high-stake environmental decisions and CE policies to be "futureproofed" based on LCA [61]. Yet an oft-silenced precondition to optimizing the CE–IoT nexus is that the digital infrastructure (5G wireless networks, servers, computer hardware, etc.) itself be sustainable, or at least, that it be energy efficient [63].

As we move on to show in Section 3, this last precondition may not be attainable, namely because of "rebound effects" and the myriad uncertainties related to the information's accessibility, how it may be used, or whether it may help inform environmental decisions and public policies [21,64,65]; in spite, that is, of the great epistemic expectations the CE–IoT nexus may fuel [66]. As the sensitivity analysis scholar Andrea Saltelli puts it:

> There has been an accumulation and maturation of structural contradictions in modern science [36], [. . .] between real and acknowledged uncertainty in science's pronouncements, between technological progress and technological risk, and in its purported structural relation to democracy [67]. [. . .] A radically new concept, practice, and ethos need[s] to be imagined and acted, by scientists—who need to be clearer about what they can deliver and what they cannot –, and by society—which must come to accept a more circumspect understanding of the role of science in informing societal and technological directions. [68] (p. 87–88)

Saltelli proposes to manage epistemic expectations more responsibly—by being clearer on "what [scientific models] can [and cannot] deliver". But what if acknowledging the extent of inevitable uncertainty ends up reducing confidence in scientists and negatively impacts public acceptance of scientific predictions and/or environmental advice? [69,70].

As paradox scholar Marianne W. Lewis clarifies, we might be faced with a perception challenge rather than a matter of clarity and fact: facing paradoxical tensions such as the ones exposed above, e.g., between scientific knowledge and uncertainty, one tends to frame the elements in contradiction as conflicting, whereas they are "two sides of the same coin" whose relatedness tends to be obscured by actors' perceptions [71] (p. 761). Said differently: "Paradoxes stare us in the face—taunting our established certainties while tempting our untapped creativity. [. . .] While seemingly distinct and oppositional, these elements inform and define one another, tied in a web of mutuality." [55] (p. 6). This paradoxical perspective on environmental modeling (and what the latter can and cannot deliver) is reflected in the sustainability research literature from a philosophy of science standpoint by authors who conceive of "uncertainty as knowledge." (e.g., [25,26]). As [26] argues, "uncertainty can be a source of actionable knowledge rather than an indicator of ignorance" in that, even though our modern-scientific ability to "look at the past to make predictions about the future [. . .] is now under threat", this "growing uncertainty about the future [. . .] ironically imbues us with the knowledge of what we can do to escape that uncertain future." [26] (p. 2–3).

Given the above, the originality of our proposition lies in our framing of the CE rebound as a "paradox of knowledge" inherent to the CE–IoT nexus and closely akin to one of the paradoxes currently faced by the LCA community [27]: that is, a paradox whereby uncertainty and knowledge come forth as inherently interdependent elements bound into a profound and persistent contradiction [53,72]. This article's epistemological rooting, therefore circumvents the barren opposition between techno-optimism and techno-pessimism, or between science and philosophy, by arguing that the most fundamental challenge posed by the expansion of the 5G-enabled CE–IoT nexus is that of facing its underlying paradox: i.e., the CE rebound we define and delve into in the next section should not be construed as a soluble problem, as "it cannot be solved in the sense of being tackled effectively, once and for all" [55] (p. 15). Once acknowledged as a paradoxical dynamic, the CE rebound can "be approached as a process which, although at times [under some circumstances] may appear to be 'solved', eventually resurfaces, bringing the action back to 'where it all started'—even though every new start is more than a repetition, a necessarily different start." [55] (p. 15).

Let us therefore clarify how the CE rebound can be understood as a paradox of knowledge inherent to the CE–IoT nexus, as opposed to a problem that may eventually be resolved through the 5G-enabled IoT and related digital infrastructure.

3. Main Theoretical Argument: The CE Rebound as a Paradox of Knowledge

In the fields of operations management [73–78], sustainability sciences [79], and circularity-related work [1], it is widely expected that the digital transformation of industry—more commonly known as Industry 4.0—will enhance CE and overall environmental sustainability. This belief stems from the idea that digital technologies hold an untapped epistemic potential for integrating efficiency gain and cost reduction in new ways. For example, technologies underlying the 5G-enabled IoT allow for data on consumer behaviors to be collected so that material flows can be traced and recovered after the use phase. With cloud manufacturing, underutilized manufacturing capability can be sensed and taped into by users from across the world [76]. Based on data and AI-driven analytics, organizations could theoretically derive knowledge to design products and services for better environmental performance over the use phase and through end-of-life (EoL), while at the same time increasing customer satisfaction [77]. Even beyond such opportunities, Industry 4.0 and enabling network technologies appear to offer a multitude of possibilities for the development of material- and energy-efficient production and consumption systems and, in turn, for supporting industrial transitions towards the CE (e.g., [78,79]). The current academic literature is thus replete with new research projects looking to recognize and unlock the potential at the CE–IoT nexus, broadly understood (cf. [79,80]). Yet whether such CE–IoT solutions can carry their own environmental weight remains debatable [81].

In relation to the above point, two important insights must be considered. On the one hand, the complexity of the CE rebound has now been aptly conceptualized [16,21] and documented (e.g., [2,82–84]). As it stands, the CE rebound can be construed as a frontier of knowledge in several fields, such as environmental economics, industrial ecology, or sustainability science in general. That is, the full knowledge that would be necessary to ensure that CE delivers on its "green" potential—regardless of political will or business commitment—seems out of reach with respect to the standards of science within these fields [21,64]. This is indeed a major reason why part of CE research has recently turned to so-called "intelligent assets": i.e., pushing back this epistemic frontier would require the total traceability that the IoT can presumably deliver [1,85].

On the other hand, however, such "intelligent assets" are creating new and increasing pressures of their own on the environment, the net balance of which must also be factored in (i.e., modeled and monitored) to ensure that the purported benefits of CE activities are not offset by the "intelligent assets" in support of traceability (cf. Section 2, *error distribution*). For example, the International Energy Agency (IEA) reported that, in 2021, only 10% of 83 billion IoT-connected devices and sensors in Europe were generating data that was being analyzed and put to use [86] (p. 17). This over-capacity is on the rise and can indeed be seen in a positive light as an untapped potential, e.g., for sustainable policy-making, more traceability, better environmental models, optimized urban planning and citizen benefits, etc. Yet it comes with its own unforeseeable environmental footprint, which already requires to be modeled and monitored if CE rebound is to be avoided. In essence, this is how modeling uncertainty is bound to expand along the same curve as scientific knowledge: although the most sophisticated systems-based modeling approaches (e.g., life-cycle assessment, agent-based modeling, deep learning) do reveal the complexity and interrelatedness of environmental sustainability issues such as economic growth, climate change or digitization [64,65], this revealing diversely contributes to expanding the complexity and opacity of systems [87]. As such, methodological development is arguably bound to fall prey to a paradoxical phenomenon known to management scholars as "paralysis by analysis", i.e., the unintended deferral of important actions by aspiring to comprehensive decision analysis [88–91].

3.1. "Paralysis by Analysis": Statistical Methods' Paradoxical Appeal to Sophistication

"In their decision-making activities—as Ann Langley emphasized in 1995–, managers need to tread a fine line between ill-conceived, arbitrary decisions ("extinction by instinct") and an unhealthy obsession with numbers, analyses, and reports ("paralysis by analysis")." [88] (p. 63). Almost three decades later, part of this general idea is strongly echoed by the newly popular dual-process theories, which are now being applied to a wide range of decision-making domains, i.e., well beyond their origins in psychology and behavioral economics [92]. As per these theories, decision-makers are now broadly recognized as prone to cognitive biases, which in effect correspond to the "extinction by instinct" end of [88]'s spectrum of decision-making impetuses. Incidentally, by conceiving of reasoning as an interaction between intuitive (System 1) and deliberate (System 2) thought processes [93], dual-process models have catalyzed the design of appealing approaches to sound decision-making, i.e., approaches that incentivize System 2 reasoning in various domains (e.g., [94–96]). As a result, however, the risks of "paralysis by analysis" tend to be overlooked: the new epistemic attractiveness of fast-rising IoT infrastructure (5G networks, AI chips, sensors, etc.) attests to this neglect, as such infrastructure tends to be construed as a means to escape decision biases, and *not in the least* as a threat to decisiveness. As with the Big Data Paradox introduced above, we might consider that the more we seek to advance frontiers of knowledge through analytical models, the more issues reveal themselves intractable or "wicked" [97] at the CE–IoT nexus. Moreover, as we argue in Section 4 using the global e-waste crisis as a revealing (or intense) case study, the more complexity we uncover about wicked problems, the more we continue to seek methodological and technological sophistication to solve them in a headlong and relentless pursuit of analytical comprehensiveness (e.g., [9,98]).

To illustrate the paradoxical dynamic of knowledge and uncertainty more plainly, let us imagine the necessity to make a strategic decision in the abstract and let us define strategic decisions as "important and non-routine decisions that require significant resource commitments and have notable influences on the performance, survival, and health of firms." [91] (p. 416). In other words, strategic decisions can be a matter of life and death for an organization, just like sustainability transitions are a matter of life and death for humanity, as it were [99]. In an article entitled "Method in the madness? A meta-analysis on the strategic implications of decision comprehensiveness", Samba et al. [91] provide just what we need to run such a thought experiment: i.e., they find themselves confronted with "paralysis by analysis" as they delved into the management science literature to ask: Is strategic decision comprehensiveness beneficial for firms? In answering this question, they, in fact, chronicle our own paradox of knowledge in a stylized form, thereby setting the stage for its "real-life" exploration in the following sections.

In their meta-analytical inquiry, Samba et al. [91] focus on quantitative studies that "give sufficient statistical information for collecting and computing correlations" [91] (p. 422), in addition to defining a series of content-related requirements for basic qualification. After thoroughly vetting the 81 papers retrieved from multiple academic databases, 33 usable papers spanning 34 years (from 1984 to 2018) are selected to provide the empirical foundation for the meta-analytic work. Based on this literature, Samba et al. [91] intriguingly conclude that the positive effects of decision comprehensiveness on performance outcomes are driven by a methodological artifact: i.e., performance is correlated with the early design choice as to whether a decision's outcome will be measured (1) through perceptual data (scale ratings) generated by key informants in the strategy process, or (2) through official data drawn by researchers from available archives. They find that comprehensiveness and outcomes are positively related only when these outcomes are measured through perceptual data (labeled as subjective by authors), whereas studies based on official archival data (labeled as objective) show no correlation between decision comprehensiveness and outcomes. In other words, the authors conclude that the statistically significant findings of comprehensiveness's effects on decision performance (i.e., positive outcomes) likely result from common method bias and other methodological factors creating fertile ground for informant biases such as social desirability, anchoring bias and availability heuristic [91].

In light of these findings, Samba et al. [91] recommend that future research on decision comprehensiveness be designed to pinpoint these potential methodological artifacts: i.e., that future research be "designed to include both objective and subjective outcome assessments." [91] (p. 431). Yet, in doing so, they tread a fine line between increased confidence in results through more comprehensive data and diminishing returns from increased model complexity and ensuing equifinality [100]. In other words, they find themselves confronted with the dangers of "paralysis by analysis". In the following long excerpt from [91], we add the italic letters in brackets to illustrate how a manager's and a researcher's comprehensiveness ordeal mirrors each other. In spite of having very different takes on performance outcomes than managers, Samba et al. [91] find themselves confronted with the same dilemma. Their conclusions therefore chronicle the paradox of knowledge we seek to clarify and the symmetry between a manager's and researcher's bias in favor of comprehensiveness:

> "Beyond a methodological explanation for our results, we build on the view that strategic decision [*or statistical*] comprehensiveness provides symbolic value for organizations [*or research*], which can be captured by managers' [*or researchers'*] accounts of organizational performance [i.e., *research impact*]. [. . .] Although advanced predictive analytics can help managers [*and researchers*] better predict complex and uncertain future states, contributors to research on the strategic implications of big data have a duty to remind readers [*and themselves*] that "unhealthy obsession with numbers" and "paralysis by analysis" remain relevant concerns. [. . .] Our findings regarding the comprehensiveness-outcome relationship suggest that while it provides some benefits, comprehensiveness may have been oversold. Thus, managers [*and researchers*] should understand that comprehensiveness is likely not the sought-after panacea." [91] (pp. 431–433)

In other words, Samba et al. [91] exemplify how the comprehensiveness-outcome relationship is paradoxical and how it also lurks within research. Most importantly, they exemplify how statistical methods' appeal to sophistication endures in spite of one's intimate knowledge of its traps.

Now, going back to the CE–IoT nexus, let us show how Samba et al. [91]'s own paradox of knowledge becomes salient to an understanding of the CE rebound. As [21] demonstrate, (1) there is nothing intrinsically green about the circular economy, and (2) the methodological comprehensiveness sought after to identify necessary and sufficient conditions for CE's green character is likely unfeasible. Firstly, "simply closing material loops is not enough to guarantee environmental improvement" since "increased production and consumption [. . .] can reduce the benefits of the circular economy" [21] (p. 600). Such an increase is what they have defined as CE rebound: i.e., a possible outcome of CE activities whereby an environmentally sound change in secondary production—i.e., recycling and repair being less impactful than primary production—fails to substitute primary production (for ex., by lowering prices on a given market and prompting greater consumption). Therefore, if researchers, decision-makers and policy designers were to avoid the CE rebound, they would have to factor in "the net consequences of increased secondary production" by "looking at all possible causal chains." [21] (p. 600).

Secondly, then, in substantiating the CE rebound phenomenon, the authors of [21] raise the bar of robust environmental sustainability and CE research so high that it becomes unattainable. From an applied epistemology point of view, one might even say that they reveal the radical incapacity of dominant environmental modeling approaches to "ferret out the truth" [20] (p. 2) from the global economy. Economists Gillingham et al. [64] make a similar argument while discussing the energy efficiency (EE) rebound effect and in finding the global economy from which it emerges to be a "single, interconnected, complex dynamic system" whereby "definitive arguments about cause and effect [are made] nearly impossible." [64] (p. 81). But as [21] more directly conclude:

> Circular economy rebound could be a serious obstacle to creating meaningful environmental improvement. How, then, can we work to avoid rebound so that the promise of the circular economy is realized? From the preceding discussion, several necessary conditions emerge for avoiding circular economy rebound. [. . .] *Unfortunately, due to the unpredictable nature of highly complex systems, such as the system of markets involved in the circular economy, it is likely impossible to derive any meaningful conditions that are both necessary and sufficient.* Unforeseen consequences may mean that a well-intentioned circular economy activity nonetheless results in rebound. [21] (p. 599. Emphasis added.)

In other words, the authors of [21] expose the impossibility of grasping and preventing CE rebound(s), or the energy efficiency (EE) rebound(s) for that matter, through advanced scientific research. They show how "paralysis by analysis" also lurks beneath CE research and practice, and beneath the sustainability sciences more broadly.

In light of this, some argue—as [21] do—that unleashing CE's "green" potential should go hand in hand with challenges to economic growth and neoliberal capitalism [101,102] such that degrowth scenarios varyingly seem to present themselves as potential responses to current environmental crises [103]. Yet, regardless of CE's conceptions as strong or weak forms of sustainability, we argue that the CE rebound substantiated by [21] and others after them provides sufficient evidence of the counterproductive dynamic underlying statistical inference and predictive analysis from Big Data: i.e., identifying and avoiding the CE rebound should not be construed mainly as a matter of quantification and/or quantitative methodological development and, by extension, of technological sophistication [104]. Instead, the CE rebound needs to be understood as a paradox: i.e., in this case, acknowledged as the ever-receding frontier of knowledge which it constitutes despite the 5G-enabled IoT and the new epistemic potential it indeed unlocks. As we clarify in the discussion (Section 4.2), for sustainability researchers and policymakers, this would allow the adoption of a *paradoxical mindset* [105], i.e., "shift[ing] [one's] expectations from rationality and linearity to accepting paradoxes [CE rebounds] as persistent." ([106], p. 385). In terms of CE operationalization, this would imply "a shift from traditional linear management approaches to more adaptive and integrative strategies" [107]; i.e., to more adaptive and integrative strategies aimed at avoiding the unwitting creation of vicious circles at the CE–IoT nexus. Let us therefore clarify the paradoxical dynamic unwittingly reinforced by CE research's dominant mindset and the unwary promotion of digital technology development to bridge knowledge gaps and push back epistemic frontiers.

3.2. The CE Rebound as an Ever-Receding Frontier of Knowledge

As seen above, for many sustainability researchers, the time seems to be ripe for a major leap in our collective capacity to monitor and govern material flows in an environmentally optimal way [75]. Thanks to the advent of fifth-generation (5G) wireless networks, the IoT can now allegedly become a critical enabler of CE [61] by not only allowing for product lifecycles to become fully traceable [108]: that is, for "all possible causal chains" to be looked at and the net consequences of increased secondary production assessed. But how do we know if the environmental benefits of exploiting the 5G-enabled IoT for operationalizing the CE outweigh the related environmental costs [109]? More broadly, "in what contexts can digital technologies mitigate the [CE] rebound effect?" [65].

If the CE rebound is to be avoided through total product traceability and CE markets transparency, the required 5G network latency and capacity gains must not come at the cost of an energy efficiency (EE) rebound [63]. Yet when it comes to operationalizing and optimizing the CE through the 5G-enabled IoT, a trade-off between the two rebound effects (CE and EE) does seem unavoidable: as the following thought experiment shows, the 5G-enabled CE–IoT nexus which epitomizes the "digital assets" expected to "unlock the circular economy potential" [1] can only seek to avoid CE rebounds by creating or exacerbating EE rebounds, hence the insight provided by a paradoxical perspective on the CE–IoT nexus, and the theorization of CE rebounds as an ever-receding frontier of knowledge.

Characterizing this impasse, Sustainable Computing (SC) researchers have been warning against one-sided rationales and overly optimistic scenarios such as those prevailing in CE research (e.g., [85,87]). As [63] put it, this is why "energy efficiency, measured in bits per Joule, has emerged as a new prominent figure of merit and come to be the most widely adopted green design metric for wireless communication systems." (p. 72) Despite all efforts, however, SC researchers foresee the proliferation of EE rebounds triggered by the 5G networks that are supposed to help neutralize the risks of CE rebounds and unlock CE's "green" potential:

> With such a tremendously expanding demand for wireless communications in the future, researchers are currently looking for viable solutions to meet the stringent throughput requirement. [. . .] Even with the [new] 5G paradigms for improving EE, the power consumption will still grow because of the explosive data rate requirements in the future. Therefore, improving EE can only alleviate the power consumption problem to a certain extent and is insufficient for enabling sustainable 5G communications. [63] (pp. 72–73)

So, what might the options be for those most intensely faced with this last predicament?

For some SC researchers, integrating energy harvesting technologies into future 5G wireless networks stands out as a new imperative [63], whereas for others, the prime solution seems to lie in the constant energy monitoring and control of 5G-enabled IoT, or ultra-scale systems (USS) [109]: i.e., "high-quality levels of measurement and power-monitoring infrastructure that can provide timely and accurate feedback to system developers and application writers so that they can optimize the energy use" [109] (p. 40). Regardless of the chosen option or combination thereof, any new solution layer brings forth its own energy requirements along with the new flows of monitoring data. In principle, then, "the amount of monitoring data, its gathering, and processing, should never become a bottleneck nor profoundly impact the energy efficiency of the overall system" [109] (p. 27), yet "similar to many systems that have to handle large amounts of data, energy monitoring can become a so-called Big Data system [. . .]" [109] (p. 40). Moreover still, "the fact that administrators, engineers, and decision makers are increasingly willing to perform predictive and prescriptive data analyses using interactive interfaces" exacerbates this last scenario [109] (p. 40). As predictive and prescriptive data analyses capitalizing on the 5G-enabled CE–IoT nexus requires adjusting data collection and monitoring metrics on demand—especially if CE rebounds are to be anticipated –, even the most sophisticated, leanest SC solutions lead right into the EE rebound.

Samba et al. [91]'s paradox hence resurfaces through SC researchers' awareness of their own field's EE rebounds. Much like the plaintiff in North American criminal courts, it falls on them to prove the extent of the phenomenon and to prevent it, yet the "system of investigation" they resort to (i.e., statistical science recast as data science) inevitably becomes self-incriminating: i.e., the standard of proof "beyond reasonable doubt" thus turns against itself—so to speak—and becomes impossible to satisfy precisely because the 5G-enabled IoT constantly improves data monitoring and control. This is how the CE rebound constitutes an ever-receding frontier of knowledge. Faced with such highly entangled causal chains and ever more diffuse environmental responsibilities, we might metaphorically say that SC research is bound by an inoperative standard of proof, whereby reasonable doubt prevails despite the very high confidence in the "guilt" of the 5G-enabled CE–IoT nexus, and by extension, of advanced digital infrastructures. This double bind is familiar ground for climate scientists whose constant struggle has long been to cope with a concept of scientific modeling fully fit for purpose, but ever unfit to stand the trial of our most common concept of science [110,111].

So, coming back to the question set forth earlier: what approaches complementary to statistical inference—or more broadly, to quantitative research—could be used to avoid "paralysis by analysis"? We argue that intensity sampling holds great potential, i.e., that of allowing the synthetic knowledge we possess but cannot prove to be true (as per the prevalent standards of knowledge quality in science) to become actionable. In the following section, intensity sampling is therefore explained and used. Based on intensity sampling principles, the e-waste crisis is framed as a paradigmatic illustration of the collective future awaiting us on many more fronts if progress in sustainability research keeps being understood primarily by researchers as a matter of methodological development and, by extension, of scientific modeling and technological sophistication.

4. Discussion: Gaining Perspective through Electronic Waste (E-Waste) Crisis

In contrast with probabilistic sampling approaches, qualitative research methods based on purposeful sampling allow for intangible, diffuse phenomena to be investigated while accounting for their intrinsic complexity. Knowledge quality is therefore built as per very different standards than those commonly shared among the natural sciences: e.g., no statistical significance is sought. For the sake of discovering greater richness and depth of insights, theorizing strategies such as the one proposed here prioritize "close data fitting" over generality or transferability of results [112]: that is, much fewer "information-rich cases whose study will illuminate the questions under study" are selected and studied to "yield insights and in-depth understanding rather than empirical generalization" [30] (p. 230). Yet, some level of generalization can be expected and will be recognized varyingly in what follows.

Our prime purpose is thus to investigate whether and how an intense case of notable CE failures—i.e., the e-waste crisis—can shed light on the 5G-enabled CE–IoT nexus and its inherent rebound effect. As we will argue, this case not only provides valuable insight into the vicious circle created by e-waste management schemes predicated on advanced digital technologies but also, and more broadly, into the paradoxical dynamics underlying CE's operationalization through the CE–IoT nexus. Not only do we acquire more actionable knowledge from studying this exemplary (information-rich) case than from statistical depictions [30]. But most of all, such an approach contributes to preventing paralysis-by-analysis by shifting sustainability researchers, policymakers or business managers' mindset from a traditional, linear problem-solving approach to adaptive and integrative strategies [107]: i.e., a decision-making mindset more cognizant of the paradoxical dynamics created at the CE–IoT nexus, or whenever sustainability transitions are hinged on advanced digital technologies.

4.1. Snapshot on the Global E-Waste Crisis

Long before the commercial advent of 5G mobile technologies or the deployment of IoT edge computing, which are both presented as very promising ways to transition towards CE [51,113], production/consumption patterns and EoL management of information and communication technologies (ICT) posed critical issues on a global scale, from an environmental, health, political, social, and humanitarian perspective [114–116]. For at least three decades now, these issues have remained intractable despite advances in modeling capacities, scientific knowledge, targeted legislation, and international agreements (cf. [117]). They are intractable to such an extent that the overall situation has come to be known as the "global e-waste crisis" [114,116]. In the face of this so-called "wicked problem" [97,118], the IoT's epistemic potential may indeed seem like a promising avenue to track the life cycles of ICT so as to control e-waste streams in optimal ways (e.g., [9,98]). However, notwithstanding the social benefits that the 5G-enabled IoT and advanced data analytics may present in some circumstances [119], these technologies have so far tended to exacerbate social inequities and environmental harm [119–123].

The challenges posed by e-waste management in many vulnerable contexts represent an intense illustration of how ICT material flows (and e-waste inflation) cannot be reined in by resorting to the epistemic potential of ICT itself, through the CE–IoT nexus, artificial intelligence (AI) and big data analytics. As it unfolds, the global e-waste crisis illuminates the "dark side" of the CE–IoT nexus as inextricably tied to the epistemic engine it also constitutes (cf. Section 2): that is, it magnifies the features of CE rebound dynamics, which arguably span the full spectrum of *digital-sophistication-for-the-environment* between the smart city [118] and environmental impacts modeling [124], thereby making them more recognizable by sustainability researchers, policymakers, and decision-makers overall. To support *digital-sophistication-for-the-environment*, among other uses, layers of ever more powerful wireless networks (LTE, 3G, 4G, and 5G) accumulate, allowing for the proliferation of various devices, such as individual mobile devices (typically smartphones) and digital data. Ubiquitous internet access induces a range of new desirable potentialities and epistemic prospects, but also highly undesirable consequences on human health and ecosystems—the desirable and undesirable effects being inextricably linked [125,126]. Even the smallest and most benign digital devices, such as single IoT edge devices (whose environmental burden is implicitly assumed to be negligible compared to the positive impacts they can generate), are very likely to induce important rebounds on a large scale [51]. So, although varying in detail and intensity depending on contexts, the digitization of environmental modeling or of rapidly urbanizing areas in low-income countries magnifies the trait of an otherwise diffuse phenomenon whose global social, economic, and environmental ramifications are still unfathomable: that is, the e-waste crisis.

Almost fifteen years ago, over the course of the year 2008, the number of connected objects in use on a global scale crossed an important threshold, exceeding the world's population for the first time [127]. The picture is even more striking given that in this same year, the "digital divide" was peaking between the Global North and the Global South, both quantitatively and qualitatively [128]. In 2008, it was estimated that less than 3% of Internet users were in Africa, while the continent held more than 14% of the world's population [128]. Over the next decade, fast-growth urban areas in the Global South (mostly Africa) rapidly gained connectivity through impressive increases in the number of smartphone users, but digital inclusion did not follow accordingly [129–131]. Like the dynamics already observed in large European or North American cities—i.e., where connectivity is now nearly universal–, the social (offline) inequities and stratification of digital uses they induce would largely inhibit the expected benefits of the otherwise essential spread of internet access [119–121]. In other words, the internet became increasingly accessible to more and more people, but this broader access did not translate into lower socioeconomic inequities or more environmental justice. In some borderline cases, inequities in digital skills and quality of technological uses even contributed to exacerbating already existing social inequities, most importantly socio-demographic inequities, despite increased connectivity [119,120].

At the same time, urban areas in many developing countries became the dumping ground of e-waste for themselves, Europe, and North America [116,120,132]: the fastest-growing stream of solid waste since the mid-1990s [133], and one of the most impactful locally (on human health, ecosystem integrity, etc.) and globally (on climate change and critical metal dispersion, etc.) when tied—as it often is—to informal, poorly managed or unmanaged recycling (see e.g., [134]). Most alarmingly, some areas in Africa and Asia became dumping grounds despite the Basel Convention (e.g., [117]) and other elaborate regulatory frameworks [135]: that is, in spite of normative frameworks and sophisticated governance schemes specifically aimed at reducing or ensuring the control of transboundary movements of hazardous waste [136]. In 2022, "only 22.3 percent (13.8 billion kg) of the e-waste generated [globally] was documented as properly collected and recycled" [116] (p. 7), and nowadays, "even countries with relatively mature e-waste systems have low collection rates" [98]. On a global scale, a considerable share of e-waste is therefore still illegally exported to "pollution havens" such as in Africa or Asia as a pretense of reuse or metal recycling [134] (p. 14).

In other words, the numerous Extended Producer Responsibility (EPR) programs in place for electronic products are still grappling with important attractors of illegal e-waste trade, such as the high economic value of metals or the general lack of incentives to comply with formal processing channels [19,98,136]. In response, most EPR programs continue to build on the presumption that the more data there is, the better it is to inform local legislative arrangements, economic incentives, or urban design. Yet even today, in many developed jurisdictions, policymakers and government officials are unable or reluctant to restrict the recycling of e-waste to those who are known to have the best available technology, thereby allowing informal e-waste flows to proliferate in competition with regulated EPR programs [137]. Moreover, in some contexts, manufacturers refused until recently to reveal the most basic information about how much ICT equipment is put on the market [19,138].

Considering these apparently basic and yet unmet conditions, how can it be expected that additional IoT-derived data would, by default, improve the situation instead of exacerbating the e-waste crisis? Are we not in the presence of a revelatory case of CE rebound whereby an ever-receding frontier of knowledge becomes salient?

As we argue below, the current deadlock partly stems from the presumption that, given total e-waste traceability, the knowledge on e-waste flows would become sufficient and that it would be transferable to decision-makers (public officials, policymakers, business leaders, etc.): typically in the form of clear conclusions on how to act according to optimal scenarios (e.g., how to incentivize large scale return of EoL electronics for optimal management, how to devise optimal Extended Producer Responsibility (EPR) policies, etc.). Yet this rationale overlooks the paradoxes underlying error reduction and distribution (exposed in Section 2), whereby the CE–IoT nexus produces uncertainty, so to speak, at the same time as it produces knowledge: in other words, unless "uncertainty [is recognized as] a source of actionable knowledge" [27], p. 1, data-intensive analytical approaches to e-waste management are likely to feed into paralysis by analysis, as described in Section 3.1, and even into the e-waste crisis itself by scaling the demand for, namely, IoT edge devices [51]. As the renowned engineer and philosopher Jean-Pierre Dupuy put it back in 2012:

> By placing the emphasis on scientific uncertainty [i.e., error reduction and distribution], [we] utterly misconstrue the nature of the obstacle that keeps us from acting in the face of [collective] catastrophe. The obstacle is not uncertainty, scientific or otherwise; it is the impossibility of believing that the worst is going to occur. [. . .] Even when it is known that it is going to take place, a catastrophe is not credible: this is the principal obstacle. [139] (pp. 577, 585–586)

That is, it remains unfathomable, especially on a collective scale. As one scientific field in charge of informing the decisions and actions of policymakers, government officials and corporate leaders in the face of environmental catastrophe, i.e., of making them believe that the worst is going to occur, Sustainable Computing research is notably caught in this double bind, as argued in Section 3.2: i.e., the paradoxical injunction of advancing our knowledge of the crisis by characterizing and measuring ICT's contribution to it, for optimization purposes, while accounting for the environmental burden of its own sensing-and-measuring apparatus. Hence, the quintessential quality of the field's relationship to the CE–IoT nexus, as it specializes in the promotion of an e-waste IoT.

4.2. *Neither Hope Nor Hoax: The E-Waste IoT as a Quintessential Paradox of Knowledge*

As this snapshot illuminates, e-waste flows (as all other material flows) result from interactions between highly complex social, economic, political, institutional, and behavioral dynamics [140,141], all of which vary according to local contexts, globalized markets, and systemic responses. These dynamics are the result of millions of separate decisions (explicit or implicit) taken by agents that are (knowingly and not) changing or determining material trajectories—including sustainability research's scientific orientations, results, and advices [138]. Whereas enthusiastic promoters of the CE–IoT nexus generally consider that a cost-effective approach to acquiring Big Data on informal, poorly managed or unmanaged EoL e-waste flows would allow hotspots identification and a gradual circularization of the ICT industry (e.g., [9,56,69,73,74,98,129], others are more cautious: e.g., Sustainable Computing researchers [98,109]. These more cautious promoters of the CE–IoT nexus do acknowledge that the multiplication of RFID tags, sensors, and other Big Data technologies complexify the management of e-waste streams [98]. Yet contrary to Jean-Pierre Dupuy's earlier warning, they cling to the belief that the currently digitizing systems of investigation purporting to seek true and actionable CE knowledge are well engineered to do so.

As a case in point, let us look at a white paper recently published by the International Telecommunication Union (ITU), the WEEE Forum, the GSMA and Sofies Group:

> The application of digital technologies in the transition to a circular electronics value chain is still developing and its impact on the space is still not completely understood or expansively studied. While there is consensus on the benefits of digitalization in accelerating circularity, it can pose negative impacts as well. [. . .] Such an evolution needs to be complemented with continuing research and efforts to understand its impact on the electronics value chain and its stakeholders, considering the most vulnerable such as those working in the informal sector. Digitalization comes with numerous benefits, but an unregulated space can alienate some of those involved and potentially underscore inequalities, infringe on privacy and even create more e-waste. [98] (p. 22, 28)

Using caution, these authors emphasize scientific uncertainty and the need to pursue analytical comprehensiveness through further research: namely, to understand the impact (environmental and social) of pairing digital technologies and CE strategies to circularize the electronics value chain. In other words, they assume that the necessary and sufficient conditions for an e-waste IoT to achieve its “green” potential can and might even already be known. As these authors consider, “in general, if IoT devices are taken back and companies are responsible in their creation, IoT can be more beneficial than detrimental” [98] (p. 26). Yet, the paradox of knowledge underlying the CE–IoT nexus becomes even more salient here, since such an e-waste IoT would also inevitably have to track and monitor its own self-induced e-waste (as per the *error distribution* paradox, described in Section 2).

In other words, the research needed to control the environmental impact of an e-waste IoT would tread a very fine line between providing the capacity to increase confidence in decisions or policymaking (through more accessible data and comprehensive decision analysis—assuming this information is made available to environmental protection agencies and actors committed to solving the e-waste problem) and its own inevitable blind-spots and diminishing returns (through modeling approaches whose technological sophistication also contributes to increasing e-waste). It is likely that, as the economy becomes more symbiotic—i.e., as material and energy flows become more intertwined in the CE–, the expected beneficial outcomes become undermined by increasingly unpredictable phenomena [16,21]. This is how the complexity, opacity, and intrinsic unpredictability of undesirable outcomes such as rebound effects come out as unthinkable for researchers, policymakers, or business leaders when the CE–IoT nexus is conceived strictly as a solution-space, i.e., not recognized as conducive to paradoxes. Although we know enough to support collective action—i.e., we know that rebounds will take place and that they may well precipitate catastrophe, much like “we know from uncertainty, with near certainty, that climate change is a problem that must be taken seriously” [26] (p. 8)–, these rebounds run the risk of remaining unbelievable (as in unthinkable, impossible to imagine or accept) in spite (and because) of our ever-growing capacity to track, monitor and measure them [139]. This is perhaps one of the most immediate obstacles to CE’s sound operationalization and overall environmental sustainability, as anticipated by [139].

Besides, and regardless of inevitable rebounds, there would likely be limited value to having complete visibility of e-waste flows. Indeed, even if all the conditions were met to translate this into a 100% recovery rate, it would only contribute a small portion of the resources needed to meet the current demand for electronics production [142] to which the IoT is contributing. As argued above, one tradeoff is, at minimum, a guarantee that additional e-waste will be generated but also that particular metals will continue to be dissipated through the initial extraction and product design, thereby challenging the recycling of IoT components. The opportunity costs of investing public and private funds in the CE–IoT nexus may be that other, already “actionable” solutions will be left aside.

As ultimately foregrounded by the idea of circularizing the electronics value chain through an e-waste IoT, the CE–IoT nexus is, therefore, neither a hoax nor grounds for hope. Instead, it should be acknowledged as a paradox whereby uncertainty confounds with knowledge and vice versa. Concretely, this means that CE's operationalization cannot be resolved through the CE–IoT nexus. Instead, it is likely that the more we buy into an ever-persistent race toward traceability and modeling/technological sophistication, the more environmental issues will become intractable. Despite all the useful digital data that would admittedly be generated by an e-waste IoT, the conjunction of multiple systemic transitions required to unleash the knowledge value of this Big Data and be able to use it to tackle the e-waste crisis is hardly imaginable, let alone implementable, without greater and yet unmeasurable environmental harm. As previously argued, the rebound effects brought upon by such systemic transitions are bound to behave as ever-receding frontiers of knowledge, while any attempt at creating a CE by promoting the IoT is sure to generate more e-waste. Hence, the intensity value of the e-waste crisis as an information-rich case whose study from an applied epistemological perspective yields crucial insights: it illuminates the paradoxical dynamic underlying the CE–IoT nexus and how it has so far been broadly overlooked by sustainability research.

As explicitly stated in the introduction, our argument is thus 100% theoretical (including the case study). As such, it is based on a logical sequence of strongly substantiated arguments (hence the very high number of bibliographic references, many of which are also theoretical) coming together to form a thought experiment showing that CE research's clinging to quantitative approaches is counterproductive. In that sense, the global e-waste crisis was selected precisely for its self-sufficient, revelatory quality: i.e., because it strongly substantiates the argument without having to resort to numerical data—the headlong pursuit of which—we argued—partly explains why CE research in general, and Sustainable Computing in particular, is stuck in a vicious circle. Choosing more than one case study for quantitative comparability reasons would, in fact, have impeded the epistemic move underlying our main thesis.

So, insofar as the global e-waste crisis is deemed to manifest the aforementioned knowledge paradox in an intense way, this paper offers two important insights from a methodological point of view: (1) the paradoxical dynamic underlying the CE–IoT nexus is indeed widespread, or generalizable to a large extent, albeit mostly under less conspicuous forms than displayed through the global e-waste crisis; and (2) our interpretations of the global e-waste crisis altogether avoid distorting or dramatizing the paradox [30]. Overall, then, if we (as sustainability researchers) continue to believe that decision comprehensiveness will eventually result from pairing the CE with the IoT, the future of rebound dynamics is likely to align with the vicious circles manifested intensely through the global e-waste crisis case study.

5. Conclusions

This paper proposed an original contribution by using an applied epistemological perspective to clarify the paradoxical nature of the relationship between the CE—which is widely acknowledged as a premise of environmental sustainability—and the IoT as a systems infrastructure expected to enable the CE. The paradox of knowledge it exposes at the root of the CE–IoT nexus challenges the assumption that a 5G-enabled green IoT could eventually be conducive to greater circularity while carrying its own environmental weight. Instead, we argue that the confidence with which many industries, governments, and NGOs are now expecting positive outcomes from the CE–IoT nexus should be questioned. Most centrally, we question the realism and the political innocuity with which some sustainability research feeds this expectation by aspiring to capture "all possible causal chains" underlying a system so complex as the CE.

Contrary to conventional scientific wisdom, however, the reason for this questioning is not merely that any scientific model is flawed, limited and incomplete, i.e., perfectible through more research. The reason is that the energy and material flow we aspire to trace, monitor and control through the CE–IoT nexus cannot be construed as “out there”, i.e., as separate from the systems of investigations we use to understand them. The digital transition of environmental assessment tools and sustainability research surely contributes to increasing the environmental impact of the phenomenon it is assessing. Yet the extent to which the CE–IoT nexus exacerbates the phenomenon it is looking to control is bound to remain in the unknown.

Our perspective on the global e-waste crisis therefore suggests that sustainability research could achieve greater social service if it diverted itself slightly from the prevalent goal of seeking analytical comprehensiveness. This historically legitimate endeavor now seems to be turning on itself, so to speak, through its own critical digital transition. As it stands, the quest for analytical comprehensiveness may indeed differ from the important political decisions and actions that sustainability research intends to support in order to confront the current environmental urgency. Because full awareness of the necessary and sufficient conditions to avoid CE rebounds cannot be known, striving to discover these conditions (through new digital technologies or otherwise) may well compound environmental sustainability issues.

Indeed, the way we disregard paradoxes and their intrinsic trait of persistence leaves us unable to think and act in the face of present environmental urgency, whereby the line between knowing and believing fades away. This explains the apparently unreconcilable perspectives on the CE rebound: on the one hand, promoters of the CE cling to the idea that “the rebound effect is expected to lessen over time as more goods and services meet ‘circularity’ aspirations and as the economy becomes more service-oriented” [143] (p. 191); and on the other hand, skeptics hold that “the more circular resource flows become, the more likely it is that it is not waste that is avoided, but rather other eco-efficient uses of resources” [16] (p. 63). However, the main challenge arguably lies elsewhere and much deeper, in our own “trained incapacity” as researchers to see beyond the self-made (artificial) oppositions between knowledge and uncertainty, knowledge and belief, and knowledge and paradox.

On a positive note, the question of how CE research and the broader field of sustainability sciences might integrate, gain from, and extend paradox research by developing an interface with Management and Organization Studies (MOS) makes for a promising interdisciplinary research agenda. Although limited in the extent to which it discusses the literature on proper paradox responses (e.g., through a paradoxical mindset), this paper constitutes a first move in that direction. For this new research agenda to be furthered, a key insight gained from this study is that paradoxical dynamics underlying the CE–IoT nexus are prevalent and that they must be recognized and addressed as such. Henceforth, uncertainty could become a source of actionable knowledge from which unforeseeable responses to the environmental crisis might arise. For this new potential to be tapped at scale, however, uncertainty would have to be more broadly construed and taught as knowledge in and of itself within sustainability research (e.g., [25,26,31,144,145]): i.e., avoiding rebound dynamics should not mainly be construed and taught as a matter of quantitative methodological development or, by extension, of modeling and technological sophistication. Instead, rebounds should be recognized as paradoxes, i.e., as the ever-receding frontier of knowledge that they constitute, despite the IoT and the new epistemic potential unlocked by Big Data analytics. Such a paradoxical (or auto-reflexive) relationship between research and its own object of inquiry has long been acknowledged in many disciplines in the social sciences (e.g., [42,44,146,147]), but it is still largely omitted in engineering and the natural sciences, where consequences are nonetheless significant.

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