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Transient Internet of Things: Redesigning the Lifetime of Electronics for a More Sustainable Networked Environment

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ABSTRACT

Mark Weiser predicted in 1991 that computing would lead to individuals interacting with countless computing devices, seamlessly integrating them into their daily lives until they disappear into the background [42]. However, achieving this seamless integration while addressing the associated environmental concerns is challenging. Trillions of smart devices with varied capabilities and form-factor are needed to build a networked environment of this magnitude. Yet, conventional computing paradigms require plastic housings, PCB boards, and rare-earth minerals, coupled with hazardous waste, and challenging reclamation and recycling, leading to significant e-waste. The current linear lifecycle design of electronic devices does not allow circulation among different life stages, neglecting features like recyclability and repairability during the design process. In this position paper, we present the concept of computational materials designed for transiency as a substitute for current devices. We envision that not all devices must be designed with performance, robustness, or even longevity as the sole goal. We detail computer systems challenges to the circular economy of computational materials and provide strategies and sketches of tools to assess a device's entire lifetime environmental impact.

CCS CONCEPTS

• **Social and professional topics** → **Sustainability**; • **Human-centered computing** → **Ubiquitous and mobile computing**; • **Hardware** → *Analysis and design of emerging devices and systems.*

KEYWORDS

Transient electronics, Sustainable ubiquitous computing

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1 INTRODUCTION

Mark Weiser envisioned the computer for the 21st century as a truly integral and seamless part of people's lives [42], where the most profound computing technologies are those that can "weave themselves into the fabric of everyday life until they are indistinguishable from it." We have made significant progress towards this vision, with the proliferation of computational devices that serve users within the same space or remotely through the internet. However, the current landscape of connected devices (an average of 22 per U.S household in 2022) and global e-waste (53.6 million metric tons (Mt) by 2020) paints a bleak picture. Our networked environment is still enabled by a limited number of IoT (Internet of Things) devices, yet we have already created far more environmental hazards than we can handle. As we continue to explore emerging fields like AI (Artificial Intelligence) and aim for fully immersive interaction experiences for users, the number of devices and the resulting waste will only increase. For example, IoT devices could increase to upwards of a trillion by 2035. This raises two pressing questions that our society must address: **1) Should we continue to add more devices to our world, given the environmental impact? 2) Where will these devices go when they inevitably break or become outdated?**

Nowadays, the dominating design goal for computational devices is to pack the most functionality and performance into the smallest form factor with robustness and longevity in mind. A typical configuration for a PCB board contains multiple layers of FR4, which is a glass-reinforced epoxy laminate material making up the bulk of the bare PCB. The properties of FR4, including a good strength-to-weight ratio, near zero water absorption, and flame resistance ensure the devices remains robust while operational, but there is little to no consideration of recycling when designing these devices. The physical form always outlasts the functional utility. Resources have been put into recycling e-waste, but the complex composition of electronic devices makes the recycling process significantly more complicated than other materials, such as cardboard. Most electronics are designed with a quite linear lifecycle, starting with non-renewable resources and ending as waste in landfills. At the same time, people still engage in unsustainable behaviors such as purchasing new products when old ones break or are end-of-lifed.

In short, the *march towards ubiquitous computing as first envisioned by Weiser should be considered harmful.* This linear model is

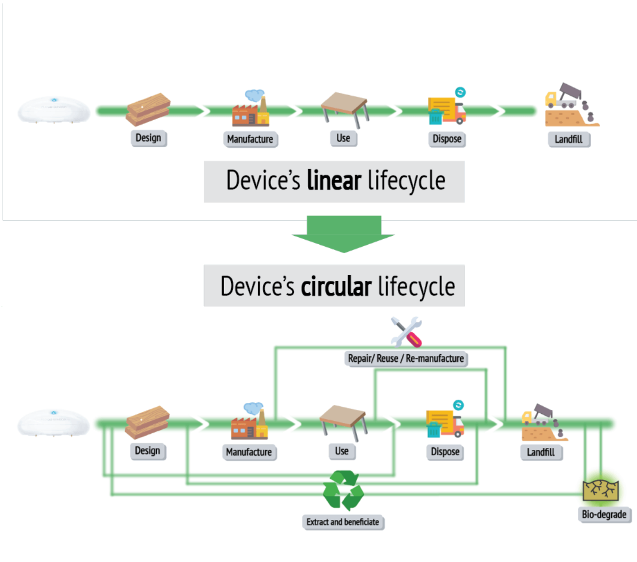

Figure 1: Device's linear lifecycle and a more circular lifecycle

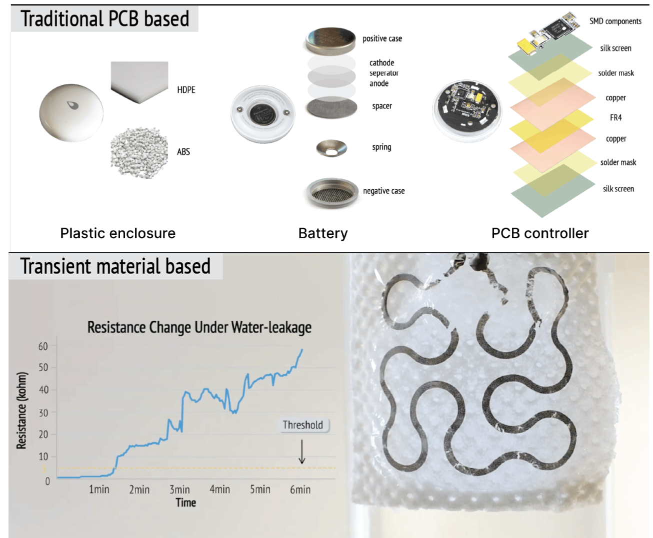

Figure 2: Comparsion of today's PCB based home water leakage sensor and our proposed transient materials based water leakage sensor.

not sustainable, and as resources become scarce and waste accumulates, we must shift towards a more circular model (Figure 1).

> **We push for *RE*-actions in computing devices.** Devices will circulate among different lifetime stages like *re*-use, *re*-manufacture, *re*-cycle, and even *re*-turn to the earth via biodegradability. Within this model, we consider a design that envisions the entire lifetime environmental impact.

As shown on the top row in Figure 2, most of today's water leakage sensors are constructed with plastic housing (*e.g.* ABS, HDPE), operated by conventional PCBs containing FR4, SMDs and powered by batteries containing lithium, lead, where each part can potentially harm our living environment if not properly processed or disposed, including plastic waste, E-waste, lithium battery pollution. One of the practical issues we face is that the epoxy in FR4 is a typical thermoset polymer material, very robust but hard to get recycled. While vitrimer or thermoplastic materials can be potential substitutions for epoxy which can be much easier recycled. At the bottom of Figure 2, we also show how PVA (polyvinyl alcohol), gelatin or cellulose based material options with printed conductive electrode that can be used to construct a greener version of water leakage sensor [14]. The device is not built for longevity but computationally designed with different levels of water-solubility (*e.g.,* by alternating thickness, porosity, hydrolyzed level) within the same sheet that can respond to different levels of water existence (*e.g.,* moisture, flood). We imagine that one day **device can begin as a water-leakage sensor for your home, detecting water presence and self-powering through water's potential energy. It later naturally degrades and transforms into a soil moisture sensor for your garden, ultimately breaking down into compost without any environmental impact.**

Unlike conventional electronics made with robustness as the main goal, transient electronics are designed with destruction in mind. This particular disposal of the hardware is integral and intrinsic to its design. These electronics span over components, devices, or systems made with transient materials that can physically dissolve over time, coinciding with their failure of the operation. Transient electronics usually require electronic materials to decompose and dissolve into the surrounding environment without leaving behind traceable or harmful chemicals. Materials such as PVA/poly(vinyl alcohol), carbon powder, or beeswax can enable sustainable transiency by constructing functional devices that can self-disintegrate under natural stimuli in a sustainable manner.

Replacing conventional circuit materials with more sustainable options will be critical for making electronics sustainable. While one missing part for an electronic system is the battery. The battery used in most of today's wearable and IoT devices is a significant contributor to unsustainable computing, which usually consist of carbon, relatively inert metals (*e.g.,* aluminum and stainless steel), nonde-gradable polymer (*e.g.,* polypropylene), oxides, and hazardous electrolyte, which are either not degradable or could be harmful to human health. While, similar to using sustainable materials to construct electronics, one solution to alleviate batteries' negative environmental impact is to utilise degradable materials to make batteries like utilizing degradable metallic electrodes, *e.g.,* magnesium (Mg) or zinc (Zn) galvanic cells, or nonmetallic ones like activated carbon and sugar-based enzymatic fuel cells [25]. The other strategy is to develop battery-free embedded devices powered by ambient energy (*e.g.,* light, wind, body temperature), together with the intermittent computing techniques which are used to enable devices to operate for long periods without batteries or other traditional energy sources, and to enable them to adapt to the dynamic and unpredictable energy availability of their environments. These control decisions must be made with limited

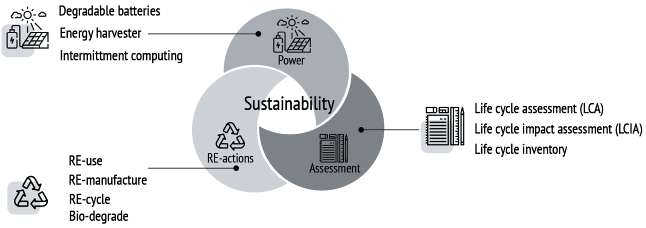

Figure 3: Overview of the transient IoT design components.

computing resources, and in a timely fashion, posing new computer systems challenges.

The last piece for our "sustainable computing" puzzle is the associated assessments for the electronic device. Can one determine if a configuration is more or less sustainable over a life-cycle? If one device is more easily recyclable or completely biodegradable, it is considered more sustainable or benign to our environment, but producing materials with such properties might higher more energy consumption than devices made with traditional materials. So, it is very crucial to perform a cradle-to-grave (Life Cycle Assessment) LCA to compare the environmental impacts over a device's entire life cycle [40].

Efforts directed towards transient electronics, green batteries, and life cycle assessment (LCA) all contribute to the overarching goal of achieving a more sustainable future. However, it is crucial to recognize that sustainability must be approached holistically, as depicted in Figure 3. Narrowing our focus to a single aspect can limit its overall effectiveness. For instance, solely prioritizing reducing the carbon emissions of fabrication of transient devices without considering the loss of utility, that more traditional computer systems might enable. Our position aims to rethink the entire computing stack with the following four key aspects:

RE-action: Foster the development of computing devices with circular and transient lifecycles, emphasizing enhanced reusability, remanufacturability, recycling, and other sustainable practices.

Power: Advance the pursuit of environmentally friendly power options for electronics, such as the creation of fully biodegradable batteries or the harnessing of energy from ambient resources.

Lifecycle Assessment: Establish comprehensive life cycle tools that model life cycle inventories, conduct impact assessments, and perform sensitivity analyses to accurately evaluate the environmental impact of electronic systems.

Reimagine Computer Systems: Finally, develop an understanding of the control, decision making, and resilience strategies that are required to provide *useful function* alongside reuse.

2 RELATED WORK

2.1 Transient Electronics

Transient electronics is an emerging area and has drawn increasing research attention, especially from the materials science community. Material innovation is a key requirement for transient electronics. Transient materials must maintain physical stability and functionality in "passive" environments (*i.e.,* those without the triggering stimuli), but respond actively when get triggered. Stimuli, like heat or moisture, should initiated its physical destruction in a controllable or otherwise intended manner. Transient electronics usually are integration of electrode materials, typically metals (*e.g.,* magnesium/Mg, zinc/Zn, tungsten/W, and molybdenum/Mo) [43, 44], encapsulation/substrate materials or dielectric materials, usually polymers (*e.g.,* poly(vinyl alcohol)/PVA, polyvinylpyrrolidone/PVP, polylacticcoglycolic acid/PLGA, polylactic acid/PLA, and polycaprolactone/PCL) [26, 28], and semiconductor materials (*e.g.,* monocrystalline silicon/Si nanomembranes/NMs) [29]. In 2012, Hwang, et al. introduced a set of materials, devices and manufacturing methods for making silicon-based complementary metal oxide semiconductors (CMOS) with transient behavior [27]. This paper introduced Mg, MgO, silk film as the electrode, dielectric and substrate materials respectively and discussed how these materials can be further developed to make capacitors, diodes, transistors, resistors and other components. The paper investigated the performance and transient behavior of the device and demonstrated it for biomedical applications.

2.2 Intermittent Computing

Miniaturized computational devices need to be deployed in massive quantities to enable interactivity in the built environment across different scales, which inevitably requires numerous batteries and causes unsustainable power consumption [23, 36]. Batteries are bad for the environment, however, just connecting an energy-harvesting source to a microcontroller does not usually work [19]. Energy from harvested sources is not constant and maybe not enough to continuously run the device, so we have to buffer some energy (typically in a capacitor). When a certain amount of energy is collected, the system activates to perform computing and sensing tasks [4]. This problem of *intermittent computing* is well-studied in computer systems literature. These batteryless energy-harvesting devices have emerged as a viable alternative to their battery-powered counterparts, which are generally expensive, hazardous, require maintenance, and are prone to failure, significantly shortening lifetime and narrowing application domain [22]. The work within intermittent computing, however, must be extended with the conception of *transient* devices. Battery-free platforms are still made with PCBs and CMOS, and tools do not yet investigate lifecycle or environmental impacts [5, 18].

2.3 Sustainable Practices

Over the years, there has been an enduring call for the establishment of sustainable guidelines and practices within various industries. Notably, there is a growing emphasis on adopting more environmentally-conscious approaches to fabrication and design, as evidenced by extensive research [7, 8, 20, 30, 37]. For instance, Lazaro Vasquez et al. proposed the utilization of Life Cycle Analysis as a guiding framework to assess the sustainability of design practices. This approach encourages researchers to consider employing materials with minimal "embodied energy" and carbon dioxide emissions [30]. Nevertheless, translating these guidelines into practical implementation poses significant challenges. Despite the availability of material selection criteria, fabrication methods, and proper disposal methods, recent reviews have indicated that one-third of prototyping or digital fabrication research still relies on plastics [41]. Even when researchers aspire to choose eco-friendly materials like PLA, the complexity of sourcing from responsible manufacturers and locating appropriate disposal facilities such as industrial composting or recycling centers often discourages their use. Consequently, it comes as no surprise that when researchers contemplate material choices for prototyping interactive systems, considerations of price and performance tend to take precedence over sustainability.

3 RE-ACTION

Our primary objective is to enhance the lifecycle of computational materials, focusing on both transiency and circularity. While these two concepts differ, traditional devices have typically followed a linear lifecycle, prioritizing performance, longevity, and robustness. We provide a review of the space as well as future potentials for mitigating environmental harm.

3.1 Repair

Electronic devices are susceptible to damage such as scratches during shipment, or circuit shorts, which are often overlooked. The process of PCB board manufacturing can involve lamination, where multiple materials are layered to create a unified board, later covered with a solder mask or silk screen, and making the damaged circuit challenging to get repaired.

To address this issue, we propose exploring novel materials for PCB manufacturing that offer self-healing or repairable properties when damaged, or even can be easily modified to accommodate circuit changes, which will ultimately save materials or create less waste. Our previous work developed a transfer-based technique enabling users to quickly fix damaged sections by re-transferring a new trace onto the affected area, effectively restoring conductivity. This retransferability can also extend to circuit modifiability, where unwanted parts of silver traces can be erased using a commercially-available circuit eraser (usually loaded with ethyl glycol), and replaced with desired traces [13]. By leveraging such advancements in material technology, we can make the circuits easier to repair by reducing the waste during stages like prototyping, while remaining challenges can include how to balance the durability and flexibility of PCBs, mitigating damage risks during shipment, and enabling easier circuit modifications when needed.

3.2 Recycle

Modern electronics are composed of a wide range of materials, including metals, plastics, glass, and various hazardous substances, which meanwhile is highly miniaturized and integrated. This intricate mix of components and materials makes the disassembling and recycling process complicated and expensive. For example, when connecting components to the PCB board, Tin-Lead (Sn-Pb) or Lead-free solders are chosen to provide robust connection with good thermal and electrical conductivity, but make the separation from components from the board challenging.

Today, PCB boards are commonly constructed using epoxy and fiberglass lamination, which are typical thermosetting materials known for their durability but pose challenges in terms of recycling. One potential solution involves exploring alternative materials such as thermoplastics or vitrimers as substitutes [11]. Vitrimer behaves like traditional thermosets at room temperature but can reconfigure its network through bond exchange reactions at higher temperatures, allowing for easy recycling. While thermoplastics may not achieve the exact mechanical and electronic characteristics of current PCBs, they can serve as recyclable alternatives for low power/voltage and low-frequency applications, which involve large quantities, short lifespans, and simplistic single-layer circuits [40].

Manufacturers use various types of adhesives to secure components to the circuit boards or apply solders to component leads or pads, which ensure components remain securely attached during the device's lifespan but much more difficult to disassemble the device. To address this issue, we propose the use of adhesion-tunable materials as alternatives. For instance, researchers have shown that adhesion tuning behavior is enabled by 1) electro- and magnetorheological materials; 2) shape memory polymers; 3) low melting point materials, including waxes or polymers [17]. However, The objective of adhesion-tunable soldering materials is to strike a balance between strong adhesion for secure component retention and weak adhesion for easy removal. Additionally, these materials need to meet the general requirements for solder, including high conductivity and resistance to mechanical stress. This class of materials/adhesives provides an interesting computer systems and signal processing problem: how to dynamically tune the adhesion at design time and operation time. This combines material knowledge, as well as computer systems approaches, to build more recyclable electronics.

3.3 Re-manufacture

Re-manufacturing and recycling are two related concepts, but they differ in their focus and approach. While recycling encompasses various stages of the general product development process, re-manufacturing specifically targets the post-consumer stage, where waste electrical and electronic equipment (WEEE) is sent back to manufacturers for refurbishment. To facilitate re-manufacturing, several strategies have been beneficial. One approach is modular design, which involves creating electronic products with easily disassembled and replaceable modular components. Another strategy is the establishment of efficient reverse logistics and collection systems to streamline the collection and transportation of discarded electronic products. Standardization and certification also play a vital role in ensuring the quality, consistency, and compatibility of remanufactured products. Additionally, raising consumer awareness about the benefits of remanufactured products and providing incentives for their purchase can foster increased acceptance and demand for remanufactured electronics [46]. Re-manufacturing requires firmware updates and software engineering approaches to facilitate easier repurposing of microprocessors, in new applications. Tools for evaluating and redesigning programs that are aware of the level of degradation of the device would be highly useful to ensure high utility in a second life of a device.

3.4 Biodegradable Devices

Biodegradability plays a crucial role in the RE-action initiative, aiming to develop electronics that can fully decompose without causing

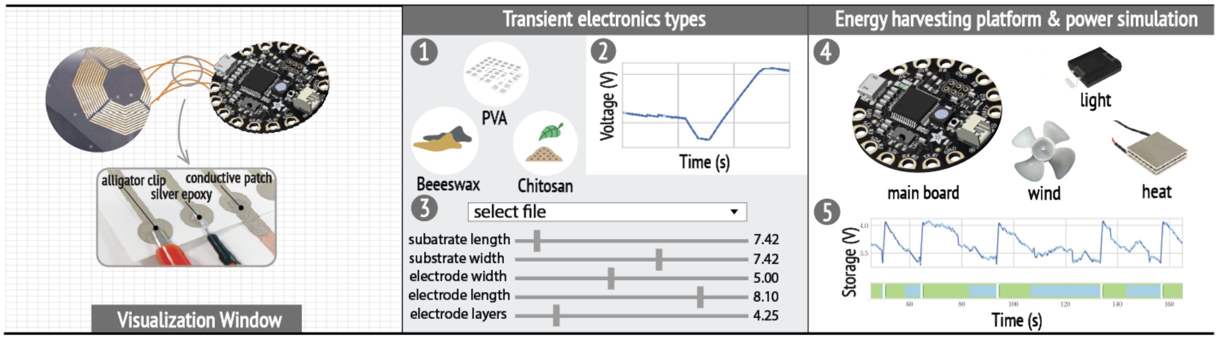

Figure 4: Lifecycle aware design editor sketch: (left) a visualization window for users to drag-and-drop different components to explore interaction design and make connections by selecting a custom method; (middle) options for different transient electronics types, their power requirements, and parameter adjustments; (right) different options for energy harvesting methods and simulated power results.

harm to the environment. Biodegradable systems often intersect with transient electronics, which are intentionally designed for destruction and disposal as an integral part of their functionality. The choice of materials for biodegradable electronics is diverse, ranging from biodegradable metals like magnesium (Mg) and zinc (Zn) [43, 44], to substrate materials such as polycaprolactone (PCL), wood, and natural wax [26, 28]. There are even options for materials that are entirely edible-friendly, like carotene derived from carrots [32] or melanins sourced from cuttlefish inks [21]. Despite the environmental benefits offered by biodegradable materials, some questions remain unanswered. For instance, how can we ensure that biodegradable computers maintain comparable functionality to conventional ones and meet the requirements of specific applications? Moreover, challenges lie in designing a controlled self-destruction process for these devices, ensuring they decompose at the intended time.

4 POWER: HARVESTING AND STORAGE

Power drives most design choices for any electronic system [33]. Approaches can range from radio frequency (RF) power electronics [12], different types of energy harvesting strategies (*e.g.,* piezoelectric, thermoelectric, photovoltaics, wind [38, 39, 45]) and battery-based systems. However, traditional batteries contain carbon, relatively inert metals (such as aluminum and stainless steel), non-biodegradable polymers (like polypropylene), oxides, and electrolytes that can pose hazards to human health and the environment due to their persistent nature. To address these concerns, our primary focus is to explore more organic or biodegradable "green" battery options. Instead of relying on non-degradable metals, batteries can incorporate material combinations like Mg−Mo or Zn−Cu systems, allowing for fully or partially biodegradable battery designs. It is important to acknowledge that there may be practical challenges associated with these approaches, such as relatively low energy density or location limitations. Nonetheless, our ultimate goal is to develop a completely biodegradable battery system that can serve as an on-board power solution, ensuring independent deployment and achieving high energy density.

Another promising avenue for reducing reliance on batteries is through the utilization of energy harvested from ambient resources, including body temperature (thermoelectric energy harvesters [31]), sunlight (photovoltaics [45]), and user interaction inputs (such as speak-induced vibrations [3]). However, a key challenge arises when attempting to directly connect an energy harvester to a microcontroller. The energy harvested from these sources is often intermittent and insufficient to continuously power the device. To overcome this limitation, energy buffering becomes necessary, typically achieved through the use of a capacitor. Once a certain threshold of energy is accumulated, the system activates for a limited duration. The issue of intermittent energy supply has been extensively studied in the context of reliable computer systems [24]. These batteryless energy-harvesting devices have emerged as a promising alternative to their battery-powered counterparts. Battery-powered systems are often costly, pose hazards to the environment, require maintenance, and are prone to failure, leading to shortened lifetimes and limited applications. In contrast, energy-harvesting devices offer advantages such as increased sustainability, reduced environmental impact, and enhanced reliability, expanding their potential range of applications.

5 TOOLS FOR LIFE CYCLE ASSESSMENT

We have put forth various design considerations to steer computational devices toward a more sustainable future, aiming to imbue them with a circular life cycle. However, a crucial aspect that remains unresolved is how to substantiate that a particular approach is genuinely more environmentally friendly when compared to its conventional counterpart, both in quantitative and qualitative terms. We posit that tools are needed to help programmers and system designers bridge the gap (see Figure 4 for a sketch).

In the context of sustainable development, life cycle assessment (LCA) is a vital methodology and tool for ensuring sustainability by evaluating the environmental impacts of a product, process, or service throughout its entire life cycle, spanning from raw material extraction to end-of-life disposal. LCA's primary objective is to provide a comprehensive understanding of the environmental burdens associated with a specific system and identify opportunities for improvement, enabling informed decision-making towards more sustainable practices. Typically, an LCA consists of four key steps: (1) goal and scope definition, (2) inventory analysis involving the quantification of material inputs, energy inputs, and environmental discharges across different life cycle phases, (3) impact assessment, which aggregates these flows into various impact categories, and (4) interpretation of the results. By following this systematic approach, LCA enables a holistic assessment of environmental impacts and facilitates the identification of sustainable pathways [10, 35].

One challenge with LCA in the context of computing is the availability and quality of inventory data, especially for emerging and ever-changing technologies like computing. Obtaining reliable data can be difficult, such as obtaining accurate information for lab-synthesized silk fibroin substrates compared to standard FR4 PCB boards (materials) or comparing different neural network workloads on alternate hardware. LCA's practical application is often limited to those with expertise, hindering widespread adoption [35]. Furthermore, it does not take any consideration of computer system components or applications— such as the number of samples one might take, or the depth of a neural net for recognition on board. To address this, we propose a more accessible solution—a programmer-friendly browser or IDE add-on that prioritizes data accuracy, accessibility, compatibility, and application specification. For instance, KiCad, a popular platform for electronic design, lacks sustainability features. An LCA tool that seamlessly integrates with KiCad and other similar software could provide users with environmental impact insights for specific circuit designs.

6 WHAT ABOUT DATA (CENTERS)?

This paper has described and explored the tiniest class of computers– generally wearable, interactive, ubiquitous, invisible– on the far "edge." However, the interactions and connections with "big iron"— the data centers and large-scale computing infrastructure, will dramatically affect the total sustainability of the trillion computers of the future. This paper discussed three crucial components that significantly reduce the embodied carbon of modern computational devices. Reimagining these tiny devices' lifecycle is the first step. However, we must also reimagine the broader infrastructure around these devices, as well as the decentralized computer operating systems that these devices will run and interact with before we see a positive impact on computing and society as a whole.

Data centers host innumerable applications, including cutting-edge large language models (LLMs), e-commerce websites, video streaming, sensor data fusion and search engines [6]. Regrettably, these data centers contribute to nearly 1% of global carbon emissions [9] and growing. *A key question is whether the enormous increase of data from a trillion computational devices, will significantly change the calculus of carbon emissions in the operation of a data center.* We expand on open challenges and future works inspired by this question below:

End-of-Life Strategies: Can individual devices within the data center embody the RE-action approach described? Management and disposal strategies are complex for high-performance devices, especially considering the logistical challenges associated with disassembling and recycling. While most devices may not be (for example) biodegradable, potentially they could be repurposed in semi-degradable substrates, and used in new edge applications. In this way, the data center literally moves to the edge over time.

Edge/Cloud Systems Co-Design: Lifecycle based tools explored here could be extended to understand and integrate data movement and data center operation, aware of geographic constraints and cost models. Much like recent calls to make data-center software carbon-aware [2], we explore whether this carbon-awareness can extend to the edge devices and vice-versa. Expanding the design tools of computational materials to include the endpoints (the data center) could assist the programmer/designer in ensuring actual sustainability. For example, RE-action tools that explore placement of applications and compute based on age of infrastructure.

Data Movement and Compute Placement: Finally, a question remains on where computing should happen if, in fact, a trillion new computing devices do enter the world. With a trillion data streams, what level of capacity must be built at the data center, to absorb and effectively coordinate these devices? What actions and tasks should be the locus of the computational material to compute versus transmitting to the data center? Many data centers today are increasingly turning to renewable energy sources like photovoltaic systems to power their operations. This complicates dispatch and workload scheduling [15, 16, 34], but offers interesting flexibility knobs to optimize in terms of computer systems (i.e., scheduling latency insensitive applications for when it is sunny) [1]. A key question is: can LCA design tools for computational materials, be "green" data-center aware in how they (as a group) offload and use this centralized resource to achieve high application utility. Would a situation exist, where it would be optimal for every small device on the edge to stream data to the data center for "free" at-scale processing powered by excess renewable energy? This is in conflict with current notions of processing *on-device* to save round trip costs. However, the benefits of a centralized computational powerhouse may be underexplored in this context.

7 CALL TO ACTION

In this paper, we call for the co-development and design of transient Internet of Things (IoT) devices alongside the larger-scale data center, computer systems, and lifecycle problems present in a circular computing electronic device ecosystem. This call is in response to the increasing health and environmental risks posed by electronic waste, as well as the necessity of computing in everyday life. Our paper provides a review of materials and processes that underlie IoT devices, and a roadmap of challenges and potentials for researchers to lead the way in creating environmentally-friendly computational materials that deviate from their traditional, performance-focused, robust, and lithium battery-powered counterparts. By adopting this approach, we can reduce the environmental burden of IoT devices and work towards a more sustainable future.

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