Global Greenhouse Gas Emissions of Video Games based on 2022 Market Data

An extended study to "*From One Edge to the Other: Exploring Gaming's Rising Presence on the Network*"

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The environmental impact of digital entertainment has become increasingly significant, with the video game industry emerging as a notable contributor to global greenhouse gas emissions. This study presents a comprehensive life-cycle assessment (LCA) of gaming platforms and services based on 2022 market data, expanding upon prior work by Marsden et al. (2020). It examines the carbon footprint across five categories: gaming consoles, handheld devices, personal computers and laptops, game streaming services, and game downloads. Findings indicate that PC and laptop hardware account for the highest emissions, followed by game streaming services, and consoles. Handheld gaming consoles and downloads exhibit significantly lower emissions. The study evaluates the validity of past projections on the adoption of streaming technologies and identifies a sharp increase in cloud gaming users since 2019, suggesting a shift in consumption trends. Design and policy recommendations are offered to mitigate emissions, including energy-efficient hardware, use of sustainable materials, and features promoting shared device use. This work also concludes with actionable insights for HCI researchers, platform designers, and sustainability advocates seeking to balance technological engagement with ecological responsibility.

CCS CONCEPTS • consumer units sold • rated power • carbon emissions per device category

Additional Keywords and Phrases: game consoles, computer gaming, carbon emissions, mathematical calculations.

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LIST OF ABBREVIATIONS AND UNITS

DC – Data Center
GB - Gigabyte
GPU – Graphical Processing Unit
FHD – Full High Definition
HCI – Human-Computer Interaction
HD – High Definition
KgCO2e – Kilograms of Carbon Dioxide Equivalent
KWh – Kilowatt hour
LCA – Life-Cycle Analysis
MB – Megabyte
Mbps – Megabits per second
NC – Network Contribution
OEM – Original Equipment Manufacturer
OS – Operating System
PC – Personal Computer
PSU – Power Supply Unit
QHD – Quad High Definition
SD – Standard Definition
tCO2e – Tonnes of Carbon Dioxide Equivalent
TDP – Thermal Design Point
UE – User Equipment
UHD – Ultra High Definition

1 INTRODUCTION

ICT contributes 1.5% to 4.0% of the annual carbon emissions ranging from data centers and networks to consumer devices [53]. Video gaming, a popular form of entertainment across the globe, has recently come under scrutiny due to its environmental impact, particularly concerning its carbon footprint. The manufacturing, distribution, and usage of gaming consoles and PCs, as well as the production and playing of video games, contribute significantly to the emission of greenhouse gases and energy consumption [14, 79]. This includes the transportation and retailing of these products, which collectively account for about 10-15% of the annual carbon footprint of major game studios like Ubisoft [40]. From an end-user execution perspective, PC gaming lands in at 29-32% of annual ICT emissions versus 41% of game consoles [15, 42].

The concept of being a part of a social congregation focused around a digital game for leisure is not a new one. As far back as the 1980s, when computer and console gaming started to gain popularity, users then throughout their various phases of life have been attracted of being part of a leisurable social event around gaming (be it in-person or through networking) [1]. Couple that with generations being familiarized with gaming over the decades and one can understand the social gravity involved around present-day leisure and social gaming through modern day devices [2]. One might ponder on the cost involved to partake in such a sociable activity while gathered around or interacting with a piece of technology. There is of course the monetary exchange for goods and services needed to establish a gaming session – mainly speaking the hardware and infrastructure. But there is another cost that is less evident – the impact of gaming on the environment caused by its carbon footprint [8, 9] where up to 15 hours of weekly gameplay is usually expected [80, 81].

The seventh generation of game consoles (Microsoft Xbox 360, Sony Play Station 3, and Nintendo Wii) sparked high performance gaming [3] and the carbon footprint from these consoles have been well-documented since their release in 2005. With the advent of the eighth generation of games consoles (e.g. Play Station 4 and Xbox One), the stark difference of carbon footprint of the seventh-generation consoles was revealed with the newer generation having nearly half the carbon footprint [4, 5].

The ninth generation of gaming and the consumable hardware and services revolved around a host of options; computer gaming, console gaming, handheld/mobile gaming, and game streaming services [6]. Each category has its credits and flaws in terms of immersion, available game titles, cost of ownership and maintenance. With each also comes a cost of setup required to initialize a desired game title to its initiable in-game playable state, and this differs by how the game title is delivered i.e. on a physical media, downloadable game media, or as a streamed game title [7].

Even digital games, which might seem environmentally friendly at first glance, have a notable impact. Most require an active internet connection meaning considerable network usage over sessions. This contributes to what is known as "internet pollution", accounting for almost 3.7% of all global greenhouse gas emissions [14]. Gaming manufacturers are compelled to improve sustainability by making their products more energy-efficient and easier to recycle but this form of pollutant still lingers on [14]. The energy needed to power gaming devices to run and maintain gaming sessions contributes approximately 40% to the total carbon footprint [15].

For a comprehensive understanding, the impact of the current generation of technology can be mapped down to the carbon emissions when manufacturing the hardware, when running the hardware, manufacturing the physical game media,

and downloadable game media and digitally delivering game streaming services [8, 9]. While there have been significant advances made to reduce the carbon footprint and emissions in the manufacturing, supply and recycling processes around gaming hardware and media, the growth towards the adoption of game streaming services continues to be positive [10]. This is witnessed especially when considering the shared ownership (reducing individual stake in environmental impact), the low client performance requirements and a selection of subscription plans to cater to varying needs [11].

To help evaluate methods of delivery, this thesis will compare video games played traditionally with local rendering on dedicated consumer hardware (such as PCs and games consoles), against games rendered in the cloud and streamed to a local client. In so doing, this thesis will update the data figures for carbon emissions calculated in the study by Marsden et al published in 2020 [9]. Since the publication of Marsden et al's study, players of video games spent much time indoors due to social distancing during the COVID pandemic of 2020-2022 [12], one of the two documented streaming services has been discontinued [13], and ninth generation consoles, handhelds, computer (gaming) components, and game streaming services were released (e.g. PlayStation 5, Xbox Series, and Nvidia's GeForce RTX 40 series graphics cards).

The contribution of this thesis is to use technical and usage data to see whether the findings and expectations of Marsden et al [9] still hold up for 2022. The study will perform an analysis into the adoption rate among users, power footprint and estimate the emissions comparatively between each category. After this analysis, the study will also look into design and HCI suggestions towards manufacturers for improved experiences without the cost of adding to the carbon footprint. Among the issues considered are the impact of the ninth generation of gaming consoles and equivalent gaming PC trends on carbon emissions, the environmental sustainability of cloud gaming, and what hardware design considerations of note should be considered by manufacturers.

With an increased consumption of gaming (by 66%) influenced by COVID-19 [12], efficient processes and supplies, competitive cloud gaming technologies, and our social urge to connect through gaming – are we progressing to cutting down our 'gaming' carbon footprint or is this a leisurable activity that will forever be taxing on our environment?

The principle research questions of this thesis are:

1. How much gaming hardware (PC, consoles, and handheld consoles), game streaming services, and game downloads have contributed to the global carbon emissions in 2022?
2. Have the projects from Marsden et al [9] been proven to be accurate?
3. What are some design choices that can heed designers and gamers towards gaming sustainability?

2 RELATED WORK

The current study draws most inspiration from Marsden et al [9] as the basis of a lifecycle analysis for gaming technologies and platforms commercially available in 2022. While the older study draws an exceptional and academically unique outlook on mobile, PC and eighth generation of video game consoles against streaming versus local downloads, the current study gains to establish a similar outlook but of a wider array of devices and services ranging from game streaming services till handheld game consoles up till commercial versions of the present ninth generation video game consoles (like the Play Station 5 and Xbox Series S and X). The connection drawn between carbon footprints for game streaming and downloading is fundamentally true, but more recent research has shown that streaming and downloading likely result in less consumption and emissions than previously thought [54]. There have been previous publications

extensively spanning the relation between gaming and environmental impact with an emphasis on hardware and infrastructure.

Take for example Mills et al [42] where a platoon of 26 game-ready systems were benchmarked for gaming performance and insights for greener policy planning and establishing design implications (albeit just for the state of California). Of course, there will always be the age-long debates of computer gaming configurations at the helm of powerful GPUs versus specialized gaming consoles as illustrated by Abraham [45] and if going diskless is a worthy gesture in saving our planet. The icing on the cake is complex calculations and projections proposed by Aslan [8] to gauge different gaming technologies, their components and effects in mathematical data sets.

While a majority of publications focus on real-time TDPs and annual emissions, publications like Horowitz [41] not only assess the impact of using handheld and stationary consoles against each other but also suggest practices to ensure more efficient hardware utlilization. Publications tend to focus on mainstream topics such as hardware efficiencies, practices, implications and comparisons between current and older generations of hardware. One publication of Cox et al [43] stands out though as it generalizes the practices of manufacturers offering backward compatibility (running older game titles on newer hardware) usually in first iterations of new consoles and weighted if this functionality should stick around for a while.

When comparing figures from Mills et al [42], the diversity in power caps is evident as the paper caps high-end gaming at 605 watts. Given the age and available hardware at that time, the larger consumer accessible power supplies suggest that gaming potential has nearly doubled and thus will require an equivalent modulator. Same can be noted for laptops where the paper caps power at 212 watts. Both sets of figures are for hardware available to consumers in 2016.

2.1 Sustainable HCI

Studies have been laying increasing emphasis on the importance of raising awareness about the environmental impacts of gaming. This includes the energy consumption of gaming devices, the carbon footprint associated with digital distribution and cloud gaming services extensively discussed throughout Marsden et al [9], Aslan et al [46] and Abraham [45] to name a few. Sustainable HCI in gaming encourages the design of games that educate players about environmental issues coupled with promoting eco-friendly behaviors as far back as Hanks et al [65] and continues to build momentum today as showcased by Earth.Org [66].

Sustainable HCI in gaming also focuses on designing games and gaming systems that are energy efficient, and to minimize the energy footprint of general gaming habits. Mattila et al [67] proposes a matrix and discusses in great detail steps of optimizing software to reduce energy consumption and encouraging hardware manufacturers to develop more sustainable gaming consoles and PCs, ranging from manufacturing, data hosting up till consumer-end products. Another approach is using gamification to promote sustainable behaviors. Games can incorporate elements, as suggested by Spors et al. [68], that encourage players to engage in environmentally friendly activities, both within and outside the game, and sequentially develop of sense of achievement and ownership of impacts on the environment. This can include challenges that reward players for reducing energy use or participating in virtual activities that mirror real-world sustainability efforts.

Aslan [8] highlights that this category of research also involves conducting lifecycle analyses of gaming products to understand their environmental impact from production to disposal by assessing the sustainability of materials used in gaming hardware and exploring ways to recycle or repurpose old gaming equipment to reduce electronic waste [69]. That is discussed later as it benefits from interdisciplinary research that combines insights from computer science, environmental science, and design forming collaborative efforts in aiming to create frameworks and tools that help game developers and researchers assess and improve the sustainability of gaming experiences.

2.2 Video Game Sustainability

The video game industry is increasingly scrutinized for its environmental impact, particularly concerning energy consumption. Studies highlight the significant energy use associated with gaming consoles, PCs, cloud gaming services, and transport (whether of hardware or software). Efforts to improve sustainability focus on designing energy-efficient hardware and optimizing software to reduce power usage [66] which has been the prime topics of discussion in Aslan et al [46], Abraham [44] and Mattila et al [67]. Collaboration within the gaming industry and with external stakeholders is crucial for advancing sustainability. Thorsen [73] emphasizes developing industry-wide standards and policies that promote sustainable practices, such as reducing carbon footprints and improving supply chain transparency.

Recent research emphasizes the role of game design in promoting sustainability. This includes creating games that educate players about environmental issues and encourage sustainable behaviors in the same magnitude as discussed under *Sustainable HCI*. Fjællingsdal et al [70] explains game mechanics can be designed to reflect real-world sustainability challenges, offering players insights into resource management and ecological balance. Gamification of this caliber is used to raise awareness about environmental issues and promote sustainable behaviors among players. By incorporating sustainability themes into gameplay, developers can engage players in activities that mirror real-world environmental challenges, fostering a greater understanding and commitment to sustainability.

As gameplay, this has been implemented in *Beyond Blue* as covered by Daiiani et al [71] where elements of plastic pollution appear on the virtual sea floor, *Plasticity* and *Alba: A Wildlife Adventure* in a study by Larreina-Morales et al [72] where the players experience and counter environmental pollution affecting ecosystems and their hosts, but there have been no commercially available examples that focus on domestic and virtual game consumption. While this study will discuss design suggestions later on for manufacturers' consideration, an important takeaway can be to empower users to foster environmentally-friendly habits in their gaming routines.

2.3 Life Cycle Assessment

Lifecycle assessment (LCA) is a critical tool used to evaluate the environmental impact of products from production to disposal for gaming. This involves analyzing the sustainability of materials used in gaming hardware and exploring recycling and repurposing options to minimize electronic waste [8, 45, 74]. For video gaming, an LCA can involve examining the different stages of a game's life, from development and production to distribution, usage, and disposal. Such assessments help identify areas for improvement in the production and disposal processes.

Each stage has distinct environmental impacts, and lifecycle analysis helps identify opportunities to reduce these impacts through more sustainable practices with mentions going as far back as Finnveden [75] and as recent as Abraham [45] and Lönnqvist [76]. This also includes evaluating extraction and processing of raw materials, energy consumption during manufacturing, and the potential for recycling or repurposing components to minimize waste as has been the

highlight of Ben Abraham's works [44, 45]. A lifecycle analysis will also consider the energy consumption and carbon footprint associated with playing games (known in LCA as the "use phase"), as has been discussed in Marsden et al [9]. These will be the focus in later sections, including the energy used by gaming devices, servers for online gaming, and data centers for cloud gaming.

Ismail et al. [78] emphasizes the need for effective end-of-life management strategies to address electronic waste (e-waste) and promote the recycling of valuable materials, thereby reducing the environmental impact of discarded gaming hardware.

3 METHODS

The current study performs an LCA in order to draw implications about where the largest impacts are in video games, and to thus enable those working in game development and HCI/games research to reflect on more sustainable pathways for the future. The inputs served here are all consumable electronic gaming devices and services, their manuals and public records from their manufacturers stating the hardware and/or software configuration, heat and power specifications to conclude the output in the form of environmental impact, power usage, technical implications and suggestions. These technical insights allow for a bottom-up approach taking information about the finished products and inferring on sold units, behaviour in contrast to past generations and dive into hardware insights as can be seen in Mills et al [42] and Joshua [8].

Table 1: Technical sources used to compile this study

Publisher	Data Sources	Motivation
Cybenetics.com	[50]	PC PSU operational power draw.
Nintendo Switch Technical Specs	[25][32]	Official sales and technical insights from 2022.
Microsoft Hardware & Networking	[18]	Official Xbox consumption and standby figures with added steps to minimize standby footprint.
Notebookcheck.net	[49][51][52]	Highest power draws on commercially available laptops.
	[20][21][24][27][77]	Sales figures for gaming consoles (PlayStation and Xbox).
Statistica	[27]	Users registered with PlayStation Network.
	[36][81]	PC hardware sold and estimated user counts.
Sony Legal	[17]	Official PlayStation power signatures.

The specified methods and research enquiries are expected to be ethically safe as they cater to records made public by corporate entities and to previous public research material and knowledge. The only restriction with this method comes with the availability of public records for gaming media of interest as only public records till 2022 are available for the focused media (key records from manufacturers and private entities described in *Table 1*). To maintain the scope of the study, the prime focus will be on the gaming services and gaming units (PCs and consoles) only. Depending on the variations of data, the LCA will be either in CO2 footprint or KWh signatures for the year 2022.

For calculating the carbon emissions of consoles, hardware and services, we will be converting peak power consumption to kWh (annual) for the maximum achievable footprint:

$$Annual\ kWh = \frac{Watts\ consumed \times Hours\ of\ daily\ use}{1000} \times 365$$

CO2e standard rates vary from region to region by their respective environmental authorities. Given that this paper is focusing on a global LCA, the CO2e rate for the continents have to be summarized into an average emissions factor of the values supplied by the 2023 report of *International Electricity Factors* by Carbon Footprint™ [19]. This leads to adapting the above formula for *Annual kWh* to determine annual CO2e emissions:

$$Annual\ kgCO2e = \frac{Watts\ consumed \times Hours\ of\ daily\ use}{1000} \times 365 \times 0.88288$$

where:

0.88288 is an aggregated factor (with unit kgCO2e per kWh) derived from the 2023 report of *International Electricity Factors* by Carbon Footprint™ [19] signifying the global carbon emissions to maintain the electricity grid (from fuel and generation till distribution)

This can be simplified to:

$$Annual\ kgCO2e = W \times H \times N \times 0.3222512$$

where:

Annual *kgCO2e* is kilograms of CO_2 emissions in a year scaled to global factors,
W is watts of electricity consumed,
H is the number of hours the electric appliance has been used in a day,
N is the number of (same category) appliances or users

with:

- supporting technologies (like televisions, audio equipment, controllers, etc.) being excluded, and
- an emissions factor which is an aggregate of fuel, generation and grid and transmission losses.

The calculations in the following sections will be based on 1-hour gameplay per day for simplicity. Recent studies [80, 81] suggest gaming sessions commonly compound to about 20 hours minimum per week per user i.e. an extended constant

multiplier of 2.85x per final number (the values to the very right of each tabulated data). The only variable factor when computing footprint with respect to categories (given each has derived power ratings and counts of adoption) is how much time duration is meaningful for the present and future analyses.

4 ANALYSIS

In 2022, the global consumption of game consoles and PCs was substantial, with the Nintendo Switch being the best-selling video game console, selling over 19 million units worldwide [77]. Meanwhile, PC sales reached gross 285.1 million units, although this represented a 16.5% decline from the previous year [36]. The environmental impacts of these devices are significant, as they contribute to the growing problem of electronic waste and require substantial energy for both production and operation. Game consoles and PCs are linked to environmental harm throughout their life cycles, from the mining of critical elements and production of plastics to their eventual disposal, which contributes to carbon emissions and environmental degradation [15]. Academic studies over the past five years have emphasized the need for more sustainable practices in the gaming industry, highlighting the importance of reducing energy consumption and improving recycling efforts to mitigate these environmental impacts [15].

Hardware design on commercially available consoles in 2022 aim for 0.3-0.5 watt standby and short inactivity thresholds to minimize power wastage when idle [15, 16, 17], but this study will focus on the approximate power draw resulting from sessions playing recent games for the worst possible carbon signature. Runtime consumption has a stark difference between the two varieties of consoles too; striking the contrast from the least peak consumption rating of a measly 13.5 watt for the Nintendo Switch Lite (HD playing while charging) to the eye-watering highest peak consumption rating of 208.8 watts for the PlayStation 5 (model CFI-1116B at 8K UHD – released in 2022) [16, 17]. The Xbox Series S and Series X are nestled in the middle of the contrast with a peak power consumption of 74 watts and 153 watts respectively (during active gameplay) [18].

The carbon footprint in manufacturing per unit per console may also paint a similar image. Granted that none of the Nintendo Switch consoles (smallest of the group) can compare to the sheer bulk of the PlayStation 5. At the time of writing, neither console manufacturer disclosed the carbon emissions resultant of manufacturing either of their 2022 consoles.

4.1 Gaming Consoles

Table 2: Carbon and power signatures of gaming consoles commercially available in 2022

Console	Peak Avg. Power Consumption During Active Gaming (Watts)	Peak Power Consumption During Standby w/ Services & Ports Running (Watts)	Cumulative Number of Units Sold Since Release Till 2022	Estimated Annual Carbon Footprint with Daily 1-Hour Gameplay ($kgCO_2e$)
PlayStation 4 Slim	84.1[17]	5.8[17]	117 million (variants combined)[20]	3.17 billion
PlayStation 5	208.8[17]	3.3[17]	38.4 million[21]	2.58 billion
Xbox Series S	74[18]	10[18]	10.5 million[23][24]	0.25 billion
Xbox Series X	153[18]	13[18]	10.5 million[23][24]	0.52 billion

Table 2 documents the gaming consoles that were commercially available through manufacturers and signed distributors up till 2022, their respective power figures (during active gameplay and standby), number of units sold up till 2022, and estimated annual footprint as a product of units sold and peak gameplay power usage.

Data figures are based on official manufacturer playtests and environmental documentation using dedicated game titles. Although Microsoft has not disclosed the parity of sales figures for either of their consoles, legal advisors reviewing revenue documents suggested in 2023 that it was almost at a 50/50 split based on [23] between Xbox Series X and S sales figures. Same is the case for the PlayStation 4 Slim where Sony only mentions sales figures for the entire PlayStation 4 family in their annual IR reports, hence the count of 117 million (combined) units of PlayStation 4 documented in *Table 2*. Though the PlayStation 4 was included due to its commercial availability despite its dated hardware, the Xbox One Series consoles were not added in the dataset as they have not been commercially sold since 2020.

Arguably, the current generation of consoles (PS5 and Xbox Series X) require more than twice the power consumption for not exactly twice the gameplay resolution and performance – one might would think! The power figures based on sessions playing recent games of the PlayStation 5s available in 2022 have sharply risen over the PlayStation 4 Slim based on [17]. It is a different perspective with peak standby times (running background services, charging devices over USB, and active network traffic) where the PlayStation 4 Slim's internals consume 1.7x more power compared to the Play Station 5. This high 'silent' power draw by the PlayStation 4 Slim makes sense on paper where a lot of the motherboard, power management, and network components were carried over from the original PlayStation 4 as a package (minus the power-intensive components like the SoC, memory modules, and storage media).

Where the PlayStation 4 Slim offers native 1080p HD resolution gaming, the Xbox Series S consumes 88% of what the PlayStation 4 Slim draws to provide 1440p QHD output at best and that too for a handful of titles while being a digital-only console (i.e. does not feature an optical disk drive). This is due to the cost-cutting and design choice for the Xbox Series S to be game-ready for FHD (or 1080p HD) gameplay natively [23]. As a home media system, the Xbox Series S can output a 4K signal for all entertainment platforms compared to the PlayStation 4 Slim's 1080p HD multimedia playback. The Xbox Series X triumphs in a comparative ratio where it consumes a peak of just over 2x the power of the Xbox Series S for a richer, denser and 4x higher native gameplay resolution. The peak standby power figures are somewhat misleading for this console family as the Xbox Series S does not have the internals to validate a peak standby power consumption of 77% of that of an Xbox Series X.

It is interesting to note that ownership of PlayStation 5 consoles is higher than the Xbox Series X despite the former's higher power consumption. From that alone, the resulting carbon footprint from PlayStation 5 consoles exceeds the Xbox Series X and S combined.

4.2 Handheld Gaming Consoles

Table 3: Carbon and power signatures of handheld gaming consoles commercially available in 2022

Handheld Gaming Console	Peak Avg. Power Consumption During Active Gaming (Watts)	Peak Power Consumption During Standby w/ Services & Ports Running (Watts)	Cumulative Number of Units Sold Since Release Till 2022	Estimated Annual Carbon Footprint With Daily 1-Hour

				Gameplay ($kgCO_2e$)
Nintendo Switch (docked)	17[16]	8[16]	88.67 million[32]	0.36 billion
Nintendo Switch Rev. 2019 (docked)	8.5[22]	3.8[22]		
Nintendo Switch Lite (charging)	13.5[16]	0.5[16]	20.4 million[32]	0.09 billion
Nintendo Switch OLED (docked)	8[22]	2.9[22]	13.49 million[32]	0.03 billion
Valve Steam Deck (charging)	15[16]	0.5[16]	1.62 million[26]	0.02 billion

Table 3 documents the handheld gaming consoles that were commercially available through manufacturers and signed distributors up till 2022, their respective power figures (during active gameplay and standby), number of units sold up till 2022, and estimated annual footprint as a product of units sold and peak gameplay power usage.

Performance handheld gaming in 2022 saw the introduction of the Valve Steam Deck in Q3 2022. Interestingly as the Nintendo Switch family nears to being the best-selling handheld console (about to surpass the total sales figures of the Nintendo DS as of 2024), Nintendo does not share power consumption figures either through annual IR reports or through third-party contracted agencies. This is specifically a disadvantage when Nintendo releases [32] without specifying individual sold device counts for the Nintendo Switch and Nintendo Switch Rev. 2019. This results in the tabulated data listing a combined 88.87 million figure for both units sold. Peak standby and game intensive power figures are courtesy of independent test results from blog outlets as well as calculating peak power delivery of OEM power adapters. The tabulated $kgCO_2$ is calculated by considering an average of the peak power consumption during active gameplay for all four Nintendo Switch variants commercially available in 2022.

Like the other handheld consoles, the Valve Steam Deck has its internals designed to consume a peak of 15 watts under stress (in part due to the battery pack is rated at a maximum of 15 watts of output) [31]. This coupled with a true 0.5 watts standby offers a remarkable performance package. One thing to note is the standby comparison for the Nintendo Switch. All variants (except for the Lite version) come with dual wireless and rechargeable mini controllers that stick to the main console. This is attributed to the higher peak standby where the main console feeds power to the mini controllers for charging and systems check. Whether the user base makes frequent use of those mini controllers in detached mode or not can be spun off to a future study.

The revision of the Nintendo Switch to the Nintendo Switch OLED shows the commitment of manufacturers considering hardware optimizations or upgrades for a lower footprint in a perspective. Although a 0.5 watt decrease in consumption during gameplay may not seem much, for a limited power pack in a handheld this means requiring less frequent charging sessions. The difference in average power consumption between the initial Nintendo Switch and the following Nintendo Switch Rev. 2019 is another tell-tale sign that manufacturers do heed towards optimizing hardware and design. The former clocked 17W during gameplay whereas the latter clocked at 8.5W, which is a straight 50% cut in operation power consumption.

4.3 PC And Laptop Hardware

Table 4: Possible data sets to calculate PC gaming footprint for the years 2020 - 2022

Year	Estimated Number of PC Gamers	Total Count of GPUs (AiBs) sold	Total Count of PCs Sold	Device Split	Peak Power Consumption During Active Gaming Per Device (Watts)	Estimated Annual Carbon Footprint With Daily 1-Hour Gameplay (kgCO2e)
2020	1746 million[36]	42 million[37]	297 million[35]	Notebooks: 235.1 million[35]	330[52]	25 billion
				Workstations: 61.9 million[35]	1650[50]	32.9 billion
2021	1775 million[36]	101 million[38]	341 million[34]	Notebooks: 275 million[34]	330[51]	29.2 billion
				Workstations: 66 million[34]	1650[50]	35 billion
2022	1799 million[36]	64.2 million[39]	285.1 million[33]	Notebooks: 223.8 million[33]	330[48][49]	23.8 billion
				Workstations: 61.3 million[33]	1600[50]	31.6 billion

Table 4 takes a by-year approach to documenting the number of unique individual that use PC for gaming, the number of add-in-board (AiB) GPUs sold commercially, the number of PCs sold (split between notebooks and workstations), documented highest power draw for each (PSU for workstations and power adapter for notebooks), and an estimated annual footprint per year based on the product of peak power and count of device split. The reason the number of individuals is not used in the calculations is under the assumption of shared PCs for gaming (e.g. gaming cafes in some parts of the world).

For absolute worst-case scenarios, the estimation in this segment relies on maximum commercially available power blocks for laptops and workstations. The section focuses on the most power-intensive laptops and the highest power-rated PSUs (for PCs) available from 2020 through 2022. However, additional peripherals (like secondary monitors, controllers, audio equipment, or add-on lighting) will not be considered due to focus on the dedicated power supply items only for near-accurate estimates.

- In 2020 – the Alienware m15 R2 [52] is bundled with a 330-watt power supply unit. This is mitigated by the SilverStone Decathlon DA1650 [50] rated at 1650 watts.
- In 2021 – the Alienware x17 R1 [51] carrying a 330-watt power supply unit. This is mitigated by the SilverStone HELA 2050 Platinum [50] rated at 1650 watts.
- In 2022 – the Alienware x17 R2 [48] and MSI Titan GT77 12UHS [49] each shipping with a 330-watt power supply unit. This is mitigated by the Seasonic Prime TX-1600 [50] rated at 1600 watts.

It is to be noted that workstations and notebooks rarely breach their rated power supplies. The reason peak power is considered for calculations is due to no lower end on power cap for gaming PCs. It can be as small as Raspberry Pi running an ARM-based version of modern OS while still consuming anywhere between 4-15W for active gameplay. Under the assumption that it will be exhaustive finding a lower limit, the calculations generalize peak power against the device counts per year.

4.4 Game Streaming Services

Table 5: Carbon and power signatures of game streaming services commercially available in 2022

Game Streaming Service	Estimated Power (DC + NC) Per User (Watts)	Recommended Network Bandwidth	Cumulative Registered Accounts Since Release Till 2019	Active Registered Accounts Since Release Till 2022	Estimated Annual Carbon Footprint With Daily 1-Hour Gameplay (kgCO2e)
Google Stadia	520[30]	10 Mbps (720p) – 35 Mbps (4K)[84]	750,000[28]	235,000[28]	0.039 billion
Nvidia GeForce Now	520[30]	15 Mbps (720p) – 45 Mbps (4K)[85]	~1 million[29]	20 million[29]	3.35 billion
Xbox Cloud Gaming	520[30]	10 Mbps (720p) – 20 Mbps (1080p)[86]	~10 million[29]	25 million[29]	4.19 billion
PlayStation Now	520[30]	7 Mbps (720p) – 15 Mbps (1080p)[87]	38.8 million[27]	112 million[27]	18.77 billion

Table 5 tabulates the *Game Streaming Services* that were commercially available until the end of 2022, except for Google Stadia which shutdown on January 18, 2023 with 235,000 unique users still registered. This was in part due to Google's announcement on September 29, 2022 to shut down the servers on closure date [47]. Granted service providers do not officially disclose *data center (DC)* and *network contribution (NC)* costs for their hosted services, this study borrows a documented cost of 520W from a previous study to generalize power requirements for infrastructure. The network bandwidth is officially vendor-specified, and the table puts a number to estimated annual footprint by considering the product highest official network usage along with active users in 2022.

Smartphones are not intended to run AAA titles, like the *Assassins Creed: Valhalla*, on their native configuration due to limited hardware resources. But with the right network bandwidth and a game streaming service of your choice, it becomes a possibility for decent gameplay of even the AAA game titles on your low-powered devices (like smartphones or TV set-top boxes). Marsden et al. [9] assumed a model where the lucrative easy access to gaming and low costs will express an annual 10% increase towards game streaming services.

Since launch, the adoption of cloud gaming services have been rapid. This may have been in part due to the chip shortage during the pandemic of COVID-22 where console manufacturers were unable to meet the demands of at-home consumers simply due to production being decreased as quarantine measures were implemented. To summarize the original projects:

- Google Stadia should have grown from 750,000 to 998,250 by 2022, instead Stadia had a total of 235,000 accounts till its closure on January 18, 2023.

- Nvidia GeForce Now from 1,000,000 to 1,331,000 by 2022 rose to 20 million.
- Xbox Cloud Gaming from 10,000,000 (launched in 2020) to 13,310,000 by 2022 rose to 25 million.
- Play Station Now from 38,800,000 to 51,642,800 by 2022 rose to 112 million.

The only factor left worth considering is the infrastructure cost per user. Handheld devices have scaled up on performance while still maintaining a respectably low power footprint (ideally less than 12W under load). The infrastructure costs can be estimated to be 340 watts for computation and an additional 180 watts for networking per user, which is significantly higher than a gross estimate of 180 watts and 120 watts respectively for console gaming (where network traffic maintains game title patches and game sessions) [30]. A positive factor of cloud gaming services is their commitment to utilizing renewable energy to power their data clusters to reduce carbon impact [7, 55].

There are of course other technical limitations to game streaming services that have been discussed in referenced works and especially by Relvas [7] which extends beyond just the sheer power infrastructure required to maintain services. These can be primed to:

1. Internet connectivity – an active internet connection is required with the required bandwidth, an acceptable ping, and acceptable packet loss as key factors among others to provide a satisfactory gaming experience.
2. Initial setup costs – unlike the consumer, the service provider has a setup cost which includes (but not limited to) planning and implementing data centers and the expertise required in the form of labour and equipment.
3. System-wide outages – this pertains to when either a facilitating infrastructure or the hosted infrastructure itself goes offline or under unplanned maintenance rendering the consumers unable to use game streaming services (unlike a gaming PC or gaming console which can be used when their hosted services are offline).

4.5 Game Downloads

Game downloads require the same backbone as game streaming; data centers, a user-end device, and networking infrastructure in between. The only difference between the two is that game downloads might incur extra storage signature due to data being committed to a storage medium. This section takes some limitations into consideration:

1. Includes package sizes available till the end of 2022.
2. Network traffic is assumed to be the same for all tiers of devices.

Table 6: Associated footprint of transferring 1GB data from data center to end-user device

	Estimate 1	Estimate 2	Estimate 3	Estimate 4
Energy Footprint (kWh/GB)	0.194 [56][57]	0.23[58]	0.08[59]	0.06[60]
Mean: 0.141 kWh/GB				

Table 7: Associated footprint of initial game setup and gameplay for 1 hour

Game Title	Size Of Install Package	Network Usage Rate Per Hour (MBs)	Number of Registered Users in 2022	Estimated (Max) Carbon Footprint with daily 1-hour gameplay per year (kgCO2e)	Estimated Annual Carbon Footprint With Daily 1-Hour Gameplay (kgCO2e)
Clash of Clans	Mobile: 298MB PC: 10GB[1]	12-20[61]	38 million[62]	33,723	17.27 million
Football Manager 2023	Mobile: 864MB PC: 7GB	15-40[88]	78,079[82]	983	0.02 million
Fortnite	Console: 18GB Mobile: 480MB PC: 16GB	45-100[63]	500 million[64]	2.22 million	408.93 million
PlayerUnknown's Battlegrounds (PUBG)	Console: 25GB Mobile: 785MB (SD), 1.02GB (HD) PC: 40GB	15-50[89]	30 million[83]	1.42 million	54.52 million

In an attempt to put a cost to every gigabyte downloaded, *Table 6* factors in four figures from past studies and uses them to calculate a mean for average power cost associated with each gigabyte downloaded. The variance between the base four values is due to different approximations ranging from emissions in their respective regions to considering line losses and network implementation (both at backend and in residential settings).

Where game streaming will constantly need a wide bandwidth for active transmissions and powerful servers to maintain gameplay, game downloads have an initial high cost in terms of setup and then smaller transactions to maintain gameplay. The numerical findings in *Table 7* consider the highest payload downloads and network usage to calculate the worst possible carbon footprint using the mean calculated in *Table 6* as a multiplier. *Football Manager 2023* was included in this section to factor in to have a more updated reference to *Football Manager 2020* benchmarked in Marsden et al [9], although the meek user base (attributed to the late-in-year launch) may affect overall footprint. Fortnite was included due to cross-platform availability and high user figures to form a competitive comparison.

The assumption in these calculations is that regardless of platform or release type (SD or HD), the end footprint reflects on the peak network usage per game title. From calculations, apart from *Football Manager 2023*, an on-network game will have a multi-million footprint if it has a multi-million user base even if its network optimization is efficient. Another factor worth considering is accessibility to the masses in the form of supported platforms, where the documented titles are compatible with most technologies of interest (except for *Handheld Gaming Consoles)*.

5 A GLOBAL PICTURE OF VIDEO GAME IMPACTS

5.1 Reflecting on the estimates of Marsden et al (2020)

For predicting future trends, Marsden et al [9] led with three scenarios: *Streaming Stays Niche*, *Streaming-as-Norm*, and *A Hybrid Future*. These are accompanied by projected units being consumed and expected power signatures from the time then with added estimates for the future to come. We will be discussing each with the calculated estimates in this

[1] Via *Google Play Games (Beta)* available since 19 January 2022 for PC.

study along with motivation. All scenarios proposed utilize manufacturing, direct and infrastructure emissions for each respective category which will be contested by the consumer estimated covered in this study. It is worth noting that Marsden et al [9] has no figures for handhelds from the time, but the study will try to factor in handheld gaming consoles along with their regular larger competition.

Another prominent note here is the power consumption figures for 2019 are "… Console 90 W, Desktop 200 W, Laptop 90 W, Mobile 4 W, Lightweight 5 W …". The present study compares the equivalent signatures of these with the worst case possible in terms of power supply and consumption ratings as of 2022. In terms of power figures for handheld consoles, these can be taken as a hybrid of mobile and lightweight but with far taxing power signatures.

Scenario 1: Streaming Stays Niche

The scenario leads with 2019 consumption figures of a total 139.1 million consoles (100 million PS4 and 39.1 million Xbox One combined) and 90 million unique Steam accounts. Marsden et al [9] propose 400 million units of consoles and PCs combined to be in use by 2030. When compared to the present study, the 2022 estimates are in close proximation to the 2019 estimates where 184 million units (6.5 million consoles, 0.5 million handhelds and 177 million PCs) which is almost a 32% rise from 2019 over a span of three years. If the growth remains linear then the 2030 estimates might still hold with the projected count of just over 410 million units.

Scenario 2: Streaming-as-Norm

The scenario projects that game streaming services dominate 90% of the gaming industry by 2030. The present study concurs with Marsden et al [9] that the infrastructure cost required to keep game streaming services operating, maintain quality of content, and data transmission is a cost strapped in between console and PC gaming at its extremes. In 2022, the worst power figures for console, streaming and PCs are 208W, 520W and 1600W respectively.

In 2019, about 40.5 million game streaming accounts existed after combining Google Stadia, Nvidia Geforce Now and PlayStation Now. This is a very pale comparison to the 157 million streaming accounts as of 2022 now including Xbox Cloud Gaming in the pack. This is a skyrocketing 387% growth rate over the span of three years. This might be attributable to the pandemic and the recent chip shortages but that can be a case study for future work to consider. When compared to total gaming media, game streaming services take up about 11% of media but is estimated to contribute to 12% of global ICT footprint at 26 million tonnes of CO_2e. The projected cost for 2020-2030 'streaming' alone by Marsden et al [9] is 2797 million tonnes of CO_2e. If the growth stays linear then 2030 might have 1525 million tonnes of CO_2e contributed from game streaming services.

Scenario 3: A Hybrid Future

This might be the most relevant trajectory to 2022 given the growth trends are a mix of *Scenario 1* and *Scenario 2*. But the proposed adoption rate of game streaming services rising to 30% does not hold given that 2022 saw a stark increase of 387% from the 40.5 million in 2019. While the gaming industry remains dominant towards PC gaming, what can be seen beneficial for this scenario is the rise of handheld gaming (supported by game streaming services and handheld consoles). What was considered 'mobile' by 2019 can be pictured as 'portable' in 2020-2030 in the form of handheld gaming consoles. A future LCA study will be needed to predict the adoption of handheld consoles and footprint, but a generalized

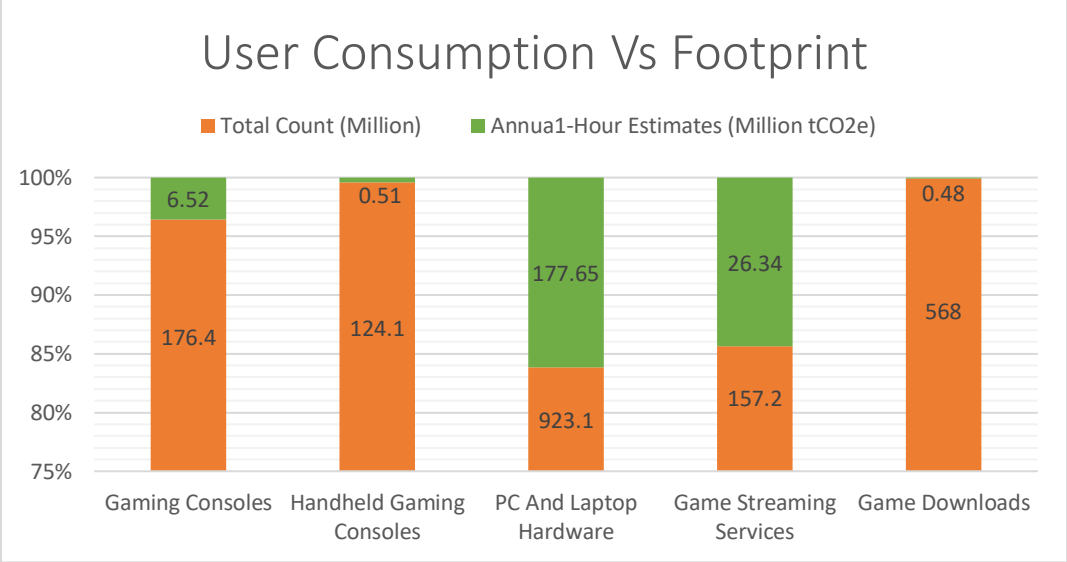
linear growth can be from null (by 2019) to 9% at 124 million units (by 2022) with emissions as low as 0.5 million tonnes per annum.

5.2 Results And Findings

Table 8: Compound counts and carbon signatures of categories covered

	Gaming Consoles	Handheld Gaming Consoles	PC And Laptop Hardware	Game Streaming Services	Game Downloads
Total Count (by 2022)	176,400,000 (~ 176 million)	124,180,000 (~ 124 million)	923,100,000 (~ 923 million)	157,235,000 (~ 157 million)	568,078,079 (~ 568 million)
Combined 1-Hour Estimates (tCO_2e)	6,522,725 (~ 6.5 million)	511,336 (~ 0.5 million)	177,657,731 (~ 177 million)	26,347,967 (~26 million)	480,752 (~ 0.48 million)
Extended Estimates Under 20-Hour Weekly Sessions (tCO_2e)	18,589,766 (~ 18.6 million)	1,457,307 (~ 1.5 million)	506,324,533 (~ 506.3 million)	75,091,705 (~ 75.1 million)	1,370,143 (~ 1.4 million)
S3 Estimates from Marsden et al. (tCO_2e)	69.9 million	-	252.7 million	894.4 million	753.8 million

Figure 1: Retrospective annual carbon emissions compared to consumption of services and hardware in 2022



To compare the *analysis* of this study with Marsden et al., *Table 8* introduces the total counts of covered technologies by 2022, the environmental cost associated with running each category for 1 hour per day for a year, and the comparative

estimates from Marsden et al. Further below *Figure 1* puts a visual representation to the ratio of carbon footprint against the actual density of each technology up till 2022. This study discusses in *Section 5.1* that *Scenario 3* (hereon referred to as 'S3') argues that it presents the ideal trend bridging 2019 with 2030 and also might allow the introduction of *Handheld Gaming Consoles* into the mix (even though this aspect is not discussed in the former study). This is with the intention of studying the large influence of handheld gaming consoles on the global ICT footprint and the variations of these commercially released.

Another interesting factor of the *S3 versus 2022* picture is how the footprint for *PC And Laptop Hardware* surpasses the 2030 estimate for *PC* as seen in *Table 8*. This is under the pretense that the current study considers the highest possible commercially available PC PSU and notebooks and calculates the category footprint based on their yearly values in 2020-2022. There is a second anomaly where Game Downloads' estimates make up ~0.19% of the footprint Marsden et al proposed for 2020-2030. This can be due to the study considering *Football Manager 2023* released in the third quarter of 2022 (the latest iteration in the franchise) along with its under 0.1 million user base as a metric.

Despite the large adoption numbers of Handheld Gaming Consoles and the popularity of Game Downloads (as exhibited by *Table 8*) when compared to other technologies, they take up a considerably minor slice of the annual ICT footprint in retrospect to PC And Laptop Hardware and Game Streaming Services. The former has a carbon footprint that is less than 1% of their consumption numbers whereas the latter hover around 15% of carbon footprints when compared to their respective consumption numbers (according to *Figure 1*). This can be discussed to Handheld Game Consoles already limited to running mobile hardware and software hinting that their performance is capped to their respective platforms. This should have been true for Gaming Consoles too, but their respective platforms operate at much higher performance levels and see a 4% footprint of actual consumption.

While Game Downloads do not possess much impact all by themselves, they should be taken into consideration with Gaming Consoles, Handheld Gaming Consoles (due to their ability to download game titles) and PC And Laptop Hardware. This is within reason that these platforms, unlike Game Streaming Services, are an additional cost towards that medium of entertainment throughout the setup and operational stages. Despite that Handheld Gaming Consoles are roughly 9% of the total gaming ICT consumption and, even when factored in with Game Downloads, have the least and most efficient footprint.

The overview of the findings in this study can be summarized in relay with *Figure 1*:

- The most carbon-intensive gaming devices are *PC And Laptop Hardware* with reference to gross 16% of their annual consumption number equaling carbon emissions. This stacks against 6.52% for *Gaming Consoles* and 0.51% for *Handheld Gaming Consoles*. Power consumption for *PC And Laptop Hardware* peaks due to the multitudinal configurations of hardware possible and range of PSUs commercially available whereas configurations in both console categories are capped and standardized.
- The most carbon-intensive method of game data consumption is through *Game Streaming Services* at a gross 14% of annual consumption versus less than 0.5% for *Game Downloads*. While both are network and server intensive, *Game Streaming Services* have been included in this study as exceptionally computation-heavy too.

- Global impacts sprout from both; manufacturers and consumers. While some manufacturing processes have a higher subsequent generational footprint (discussed later), the consumer adoption of technologies and habits also play a role in emissions footprint.

5.3 Delimitations

- The current study considers game streaming services, (some) game titles, video game consoles, handheld consoles, and PC and laptop hardware commercially available in 2022.
- While some officially released public documentation is made available from providers and manufacturers about their services and/or products, there is no official documentation available that puts a number on the footprint of manufacture, logistics, distribution, and recycle of these services and/or products.
- Numbers and statistics tabulated in this study have been portrayed as specifically as possible from credible statistics and independent research. However, there are still components that are carried over from approximates based on real-world data, meaning the study figures may be higher than actual (considering worst possible power consumption will be assumed for all calculations).

6 DESIGN SUGGESTIONS

Design and production depend on the industry, practices and continuous technical evolution. While technical documentation for manufacturing and carbon compliance from manufacturers is not available to the public, there are a few areas where the overall impact can be minimized.

Firstly, a previous console generation or hardware milestone should not only mark a performance threshold but also mark a sustainability cap. A newer generation should optimize rather than add to the carbon compliance of the devices of the past. Taking into example that a PlayStation 4 weighs at 2.7kg versus the PlayStation 5 coming at 4.5kg. The same PlayStation 5 peaks at 2.5 times power for double the resolution when compared to the PlayStation 4. With the presence of superior materials, designs and optimizations should be implemented to keep manufacturing capped. Console manufacturers have considered and implemented measures to use recycled and/or biodegradable materials for the packaging of their devices. While this does reduce the footprint of manufacturing new materials, it can be adapted to produce majority of the non-technical parts of the devices themselves, e.g. the shells or structure of consoles.

Secondly, gaming devices should strive to reduce active gameplay signatures without major compromise on quality, a blindsided aspect is standby signature where a device is plugged in but in a low state of power to maintain essential processes. The PlayStation 5 notoriously consumes 208.8 percent at peak of active gameplay but also surpasses the competition with the lowest standby signature of 1.58% of its peak power. The consoles that compete with this signature are docked handheld consoles whereas the PlayStation 4 and Xbox Series X and S operate well over this threshold under standby.

Thirdly, game designers should consider bringing back local multiplayer, regardless of hardware category. In the past, a game console could support up to 4 physical players without any compromise on social experience. It is not mandated that every player should have their own console to enjoy a game title with acquaintances and sharing a console like such will reduce device dependability and strain on manufacturers.

7 REFLECTION AND FUTURE WORK

The approach of the thesis project is revisited and evaluated. Compared to the resources available at the time of publication of Marsden et al's [9] work, the current thesis has had access to not only manufacturer releases but also statistical increments from the past half decade. Both publications still feature estimations and predictions from available scholarly and independent research, making the final figures skew from actual without a centralized estimate. This is expected that LCAs on gaming technologies have to tend to non-standard equipment (apart from gaming consoles) and delivery environments with varying component configurations.

The study defines a mathematical formula that calculates 'peak' signatures based on highest power rated for devices. While the study benefits from multiple resources of period-correct consumption numbers and commercially documented highest power ratings, the study could not determine the lowest power figure required to maintain a smooth gaming experience from commercial and academic sources.

Of the *scenarios* considered from Marsden et al, *Scenario 3 (S3)* was most viable due to its balanced blend of footprints despite some outlying anomalies. *Scenario 1 (S1)* was not deemed suitable as it states zero carbon emissions to 'streaming' technologies. *Scenario 2 (S2)* is not suitable either as it puts heavy emphasis on 'streaming' to contribute to the global footprint, coming at a dedicated 2797.7 million coupled with compound 40.7 million and 104.3 million operational costs for gaming consoles and PC hardware respectively for 2020-2030 estimates. Both, *S1* and *S2*, are at extremes that deviate from the estimates proposed by this study.

What could have benefited this study immensely is official figures from manufacturers with regards to carbon emissions resultant of their manufacturing process. Manufacturers did supply technical and market figures (only Nintendo provided yearly sales counts) of their products but much of this is investigated by external sources with estimates. This skews the concluding data further from an intended actual figure making LCAs slightly inconsistent.

Improvements can be suggested in two key areas: either improving the manufacturing and delivery or optimizing hardware execution or both! This can be split into further proposed works such as:

- LCA on adoption of handheld consoles through 2020-2030 and its impacts as technology and user bases evolve with more research into this domain.
- Case study on development or incorporation of more efficient SoCs for consoles with TDPs decreasing and more efficient systems being integrated into processing units.
- AI-upscaling to complement gameplay experience at a fraction of the footprint leading to less strain on embedded hardware to deliver an equally immersive gaming experience.

7.1 Ethical Considerations

The sources, manufacturer documents, sales data, and technical information featured in this study have been obtained from public sources especially those concerning design and performance of vendor-specific details and hardware. All sources have been referenced and attributed to where duly needed.

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APPENDICES

TABLES

Table 1: Technical sources used to compile this study

Publisher	Data Sources	Motivation
Cybenetics.com	[50]	PC PSU operational power draw.
Nintendo Switch Technical Specs	[25][32]	Official sales and technical insights from 2022.
Microsoft Hardware & Networking	[18]	Official Xbox consumption and standby figures with added steps to minimize standby footprint.
Notebookcheck.net	[49][51][52]	Highest power draws on commercially available laptops.
	[20][21][24][27][77]	Sales figures for gaming consoles (PlayStation and Xbox).
Statistica	[27]	Users registered with PlayStation Network.
	[36][81]	PC hardware sold and estimated user counts.
Sony Legal	[17]	Official PlayStation power signatures.

Table 2: Carbon and power signatures of gaming consoles commercially available in 2022

Console	Peak Avg. Power Consumption During Active Gaming (Watts)	Peak Power Consumption During Standby w/ Services & Ports Running (Watts)	Cumulative Number of Units Sold Since Release Till 2022	Estimated Annual Carbon Footprint With Daily 1-Hour Gameplay ($kgCO_2e$)
PlayStation 4 Slim	84.1[17]	5.8[17]	117 million (variants combined)[20]	3,170,855,132.64
PlayStation 5	208.8[17]	3.3[17]	38.4 million[21]	2,583,784,341.5
Xbox Series S	74[18]	10[18]	10.5 million[23][24]	250,389,182.4
Xbox Series X	153[18]	13[18]	10.5 million[23][24]	517,696,552.8

Table 3: Carbon and power signatures of handheld gaming consoles commercially available in 2022

Handheld Gaming Console	Peak Avg. Power Consumption During Active Gaming (Watts)	Peak Power Consumption During Standby w/ Services & Ports Running (Watts)	Cumulative Number of Units Sold Since Release Till 2022	Estimated Annual Carbon Footprint With Daily 1-Hour Gameplay ($kgCO_2e$)
Nintendo Switch (docked)	17[16]	8[16]	88,670,000[32]	364,318,677
Nintendo Switch Rev. 2019 (docked)	8.5[22]	3.8[22]		
Nintendo Switch Lite (charging)	13.5[16]	0.5[16]	20,400,000[32]	88,747,980
Nintendo Switch OLED (docked)	8[22]	2.9[22]	13,490,000[32]	34,777,349
Valve Steam Deck (charging)	15[16]	0.5[16]	1,620,000[26]	23,492,112.48

Table 4: Possible data sets to calculate PC gaming footprint for the years 2020 - 2022

Year	Estimated Number of PC Gamers	Total Count of GPUs (AiBs) sold	Total Count of PCs Sold	Device Split	Peak Power Consumption During Active Gaming Per Device (Watts)	Estimated Annual Carbon Footprint With Daily 1-Hour Gameplay (kgCO2e)
2020	1746 million[36]	42 million[37]	297 million[35]	Notebooks: 235.1 million[35]	330[52]	25,001,214,850
				Workstations: 61.9 million[35]	1650[50]	32,913,126,312
2021	1775 million[36]	101 million[38]	341 million[34]	Notebooks: 275 million[34]	330[51]	29,244,296,400
				Workstations: 66 million[34]	1650[50]	35,093,155,680
2022	1799 million[36]	64.2 million[39]	285.1 million[33]	Notebooks: 223.8 million[33]	330[48][49]	23,799,540,125
				Workstations: 61.3 million[33]	1600[50]	31,606,397,696

Table 5: Carbon and power signatures of game streaming services commercially available in 2022

Game Streaming Service	Estimated Power Consumption Per User (Watts)	Recommended Network Bandwidth	Cumulative Registered Accounts Since Release Till 2019	Cumulative Registered Accounts Since Release Till 2022	Estimated Annual Carbon Footprint With Daily 1-Hour Gameplay (kgCO2e)
Google Stadia	520	10 Mbps (720p) – 35 Mbps (4K)[84]	750,000[28]	235,000[28]	39,379,096.64
Nvidia GeForce Now	520	15 Mbps (720p) – 45 Mbps (4K)[85]	~1 million[29	20 million[29]	3,351,412,480
Xbox Cloud Gaming	520	10 Mbps (720p) – 20 Mbps (1080p)[86]	~10 million (launched September 15, 2020)[29]	25 million[29]	4,189,265,600
PlayStation Now	520	7 Mbps (720p) – 15 Mbps (1080p)[87]	38.8 million[27]	112 million[27]	18,767,909,888

Table 6: Associated footprint of transferring 1GB data from data center to end-user device

	Estimate 1	Estimate 2	Estimate 3	Estimate 4
Energy Footprint (kWh/GB)	0.194 [56][57]	0.23[58]	0.08[59]	0.06[60]
Mean: 0.141 kWh/GB				

Table 7: Associated footprint of initial game setup and gameplay for 1 hour

Game Title	Size Of Install Package	Network Usage Rate Per Hour (MBs)	Number of Registered Users in 2022	Estimated (Max) Carbon Footprint with daily 1-hour gameplay per year (kgCO2e)	Estimated Annual Carbon Footprint With Daily 1-Hour Gameplay (kgCO2e)
Clash of Clans	Mobile: 298MB PC: 10GB	12-20[61]	38 million[62]	33,723	17,266,219
Football Manager 2023	Mobile: 864MB PC: 7GB	15-40[88]	78,079[82]	983	24,834
Fortnite	Console: 18GB Mobile: 480MB PC: 16GB	45-100[63]	500 million[64]	2,218,624	408,936,773
PlayerUnknown's Battlegrounds (PUBG)	Console: 25GB Mobile: 785MB (SD), 1.02GB (HD) PC: 40GB	15-50[89]	30 million[83]	1,416,143	54,524,903

Table 8: Compound counts and carbon signatures of categories covered

	Gaming Consoles	Handheld Gaming Consoles	PC And Laptop Hardware	Game Streaming Services	Game Downloads
Total Count (by 2022)	176,400,000 (~ 176 million)	124,180,000 (~ 124 million)	923,100,000 (~ 923 million)	157,235,000 (~ 157 million)	568,078,079 (~ 568 million)
Combined 1-Hour Estimates (tCO_2e)	6,522,725 (~ 6.5 million)	511,336 (~ 0.5 million)	177,657,731 (~ 177 million)	26,347,967 (~26 million)	480,752 (~ 0.48 million)
Extended Estimates Under 20-Hour Weekly Sessions (tCO_2e)	18,589,766 (~ 18.6 million)	1,457,307 (~ 1.5 million)	506,324,533 (~ 506.3 million)	75,091,705 (~ 75.1 million)	1,370,143 (~ 1.4 million)
S3 Estimates from Marsden et al. (tCO_2e)	69.9 million	-	252.7 million	894.4 million	753.8 million

FIGURES
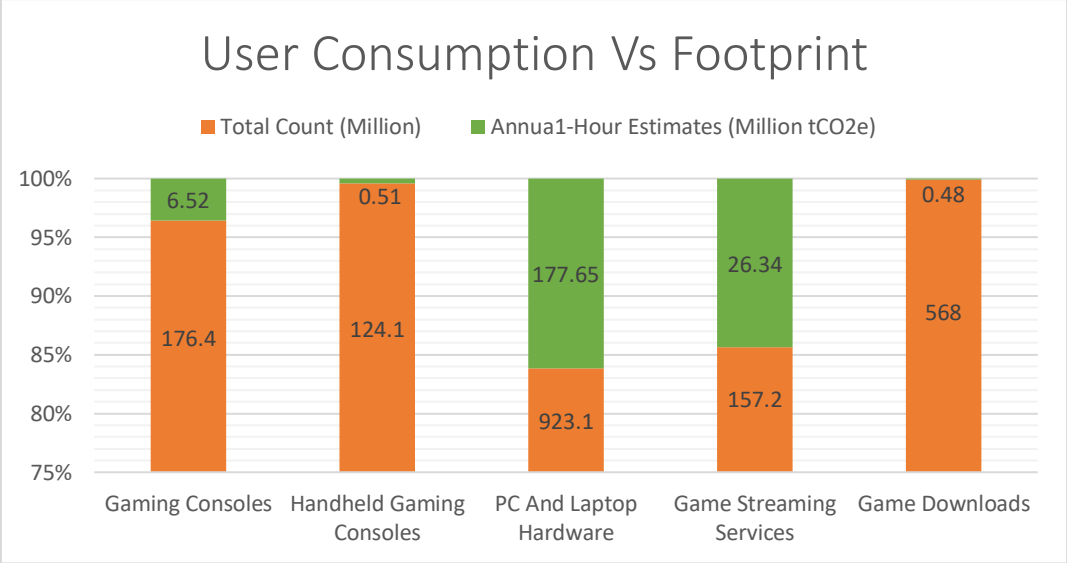
Figure 1: Retrospective annual carbon emissions compared to consumption of services and hardware in 2022