Beyond the Surface: The Necessity for Detailed Metrics in Corporate Sustainability Reports

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***Abstract*—The smartphone industry is advancing rapidly, emphasizing the development of smaller, energy-efficient devices with enhanced features. However, this progress often overlooks the significant environmental impacts of these ubiquitous devices. While corporate sustainability reports from mobile product companies aim to address these concerns, they typically provide high-level overviews that obscure critical details, particularly regarding the carbon footprints (CFP) of individual components such as processors and memories. This paper investigates the discrepancy between the overall CFP trends reported and the actual increasing CFP contributions of processors over the years. Through a detailed analysis, the inadequacies in current reporting practices are highlighted, underscoring the necessity for more granular data and metrics in corporate sustainability reports. Specific, detailed metrics are proposed for inclusion in these reports to enhance transparency and help align the chip architecture, design, and manufacturing communities toward addressing relevant sustainability-related challenges.**

***Index Terms*—sustainable computing, metrics, carbon footprint**

I. Introduction

The carbon footprint (CFP) of the information, computing, and technology (ICT) industry contributes to 2-3% of the world's total carbon footprint [1]. There is an urgent need for significant reductions in greenhouse gas emissions across all sectors, including ICT. As semiconductor companies strive to meet their net-zero commitments by 2030, they release corporate sustainability reports each year that show metrics from a lifecycle analysis (LCA) of their products [2], [3]. These reports offer insights into the company's environmental, social, and governance trends. These reports lay the path for sustainability development goals (SDGs) that the company works to achieve. The reports showcase the company's work towards its SDGs in reducing carbon emissions, using renewable energy, social responsibilities, and sustainable practices.

While the reports show that the efforts to lower their carbon are on the right trajectory, achieving those net-zero commitments will require a community effort to identify, realize, and optimize the CFP from various sources, stages of the lifecycle, and components of these products. However, the released reports are extremely high-level, focused more on marketing, and do not provide detailed insights that are essential for researchers, environmentalists, and computer architects.

With the widespread adoption of cellphones, our focus in this paper is the LCA of the cellphone, particularly its processor and memory. The corporate sustainability reports of Apple [2], [4] for their iPhone offer a broad overview of the product's LCA, covering the carbon footprint (CFP) during

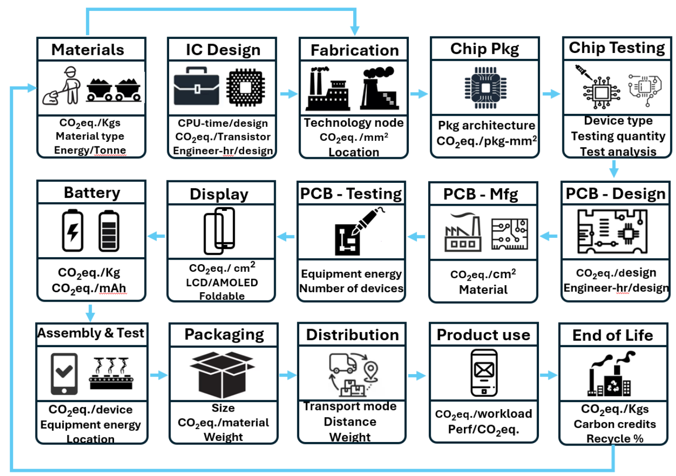

Fig. 1. Lifecycle analysis (LCA) of a cellphone.

production, transportation, and use. However, they lack the granularity required to drive research directions and identify bottlenecks in LCA. These reports break down the lifecycle into only four stages: production, transport, use, and end-of-life, and provide the overall CFP of the whole product for these stages. The reports include net carbon emissions, factoring in carbon credits from activities like tree planting, making it unclear what the CFP of the product truly is.

In contrast, the complete lifecycle of a typical cellphone is shown in Fig. 1. It includes several stages: material extraction, design of each chip (processor, memory, RF transceiver, modems, etc.), fabrication of each chip, packaging of each chip, testing of each chip, PCB design and assembly, product testing, packaging, distribution, use, and end-of-life [5]. There is a need for a holistic ground-up approach that can measure all aspects of a semiconductor product lifecycle, from cradle to grave, and across all the components and integrated circuits (ICs) within the phone to identify key challenges and trends over the years. The ground-up approach must report the carbon at the source and the purchased credits separately [6].

Computer architects have focused on modeling the CFP of the processor [7]–[9], FPGAs [10], and memory [11], [12]. However, validating these models has presented challenges, including determining the values of input parameters to these tools, and the models encompass significant uncertainty and best-guess estimates [13]. There have been several discussions on which lifecycle stage (manufacturing vs. use) dominates in its carbon contribution [14], [15]. To help address these questions, industry sustainability reports must provide detailed metrics and benchmarks to guide and validate research. If these metrics are not provided, people may use incorrect metrics and ballpark estimates, such as using cost as an indicator of CFP, which has been proven incorrect [16].

In this paper, we propose different metrics that would be beneficial to include in corporate sustainability reports for transparency at various stages of the lifecycle. We propose high-level metrics for the cellphone across its entire lifecycle and detailed metrics for the two key ICs within the cellphone, i.e., processor and memory. Our focus is primarily on mobile phones, as sustainability reports from major vendors on a per-product basis are available. This contrasts with other semiconductor companies such as Intel, TSMC, NVIDIA, etc., where the corporate sustainability report encompasses the whole company, making it even more challenging to estimate the CFP per product, let alone a processor. While we focus on mobile processors, many of our key analyses and proposed metrics also apply to CPUs, GPUs, and other ICs.
Our paper has the following key contributions:

1) We highlight metrics within the LCA of a cellphone that would be useful to include in corporate sustainability reports for the entire lifecycle.
2) We provide detailed sustainability metrics for processor and memory design.
3) We provide a detailed analysis of how current corporate sustainability reports mask critical IC design and manufacturing sustainability trends.
4) We compare the CFP of competing smartphones (released in the same year) from different major vendors, highlighting that these metrics must be provided to consumers as they make purchasing decisions.

All data and analysis in this paper is available on GitHub [17].

II. Cellphone LCA and Sustainability Metrics

A. Lifecycle analysis and corporate sustainability reports

Several works in the past have performed LCA of a cellphone [5], [18]–[20]. Fig. 1, shows the different stages in the lifecycle of a phone. Although prior work lists the stages in the phone's lifecycle, they do not comment on the crucial sustainability-related metrics at each stage to establish a standard ground-up approach to sustainability-oriented LCA.

In this work, we propose relevant sustainability-related metrics across the lifecycle and call out the necessity of including such detailed metrics in corporate sustainability reports. In the later sections of the paper, we highlight the importance of various processor and memory-related metrics from a computer architecture community perspective and do a detailed analysis of how corporate sustainability reports mask key information that is useful to the community.

The corporate sustainability reports for cellphones split the product lifecycle into four stages: (i) production, (ii) transportation, (iii) use, and (iv) recycling [2], [4]. In Fig. 1, the first 12 stages correspond to production, and the last three stages correspond to the distribution, use, and recycling of the phone. According to the corporate sustainability report, the production phase contributes to 87% of the total CFP of the phone. Therefore, we focus on a detailed breakdown of the production stage into multiple stages as shown in Fig. 1. Such a fine granularity is useful for research in different areas and addressing sustainability challenges from different disciplines, which is critical to lowering the overall CFP of ICT.

B. Sustainability metrics across the lifecycle

We urge for more transparency in sustainability reports for research direction and propose various metrics that are critical at each stage to be included as a part of LCA in reports[1][2]:
Materials sourcing: CO_2 eq. per kg for mining and sourcing the different materials used in the phone and the carbon credits for materials that can be recycled.
IC design: CO_2eq. per unit area of the chip to guide chip area estimates, CPU-time engineering-hours, and design iterations to help estimate the energy spent on IC design.
Fabrication: CO_2eq. per mm^2, location of the fab, technology node, energy source for the fab, energy per equipment, energy used per lithography step, and yields.
Chip packaging: CO_2eq. per pkg-mm^2, packaging type, 2D/3D packaging architectures, etc.
Chip testing: Quantity of testing, type of test analysis run, device type that is tested, energy usage of testing equipment.
PCB design, manufacturing and test: CO_2eq. per cm^2, material extraction, engineering design hours for PCB design, equipment energy, and the number of devices.
Battery: Material extraction CFP, CFP per Kg of the battery, CFP per unit capacity of the battery, etc.
Product assembly and test: Device quantity, energy of equipment, source of energy, location of the assembly units.
Product packaging: The size of the device, weight, packaging material, and CO_2eq. per unit area of pkg material.
Distribution: Transport mode, weight, transport distance, etc.
Use: Power, energy-efficiency, Perf-SI (Sec III-B), energy per workload, operational CO_2eq. per workload.
Recycle: Credits for recycling the devices, % of recyclable materials, CO_2eq. credits per kg of device that is discarded.

Including these metrics in sustainability reports can significantly improve transparency and allow stakeholders to better understand the environmental impact of each stage in the product lifecycle. We emphasize the importance of standardizing reports with data at multiple levels of granularity throughout the lifecycle. The participation of companies in standard bodies and consortiums[3], can help in standardization. This approach can identify areas for improvement and innovation in reducing CFP at the computer architectural level and help validate models developed in [7], [8].

III. CFP of Mobile Processors and Metrics

The processor, as a key IC within the cellphone, is a significant contributor to its CFP. Indeed, the processor alone accounts for more than 10% of a cellphone's total CFP (as we will

[1]This is not an exhaustive list.
[2]We understand that some of these metrics (yield, etc.) may be proprietary, and corporate sustainability reports will not release such information; however, even a subset of these metrics is useful for sustainability research.
[3]Semiconductor Climate Consortium, Sustainability Accounting Standards Board (SASB), Carbon Disclosure Project (CDP), GHG Protocol.

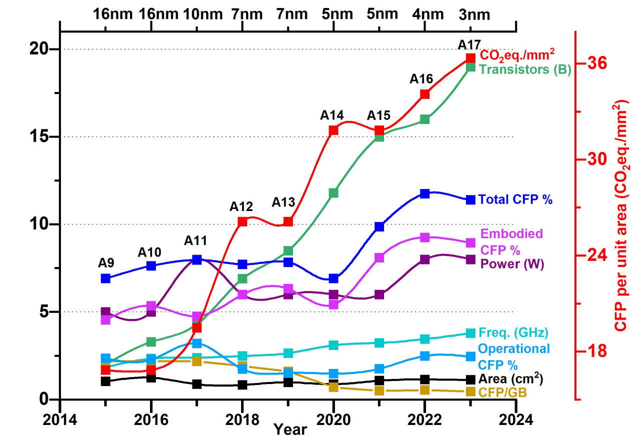

Fig. 2. Evolution of iPhone processor CFP as a percentage of total iPhone CFP, juxtaposed against traditional processor specs.

show). Notably, this figure pertains only to the system-on-chip (SoC) and does not include the CFP of other ICs in the phone. As highlighted in prior works [7], [8], [10], the processors' embodied carbon is attributed to the carbon contributed by the processor's manufacturing, design, and packaging, and operational carbon is attributed to the operational power and energy consumption during end use. [8] claims that edge devices have higher embodied carbon than operational. Therefore, there is a need to lower both embodied and operational CFPs to reduce the environmental impact of the processor. The goal of our work is to quantify the contribution of the processor to the phone's overall CFP, highlight the trends in the mobile processor's CFP over the years, and propose metrics that corporate sustainability reports must include to drive research.

We model the CFP of the processor using prior carbon modeling tools [7], [8]. These works obtain their manufacturing CFP values from [21]. In the rest of this section, all our data is shown on iPhone processors, Google Pixel 4 processors, and Samsung S8 processors. The die area for processors are obtained from [22], [23], [24]. The operating frequency, technology nodes, and other parameters for each mobile processor were obtained from [25]. Our assumption for the lifetime was the same as that mentioned in [26], [27]. The rest of the parameters are the same as [8], [7].

A. Mobile processor CFP over the years

The semiconductor industry has long tracked roadmaps and Moore's law-related trends for various processors. Inspired by these trends, predictions, and processor evolution, we propose tracking the processor's CFP over the years. We juxtapose traditional processor specifications, including power, performance, and area, against the CFP to understand how processor CFP has evolved and to project future trends.

Fig. 2 shows the variations in various metrics of the iPhone processors over the last decade. The plot shows the variation in the processor's frequency, power, area, and number of transistors. As per Moore's law trends, the number of transistors in the processors has been increasing with a very small change in area, indicating the increase in transistor densities over the years as the technology nodes advance. Further, processor frequency has almost saturated over the last several years.

While these traditional metrics have been observed and well-understood, the processor's CFP trends have not been studied. Fig. 2, shows the percentage CFP the processor (iPhone's SoC) contributed to the total CFP of the product. We obtain the total CFP of the iPhone from Apple's sustainability reports [4] and the CFP of the processor from [7], [8]. It is clear that as the technology node advances, processor architecture is moving towards more energy-efficient architectures, and the operational CFP of the processor to the total CFP (Ope CFP %) has been more or less a constant despite the increase in transistors. However, the embodied CFP of the processor and its contribution to the overall CFP (Emb CFP %) has been increasing. In the latest iPhone, it contributes over $\approx 8\%$ of the CFP of the entire phone in its 3-year lifecycle. This is significant, given that the processor is only one of several other ICs in the phone. The reason for the increase is the increase in design times and the decrease in yields in advanced technology nodes [8] that result in a larger CFP per unit area of the chip manufactured as shown in the red curve of Fig.2.

For the computer architecture community, the increasing embodied CFP is a cause of concern. It is crucial to make architectural decisions and take measures that help significantly reduce the impact of the processor on the overall CFP. For these reasons, we propose that companies include the processor's total CFP as an additional specification metric alongside frequency, area, power, memory, etc. This additional new metric will not only help companies reach their net-zero commitments but also instill a sense of sustainable responsibility in consumers when the processor's CFP is released as a part of the processor specification.

We highlight the importance of including processor operation and embodied CFP in the sustainability reports. Fig. 3, and Fig. 4 show the breakdown in embodied and operational CFP of the processors in Pixel and iPhone models, respectively. The embodied CFP has been increasing over the years due to the increase in complexity of design and process of the ICs, as shown in Fig. 3(a), and Fig. 4(a). The operational CFP has decreased for the Pixel processors, whereas for the iPhone processors, it has remained nearly constant and even increased in recent generations. We determined the embodied and operational CFP of the processors using [8].

Fig. 3(c), and Fig. 4(c) illustrate that the total processor CFP has increased with each new model over the years, highlighting the significant sustainability impact of the silicon mobile processor. The red line plot shows the sustainability report trends of the entire phone [26], [27] contrasted with total processor CFP. On one hand, the processor CFP has been increasing, but on the other hand, the overall phone's CFP (red line) has been decreasing in the recent past. For example, from the release of the iPhone 6 to that of the iPhone 11, there was a steady increase in the CFP. However, from the iPhone 12 onwards, there has been a steady decline to the latest iPhone 15 Pro models. This downward trend is primarily due to Apple's shift towards using 100% renewable energy sources for their scope 1 and scope 2 operations [28]. Additionally, customer incentives for recycling and trading in old phones

TABLE I
PROCESSOR SPECIFICATIONS, COST, AND CFP, FOR DIFFERENT COMPETING CELLPHONES.

Processor	Pixel 8	iPhone 15	Galaxy S24	Pixel 7	iPhone 14	Galaxy S23
Freq. (GHz)	3	3.78	3.3	2.85	3.46	3.2
Power (W)	6	6	6.3	5	8	6.3
Area (mm^2)	135.2	112.8	137.19	114.28	114.66	118.38
Processor CFP ($kgCO_2$eq.)	8.578	7.519	8.73	7.044	7.6388	7.599
Year released	2023	2023	2024	2022	2022	2023
Dollar Cost (July 2024)	999	999	949	899	699	849
Memory options	128GB - 1TB	128GB - 1TB	256GB - 1TB	128GB - 512GB	128GB - 1TB	256GB - 1TB
Phone CFP ($kgCO_2$eq.)	79	66		85	65	

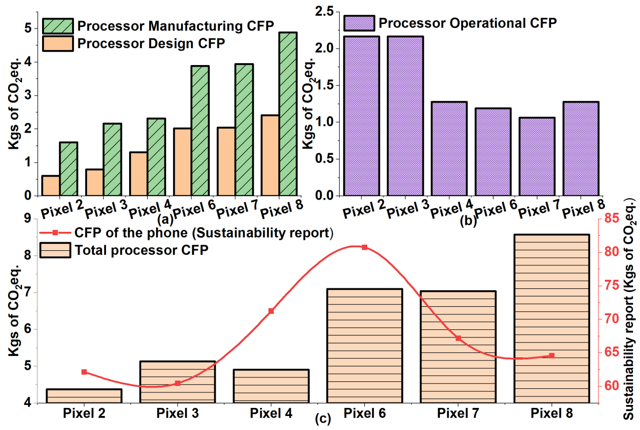

Fig. 3. Pixel processors CFP from (a) design and manufacturing, and (b) operation. (c) Total CFP of the processor and the CFP of the Pixel phone (red curve) from the Google sustainability reports [29].

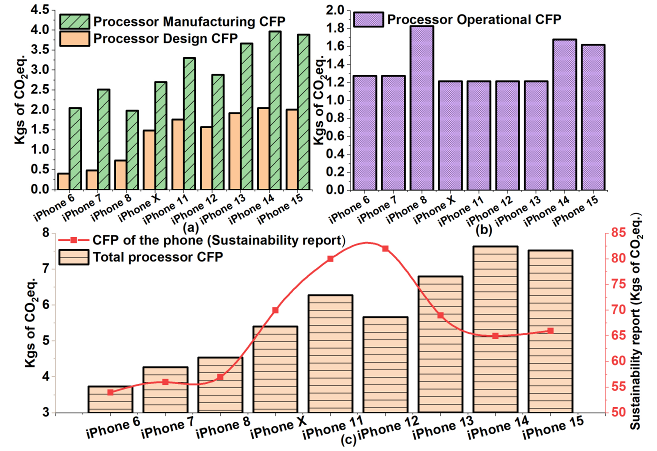

Fig. 4. Apple's iPhone processor (A series) CFP from (a) design and manufacturing, and (b) operation. (c) Total processor CFP and the CFP of the iPhone (red curve) from the Apple sustainability reports [2], [4].

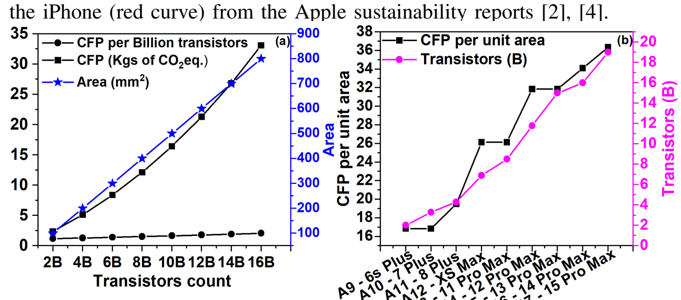

Fig. 5. (a) The exponential increase in processor CFP per billion transistors due to the increase in area and an exponential reduction in yield in a 10nm technology node. (b) Processor CFP per unit area for different processors.

have increased the recycled materials used in new device manufacturing. Therefore, sustainability reports that provide the CFP of the entire product (red line) mask intricate details.

Making consumers aware of the CFP of the phone and processor they are purchasing is important for sustainability. Table I highlights metrics typically considered when purchasing a new phone, such as cost, year released, processor frequency, power, and memory configurations. Consumers could make more informed decisions if the CFP of the processor and phone were mainstream metrics—similar to how the aviation industry presents emissions data for flights. The table lists the CFP of recently released phones and their processors.

B. Sustainability metrics for mobile processor design

This section proposes novel metrics to drive the chip design, architecture, and manufacturing communities toward more sustainable practices, in addition to the processor's total CFP.

(1) CFP per billion transistors and CFP per unit area During chip design, it's essential to consider CFP as a first-order optimization metric alongside traditional power, performance, and area metrics. Although chip designers already focus on reducing the area, lowering the area is more critical to sustainability because the CFP increases exponentially with the increasing area due to the exponential dependence of yield on the area [8]. As chip designers become aware of the sustainability consequences of their design decisions, the CFP of the processor can be reduced. Fig. 5(a) shows the CFP per billion transistors in a 10nm technology node. A larger number of transistors increases the area of the chip, which then exponentially increases the CFP. Fig. 5(b) shows the CFP per unit of different technology nodes of various mobile processors across the past decade. If mobile processor companies or chip manufacturing companies such as [3] report CFP per unit area or unit transistor, it can provide valuable insights and guide designers to make more sustainable choices.

(2) Performance per CO_2 equivalent Traditional power, performance, and area metrics often involve trade-offs. Larger chip areas can lead to better performance, but they also increase power consumption. Typically, the industry uses performance per Watt (Perf/Watt) as a metric to measure chip efficiency. Similarly, CFP and performance typically trade off against each other. These trade-offs are non-trivial. For instance, lowering operational power does not directly lower the total CFP if the embodied CFP dominates. Furthermore, reducing operational power requires significant effort, increasing the design time, further increasing the embodied CFP. Similarly, reducing the area would lower the embodied CFP, but could hurt performance and increase design time. Understanding and managing these complex trade-offs is crucial for sustainable chip design. By carefully balancing performance, power, area, and CFP, designers can make informed decisions. To incorporate sustainable practices into design, we propose a performance sustainability index, given by:

$$\text{Perf-SI} = \frac{\text{Performance}}{\text{Total } CO_2\text{eq}} \quad (1)$$

where the Total CO_2eq is the CFP of the processor (sum of the embodied and operational). Based on the application, performance units may be GFLOPS, inferences/sec, etc.

Fig. 6 shows the values of the Perf-SI of the iPhone 15 Pro processor and Galaxy S23 processor normalized to the Perf-SI of the Pixel 8 Pro processor for different workloads. A value of less than one indicates that the Pixel 8 Pro processor has a larger Perf-SI than the compared processor. A larger Perf-SI indicates a more carbon-efficient chip. We perform comparisons for these workloads for the following applications and obtained performance numbers from GeekBench [30]: text processing (TextProc), navigation (Nav), image classification (ImgC), image segmentation (ImgSeg), object detection (ObjDet), and face detection (FaceDet). Fig. 6(a) and Fig. 6(b) show the normalized Perf-SI values for multi-core and single-core TextProc and Nav testcases respectively. For both testcases, iPhone 15 Pro has better Perf-SI for both single and multi-core cases, when compared to the other two processors. Fig. 6(c) and Fig. 6(d) show the normalized Perf-SI values for different precisions (FP16 and FP32) for ImgC, FaceDet, ImgSeg, and ObjDet applications. For FP32, iPhone 15 Pro processor has a higher Perf-SI compared to the other two processors for all applications. For FP16, the iPhone 15 Pro processor is better than the other two processors for the ImgC and ObjDet applications. *This metric highlights that comparing two devices based solely on their performance is insufficient. Perf-SI considers the device's area, power, and sustainability impact, providing a more comprehensive evaluation of its overall efficiency and CFP.*

(3) Workload CFP Inspired by how the battery life is characterized for commonly used applications, we propose characterizing the CFP for common workloads (C_{workload}) by using:

$$\text{C}_{\text{workload}} = T_{\text{workload}} \times P \times CI \quad (2)$$

where, T_{workload} stands for time it takes to run the workload on the processor, P is the processor's power, and CI is the carbon intensity in kgs of CO_2 eq. per KWh. We propose that C_{workload} be included in sustainability reports for common applications to drive sustainability-aware hardware-software co-design.

Using Eq. 2 we evaluated the C_{workload} for multiple CPU, ML, and GPU workloads. Fig. 7 shows the operational CFP for frequently-analyzed ML workloads: image segmentation ImgSeg, ObjDet, FaceDet, text classification (TextC), machine translation (MT). For CPU workloads, we analyzed operational CFP for file compression (FComp), Nav, PDF render (PDFRen), photo library (PhotoLib), TextProc, asset compression (AssetComp), object removal (ObjRem), and HDR. For GPU workloads, we evaluated for background blur (BBlur), stereo matching (SMat), horizon detection (HorizonDet), edge detection (EdgeDet), gaussian blur (GBlur), and feature matching (FMat). All the performance and power numbers for multiple devices were obtained from [25], [30]. The number in parenthesis in the plot depicts the data size used; for ImgC, we use 10M images. The iPhone is the most sustainably efficient device for all three categories of workloads (ML, CPU, and GPU), with the least workload CFP for almost all applications. Pixel is better for FP16 for ImgSeg and ObjDet. However,

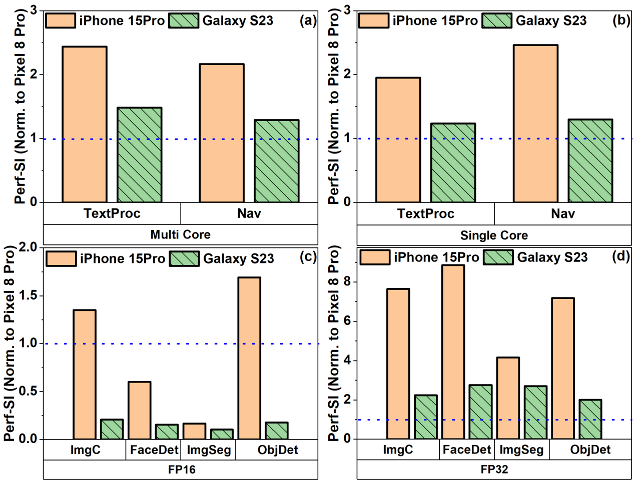

Fig. 6. Perf-SI (normalized to Pixel 8 Pro, higher is better) values of iPhone 15 Pro processor and Galaxy S23 processor for various benchmarks [30].

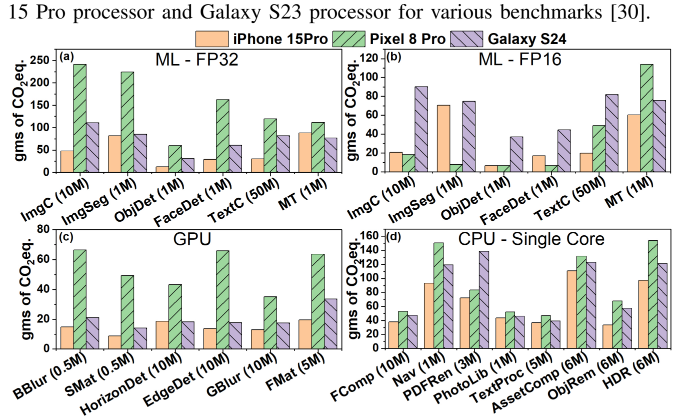

Fig. 7. Operational CFP for different workloads on mobile CPUs and GPUs.

Pixel's GPU's sustainable efficiency is poor compared to the other two devices. By comparing the Pixel 8 Pro and Galaxy S23, we observe application-specific results where the Pixel 8 Pro is more efficient than the Galaxy S23 in some cases.

(4) CPU design time and engineering hours The time it takes to design a chip, the CPU-compute time, and the engineering hours put into each processor also contribute to the processor CFP [8]. These metrics are important for accurately modeling the processor CFP, setting benchmarks, and guiding research.

IV. CFP of Mobile SSDs and Metrics

A. SSD CFP over the years

There is a consistent demand for storage on mobile phones to satisfy the needs of modern data-intensive applications. Larger memory systems come with a sustainability price. Fig. 8(a) shows the variations in total phone CFP of various iPhone models for the different memory configurations.

B. Sustainability metrics for SSDs

The work in [12] proposes the storage embodied factor metric as a sustainability metric for SSDs. We propose including metrics. This metric, which is also given by the CFP per GB of storage, must be included in corporate sustainability reports.

Fig. 8(b) illustrates the changes in cost per GB for flash memory over the years [31], [32]. The variation in CFP per GB is obtained from memory vendor's sustainability reports

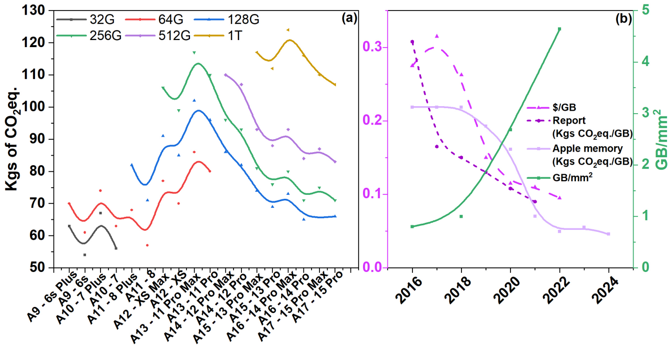

Fig. 8. (a) iPhone series CFP across different memory configurations (b) variation in cost and CFP/GB over the years.

[33] and from Apple's product reports [26] are shown in the figure. The flash memory density, depicted in green, has increased over the years, allowing more memory to be packed into the same unit area. Although transitioning to lower technology nodes tends to raise the overall CFP due to lower yields, the improvement in memory density has offset this effect, resulting in a decrease in the overall CFP per GB, as evidenced by reports from Apple and SK Hynix.

However, the CFP of a phone with larger storage is significantly higher than its lower storage counterparts. Apple reports that the iPhone 15 Pro, available in 128GB, 256GB, 512GB, and 1TB configurations, has a CFP ranging from 70 to 110 kg CO_2 eq. While it may seem that a phone with more extensive local storage is worse for memory CFP, it's important to note here that cloud-based storage also has a large CFP. Flash storage has a carbon impact ranging from 0.044 to 0.218 kg/GB shown in Fig. 8(b), whereas cloud storage has three orders of magnitude greater CFP [34]. This is due to the several backup servers for data storage on the cloud used by cloud providers such as Google, Apple, etc. We propose that corporate sustainability reports include the CFP of the device and equivalent cloud options for consumers to make sustainable choices and the industry to drive research.

V. Conclusion

With the widespread adoption of cellphones, our focus in this paper is a call for action for detailed CFP data for various lifecycle phases and components of a cellphone. We provide a detailed analysis of how current corporate sustainability reports mask critical CFP trends, with a particular focus on processor and memory components. We propose and highlight what metrics must be included in reports for sustainability-driven design, architecture, manufacturing, and consumer purchasing decisions. We emphasize the importance of standardizing reports throughout the supply chain.

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