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A Plug-Loads Game Changer: Computer Gaming Energy Efficiency without Performance Compromise

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FINAL PROJECT REPORT

A Plug-Loads Game Changer: Computer Gaming Energy Efficiency without Performance Compromise

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PREFACE

The California Energy Commission's Energy Research and Development Division supports energy research and development programs to spur innovation in energy efficiency, renewable energy and advanced clean generation, energy-related environmental protection, energy transmission and distribution, and transportation.

In 2012, the Electric Program Investment Charge (EPIC) was established by the California Public Utilities Commission to fund public investments in research to create and advance new energy solution, foster regional innovation and bring ideas from the lab to the marketplace. The California Energy Commission and the state's three largest investor-owned utilities – Pacific Gas and Electric Company, San Diego Gas & Electric Company and Southern California Edison Company – were selected to administer the EPIC funds and advance novel technologies, tools, and strategies that provide benefits to their electric ratepayers.

The Energy Commission is committed to ensuring public participation in its research and development programs that promote greater reliability, lower costs, and increase safety for the California electric ratepayer and include:

- Providing societal benefits.

- Reducing greenhouse gas emission in the electricity sector at the lowest possible cost.

- Supporting California's loading order to meet energy needs first with energy efficiency and demand response, next with renewable energy (distributed generation and utility scale), and finally with clean, conventional electricity supply.

- Supporting low-emission vehicles and transportation.

- Providing economic development.

- Using ratepayer funds efficiently.

A Plug-Loads Game Changer: Computer Gaming System Energy Efficiency without Performance Compromise is the final report for the project by the same name (Contract Number EPC-15-023) conducted by the Lawrence Berkeley National Laboratory. The information from this project contributes to the Energy Research and Development Division's EPIC Program.

For more information about the Energy Research and Development Division, please visit the Energy Commission's website at www.energy.ca.gov/research/ or contact the Energy Commission at 916-327-1551.

ABSTRACT

Two-thirds of Americans play computer games. Although among the most complex and energy-intensive plug loads, gaming has been largely overlooked in energy research and development and policy. Systems used for computer gaming in California consumed 4.1 terawatt-hours/year in 2016 or $700 million in energy bills, with emissions of 1.5 million tons carbon dioxide-equivalent allocated 66 percent to consoles, 31 percent to desktop personal computers, 3 percent to laptops, and less than 1 percent to emerging media streaming devices. Key findings include:

- Aggregate energy demand places gaming among the top plug loads in California, with gaming representing one-fifth of the state's total miscellaneous residential energy use.

- Market structure changes could substantially affect statewide energy use; energy demand could rise by 114 percent by 2021 under intensified desktop gaming, or fall by 24 percent given a major shift towards consoles coupled with energy efficiency gains.

- Unit energy consumption is remarkably varied across gaming platform types: across 26 systems tested, client-side electricity use ranged from 5 to more than 1,200 kWh per year, reflecting equipment choice and usage patterns.

- Some emerging technologies and activities are driving energy demand higher, including processor overclocking, cloud-based gaming, higher-resolution connected displays, and virtual reality gaming.

- User behavior influences gaming energy use more than technology choice; duty cycle and game choice are particularly strong drivers of demand.

- Energy efficiency opportunities are substantial, about 50 percent on a per-system basis for personal computers and 40 percent for consoles if past rates of improvement continue.

While simultaneously quantifying efficiency and gaming performance is problematic, evidence suggests that efficiency can be improved while maintaining or improving user experience. Familiar energy policy strategies can help manage gaming energy demand, although mandatory system-level standards are not promising (component-level measures may be).

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Introduction

California has a long history of commitment to a wide variety of energy mandates, policies, programs, and actions to make new and existing buildings more energy efficient. Increased energy efficiency benefits the state's citizens by reducing energy use and costs, lowering greenhouse gas emissions, and avoiding the need for new power plants to meet California's energy demand.

Plug loads – items plugged into electrical outlets by the user – are one of the fastest growing sources of energy demand in residential and commercial buildings. Depending on how plug loads are defined, they can represent almost a third of household energy use in California today, making them a key element in the state's actions to increase building energy efficiency.

A relatively new contributor to plug loads is computer gaming, defined in this report as gaming on computers, video game consoles, or media streaming devices. While Pong and other simple games in the 1970s ran on machines drawing about 10 watts of electricity, today's high-performance gaming computers are among the most energy-intensive residential plug loads in use and can draw many hundreds of watts (Figure ES-1)

Figure ES-1: Evolution of Gaming Equipment, User Experience, and Power Requirements

Source: Lawrence Berkeley National Laboratory

California is arguably the epicenter of computer gaming, with deep roots in gaming technology, software innovations that enable the development of increasingly powerful games, and networks that carry vast amounts of data used for cloud-based games. The state is on the cutting edge as the home of leading component manufacturers in central processing units (Intel and AMD), graphics processing units (NVIDIA and AMD), power supplies (Corsair), virtual reality

headsets (Oculus/Facebook), and gaming personal computer assemblers and system integrators (Digital Storm). The two top game development studios (Activision Blizzard and Electronic Arts) are also located in California. Californians are particularly avid gamers, and have somewhat higher rates of gaming system ownership than most other parts of the country.

The rise in gaming energy use drives demand for electricity throughout the state, which in turn boosts consumer energy bills as well as the indirect costs of energy embodied in local air quality and climate change impacts. While the efficiency of gaming components is improving, overall energy use remains constant or increases as the result of growing numbers of gamers, time spent in gameplay, and demand for an increasingly (and energy intensive) vivid and immersive user experience. However, despite its significant energy use and the potential for energy efficiency improvements, gaming has been almost entirely overlooked in energy research and development, policy, and planning.

The full extent of energy use by computer gaming has been largely a mystery, reinforced by its being statistically rolled in with undefined "other" uses of energy. Private industry has made strides in raising energy efficiency for particular products, but has not provided a comprehensive view of the scale of energy demand from gaming products or how it might evolve in the future. In addition, the existing literature on gaming energy use focuses almost exclusively on game consoles. Only one formal study (now dated) has looked in depth at gaming on desktop computers, and no work had been published regarding gaming on laptops or with emerging television-linked media-streaming devices such as Apple TV or Android TV, which are also used for gaming. Neither has the energy used in associated networks and data centers for cloud-based gaming been quantified. There is also no analysis of the energy use of many specific supplementary components, such as virtual reality equipment, high-end displays, and external graphics processing unit docks. The effect of another key driver on energy use—game choice—has only been examined for one brand of consoles. The duty cycle (the proportion of time during which a device is operated) unique to gamers has also not been well-characterized, and the open literature does not describe the sensitivity of gaming energy use to user behavior (for example, hours spent gaming).

Additional data is needed to enable the California Energy Commission and others to better understand gaming as a driver of energy demand and to improve energy efficiency in computer gaming as part of well-established broader strategies for managing that demand.

Project Purpose

This project meets the need for additional data by characterizing the California gaming marketplace (technology and user behavior), defining baseline energy use and savings opportunities in light of emerging technologies, and identifying policy strategies and recommended actions for energy planners.

Using existing data and new measurements and drawing together the lines of data, the researchers developed a comprehensive set of energy use estimates at the individual system level and in the aggregate for California. These estimates provide insight into the drivers of demand and will be useful for industry, policymakers, utilities, and consumers.

By filling the voids in the existing knowledge base, this project provides a novel energy-relevant assessment for California. A key overarching premise is to identify energy efficiency opportunities that further the state's energy and environment goals without compromising the gaming experience in ways that would impede adoption of improved equipment and practices.

Project Approach

The researchers' focus in this project was on a complex energy-using activity rather than a single energy-using device. Gaming systems are multi-function devices that perform gaming as well as other tasks for their owners. The researchers considered all grid-connected devices used for gaming and their displays, but did not address gaming on primarily mobile devices (Figure ES-2). The project team also considered energy use within data centers hosting gaming workload (cloud-based gaming) together with the networks connecting them to gamers.

Figure ES-2: Boundary Conditions for Technology Included in This Study
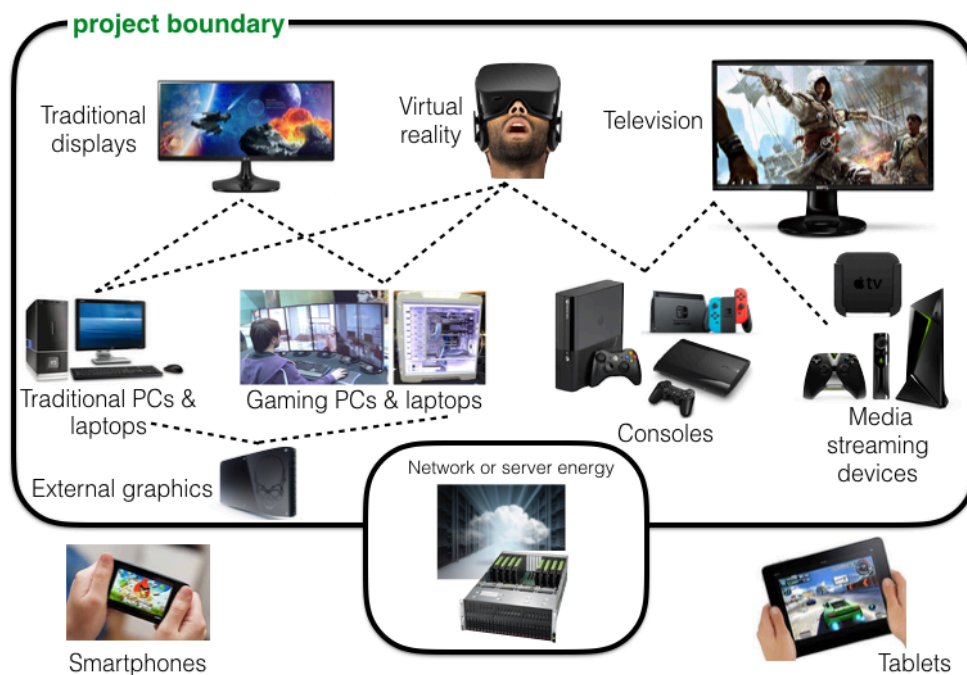
Source: Lawrence Berkeley National Laboratory

The researchers drew from Lawrence Berkeley National Laboratory staff expertise across several groups, departments, divisions, and major research areas. The project team also retained leading gaming market researchers (Jon Peddie Research), and assembled a Technical Advisory Committee representing industry (AMD, NVIDIA, the Entertainment Software Association), national policymakers (United States Environmental Protection Agency/ENERGY STAR®), and other stakeholders.

The researchers consulted with industry actors such as game developers and consumer product evaluators (PC Perspective, Hardware Canucks, Tom's Hardware, eXtreme Outer Vision, and Bob

King), other researchers and institutes (Fraunhofer USA, Stanford University, Xergy), and non-governmental organizations (Natural Resources Defense Council). During project start-up the team held a workshop with leaders in the console industry (Microsoft, Nintendo, and Sony) to introduce the research plan and solicit feedback. Researchers consulted the Technical Advisory Committee, offered review drafts of key documents, and considered feedback in preparing work products.

Early in the project, the researchers developed a detailed description of the California gaming marketplace including hardware, software, types of users, and other drivers of the duty cycle. The researchers developed test procedures and established a Green Gaming Systems Test Lab at LBNL for analyzing the representative gaming devices and associated settings and software variables, and created a data-acquisition system to aggregate and analyze the large volumes of information collected.

The research team evaluated 26 gaming systems (10 personal computers, 5 laptops, 9 consoles, and 2 media streaming devices) representing the range of systems found in the installed base and on the market circa 2016 (Figure ES-3). The research incorporated componentry representing a cross-section of major manufacturers. Bench testing included various combinations of systems, and 37 popular games.

Figure ES-3: Baseline Systems: Desktops, Laptops, Consoles, and Media Streaming Devices

System ID codes (C1, L1, and so on) can be cross-referenced to more technical information in Appendix A.

Source: Lawrence Berkeley National Laboratory

The researchers extensively reviewed emerging technologies that may shape energy demand in the future, as well as commercially available technologies and techniques for potentially improving energy efficiency, including high-resolution 2D displays, virtual reality headsets, external graphics card "docks" fitted to laptops, and a range of software. Promising strategies currently available in the market were implemented on selected base systems and retested to determine savings. The team did not estimate the potential of future technologies yet to be commercialized.

The key barriers encountered during the project included the lack of an existing testing protocol and the enormous variety of equipment, software, and user types that comprise the market. Drawing on the team's expertise, researchers captured a "snapshot in time" to characterize the market landscape. While the tests conducted represent only a sampling of the large combination of variables that influence gaming energy use, they do bracket the many factors that shape energy use in this complex and rapidly changing marketplace.

Project Results

At a high level, the researchers found an enormous range in energy use among various platforms driven as much by technology "family" (consoles versus desktops) as by gaming behavior (hours in gameplay). While there are far fewer desktop and laptop gaming systems than consoles in the installed base, their higher per-unit consumption makes them a significant portion of overall statewide energy consumption, particularly under certain future market scenarios. These variations are amplified by the role played by game choice.

Researchers were surprised by some project findings, including the dominance of consoles in overall energy use, the impact of user behavior on outcomes, the large energy requirements of cloud-based gaming, the significant energy efficiency gains made through the industry's own initiative (many through software rather than hardware), and the problematic obstacles to applying standards as an energy savings policy strategy.

Other notable findings from the research include:

- **Gaming is among the top plug loads in California**. In 2016, California computer gaming used 4.1 terawatt-hours per year of electricity, representing $700 million of annual energy costs and 1.5 million tons carbon dioxide-equivalent emissions, or one-fifth of all residential "miscellaneous" electricity use. Of the total energy consumed in 2016 by computer gaming equipment, 66 percent was for consoles, 31 percent for desktop computers, 3 percent for laptops, and less than 1 percent for emerging media streaming devices. Electricity use equated to 5 percent of overall statewide residential consumption among the investor-owned utilities, or the equivalent of about 10 million new refrigerators that use 400 kilowatt-hours per year. Gaming mode is responsible for 41 percent of statewide client-side energy use for consoles, 32 percent for desktop PCs, 29 percent for laptops, and 7 percent for media streaming devices based on time used.

- **Changes in market structure can have huge impacts on statewide energy use.** Despite the increase in gaming devices, customer energy demand was roughly constant between 2011 and 2016 as customers shifted from desktops to less energy-intensive consoles. Alternate scenarios of market share and gamer activity projected to 2021 suggest baseline energy consumption could increase 114 percent or decrease by 24 percent compared to 2016 demand based on certain drivers and consumer choices. In future scenarios, as much as 27 percent of total gaming energy used shifts to the Internet and data centers.

- **Energy consumption per unit varies widely across gaming platform types and by game choice.** Across individual systems and game titles, average power during

gameplay varied from 34 watts to 410 watts for desktop computers, 21 watts to 212 watts for laptops, and 11 watts to 158 watts for consoles. The two media streaming devices used similar amounts of power, under 2016 conditions

- Non-gaming power requirements for PCs and consoles are within the same order of magnitude, with a good degree of overlap although consoles use less power in this mode on average than desktop PCs, but more in most cases than laptop PCs.

- Energy use while gaming on a *given gaming platform* varies considerably depending on game choice: by up to 3.5-fold among various games on PCs and by up to 1.6-fold on consoles (with no apparent correlation between game genre and energy use).

- Energy use while gaming for a *given game* varies by 8-fold and 21-fold of the two games playable on the widest range of platforms in the sample.

- Unexpected spikes in PC power during idle mode[1] corresponded to an average of 9 percent of total energy use above that of the expected idle state across all systems (up to 55 percent on one system). This suggests a need for more realistic test procedures. The research team did not observe similar patterns for consoles.

- Energy used by the GPU ranges from 45 to 77 percent of the total in gaming mode, and is surprisingly significant in idle mode as well (12 to 33 percent of the total).

Some emerging technologies and activities are driving energy demand higher.

- Cloud-based gaming (with graphics processing in data centers) has more energy "overhead" than local gaming, adding about 300 watts atop local power requirements for console-gaming and 520 watts for PC and media-streaming-device gaming.

- Cloud gaming adds approximately 40 to 60 percent to the otherwise total local annual electricity use for desktops, 120 to 300 percent for laptops, 30 to 200 percent for consoles, and 130 to 260 percent for media streaming devices.

- Virtual reality can be a very energy-intensive emerging technology, with 38 percent higher system energy use in some cases and 15 percent less in others. When left on continuously, the peripheral virtual reality sensors appreciably contribute to overall energy use.

- 4k displays result in significant increases in energy (25 to 64 percent) used by PCs while gaming, with reductions in frame rate, resulting in reduced energy efficiency. Consoles have also shown to exhibit significant power increases across the duty cycle.

User behavior has a stronger influence on gaming energy use than technology choice.

- Duty cycle and game choice are strong drivers of demand.
- While the lightest gamers considered in the study game only about 10 minutes per day, others game 7 hours per day.

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[1] All idle measurements made in using the "short-idle" test procedure.

Energy efficiency opportunities are substantial.

- Packages of commercially available efficiency improvements (hardware, BIOS, and software) offer a ~50 percent energy savings in PCs (in both gaming and non-gaming modes of operation). For example, improved graphics cards reduce the amount of power required to render games and improved power management reduces loads when not gaming). If maintained, the observed historic rate of improvement in consoles would reduce per-system consumption by about 40 percent between 2016 and 2021.

- Strategies for improving virtual reality efficiency can lower energy use by ~30 percent.

- Power management is quite poor on most PC gaming systems, including idle mode, and the componentry is not yet supportive of energy reporting as a means of user feedback.

- While simultaneously evaluating efficiency and performance is a highly problematic undertaking, the evidence suggests that energy efficiency can be improved without apparent reduction in user experience, although user experience is highly subjective and resistant to quantification.

- User behavior (for example hours in gameplay, overclocking, game choice, in-game settings) has a stronger influence on gaming energy use than technology choice.

- Frame rates don't correlate with power; high performance doesn't require high power.

- Significant non-energy benefits accrue from many energy efficiency strategies.

The gaming marketplace is in constant flux, including powerful technology developments shaping the installed base of equipment and the preferences and behaviors of gamers in a state of perpetual change. These factors directly influence the energy intensity of individual systems as well as in the aggregate.

Between 2011 and 2016, a shift to a less energy-intensive mix of gaming products in the marketplace and improvements in display efficiency offset the growth in electricity demand that would have occurred due to increasing numbers of systems in the installed base. However, actual gaming electricity demand fell considerably as a result of significant reductions in the electricity intensity of internet infrastructure which lowered energy use for video streaming.

Energy savings opportunities can be captured through a combination of initiative from within the industry, consumer choices, and the energy policy and R&D community.

Technology/Knowledge Transfer/Market Adoption

Technology transfer was integral to the project approach. Key audiences included utilities, researchers, policymakers, gaming industry representatives, and consumers. Defined in terms of current energy use by 15 million gaming systems in California, two thirds of the current market is comprised by console users with the remaining being PC users.

The approaches included formal publications, newsletters, websites, convening stakeholders, engagement in industry activities, and media outreach (Mills 2018). All project activities have been described on one public-facing website for technical audiences (http://greengaming.lbl.gov) and another for consumers (http://greeningthebeast.org).

LBNL's work in this area received considerable mainstream and trade media coverage prior to and during the EPIC project period.[2] Coverage included *Forbes, Grist, Newsweek, R&D Magazine, Science Daily, Slate,* and *Wired*. LBNL produced news releases at the project outset and conclusion, and a 15-minute interview was broadcast on BBC radio near project completion. Results were disseminated through the TAC and one-on-one contacts with industry and other stakeholders at trade meetings and other venues. One consumer information provider included the research team's analyses in their web-based decision tool aimed at consumers. The Consumer Electronics Association, through reports prepared for them by Fraunhofer USA, expanded their market survey work to incorporate PC gaming.

The technology transfer process was used to disseminate the testing protocol development. As part of this strategy, researchers engaged with energy policy agents such as ENERGYSTAR® for whom standardized energy-efficiency measurement techniques are essential. That said, because most aspects of the user experience and "energy services" provided by gaming systems are not directly measurable, and thus simple quantitative energy-per-performance metrics cannot be articulated beyond frame rates per unit power, which is too crude for standards-setting.

Broad-based uptake of "energy thinking" in the gaming marketplace, and among gamers themselves, is a long-term challenge that cannot be addressed by a single project or report. The team made concerted attempts to convene sessions at two of the industry's annual Game Developers Conferences (GDC) without success. Attempts to collaborate with third-party information providers that help gamers specify and build do-it-yourself systems were also largely unsuccessful. Energy efficiency is not a high priority in the minds of most gamers and there is no unified initiative within the industry (although there are many individual efforts). Early experiences with disseminating energy information directly to gamers were met with a degree of skepticism and disinterest. If gaming energy issues become more widely known and appreciated, the marketplace should grow more receptive to the information.

The researchers explored whether the providers of the underlying software used to develop games would be receptive to various forms of collaboration, such as integrating consideration of energy-oriented metrics into the game-design process. Interest in this group is nascent.

Benefits to California

The introduction of a gaming device into a home can significantly increase energy costs. For the most avid gamers, the associated energy bills can amount to hundreds of dollars each year, particularly at a household level where multiple users and systems are in use. At the marginal electricity prices actually paid by households, the high-end tier of desktop PCs cost light gamers about $550 and extreme gamers $1,700/year to operate over the product's life. This is

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[2] http://greengaming.lbl.gov/media.

in some cases more than the initial purchase cost of the gaming system. Best practices can reduce these values by half. Conversely, significant traditional efforts to reduce a home's energy use (for example, improved appliances) can easily be offset or otherwise thwarted by unaddressed computer-gaming energy.

The study identifies many readily available technologies and practices that can be adopted by consumers, and the implications of user choices among gaming platform families as well as discretionary in-game and system-level settings. Many of the results point the way to promising longer-term avenues for future R&D (in partnership with industry) and more accurate approaches to energy demand forecasting.

Computer gaming in California consumed 4.1 TWh/year in 2016 at an energy cost of $700 million, with emissions of 1.5 million tons CO_2-equivalent. These amounts could more than double under a near-term evolution of market structure. Conversely, the energy savings opportunity for the measures considered is on the order of 50 percent for the desktop systems and 40 percent for consoles. Overall savings will also depend heavily on efficiency improvements in displays, networks, data centers, and energy efficient design principals in the development of games themselves, and well as user behavioral choices.

Although many methods of achieving energy savings are accessible in today's marketplace, realizing the energy savings opportunities identified in this report is an enormous challenge, particularly given the complexity of the computer-gaming energy end use. While remarkable technological progress is being made within the gaming industry, the continual rise in consumer expectations regarding user experience tends to offset these gains, particularly for desktop and laptop PCs. The shift of energy to networks and data centers promises to further obscure the energy cost of gaming. Consumer awareness of energy considerations is minimal, and there is often resistance to the subject, based in part on misperceptions that high efficiency and high performance are mutually exclusive. Thus, new efforts to improve awareness and provide decision-support tools to gamers are an essential complement to R&D.

CHAPTER 1:
Why This Report Is Important

Household electric plug loads are loosely defined as the residual segment of energy use that remains aside from core uses such as space conditioning, water heating, cooking, laundry, and lighting. Depending on the definition, miscellaneous plug loads[3] represent almost a third of household energy use in California today, and a far larger proportion of energy use in otherwise highly energy efficient homes.

Computer gaming,[4] a little-discussed plug load, is a major social and technological phenomenon, engaged in by a third of humanity. California is a major global hub for the computer gaming industry. The associated energy use is among the most significant of all plug loads. The issue has been understudied, and it has been passed over in most energy R&D, policy, and planning initiatives.

Computer Gaming: A Largely Overlooked Use of Energy

Energy researchers have long recognized the importance of miscellaneous uses of electricity, often referred to as "plug loads" (Meier *et al.,* 1992). Consumer electronics have emerged as a particularly important type of plug load (Rosen and Meier 2000). Lacking good accounting, energy used by plug loads can remain uncounted for altogether or incorrectly attributed to other end-uses. Quantifying the energy use of plug loads is an elusive challenge, by simple virtue of their number, dynamism in the markets that drive them, and the particularly heavy role of user behavior in determining the associated energy use.

Computer gaming, is perhaps the most extraordinary instance of this challenge, as it comprises a myriad of platforms and use cases, in turn tempered by the consumer's time spent gaming, choice of software, as well as settings within the application during gameplay. Game consoles have received some attention, but desktop and laptop computers used for gaming have only recently come into focus (Mills and Mills 2015). The implications of a new wave of media streaming devices that deliver gaming content based on workloads shifted to networks and data centers have not been quantified at all. The misperception that computer gaming is conducted only at the "fringe" of society has dampened curiosity about their role in energy use. In this study, the researchers estimate that the entire category of computer gaming (all devices, displays, associated network, energy, and so on) represent about a fifth of miscellaneous

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[3] Statewide residential electricity energy use among investor-owned utilities was 77.4 TWh in 2015 – see http://www.energy.ca.gov/contracts/GFO-15-310/12-Attachment-12-Energy-Efficiency-Data_2015-11-10.xlsx.

[4] The researchers adopted the term "computer gaming" to describe gaming on computers, video game consoles, or media streaming devices used for gaming. The terminology is inconsistently used in this industry. In some documents, "computer" gaming refers only to PCs, while "video" gaming refers only to gaming on consoles, but in many cases the terms are used interchangeably. The team adds references to specific platform types where a distinction is being made in the data or discussion. Note that our analysis does not include mobile gaming on predominantly or exclusively battery-powered devices such as tablets and smartphones.

electricity use in California households (Figure 1). The "Computer Gaming" category includes multiple device types including desktop and laptop computers, consoles, and media streaming devices and associated displays, local network equipment, and speakers, as well as associated network and data-center energy. Values shown for Color TV are net of the estimates for their use while operating the gaming devices, and the Miscellaneous total is net of Computer Gaming. Gaming estimate for 2016; other end uses are estimates for 2015. See http://www.energy.ca.gov/contracts/GFO-15-310/12-Attachment-12-Energy-Efficiency-Data_2015-11-10.xlsx.

Figure 1: Computer Gaming Consumes More Electricity in California Than Many Familiar Residential Uses
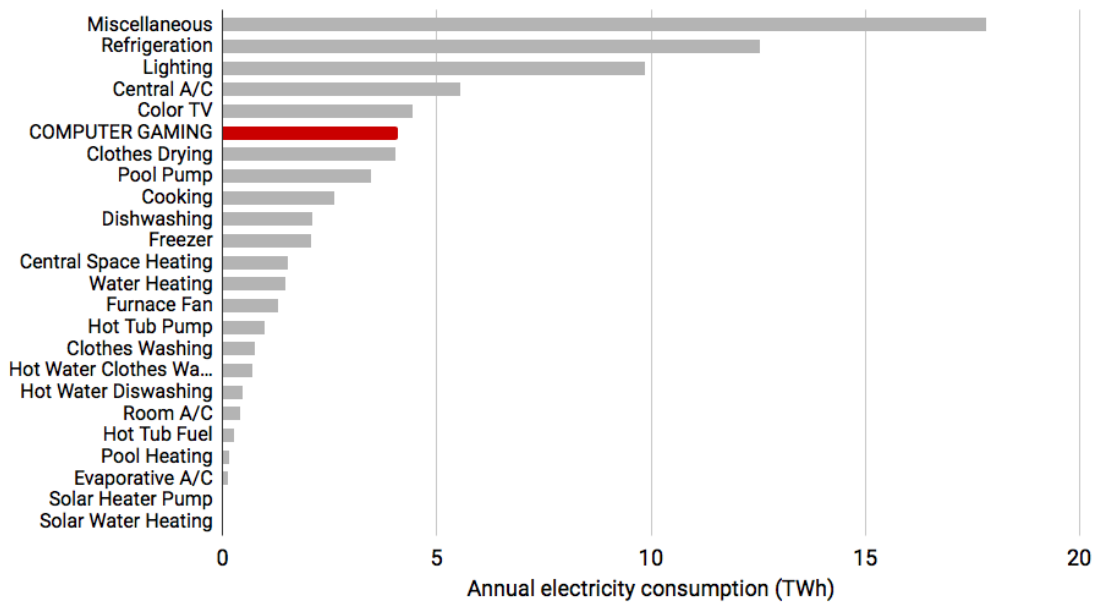
Source: Lawrence Berkeley National Lab

As is the case for plug loads more broadly, little attention has been paid to developing policies and programs to achieve more energy efficient computer gaming. The two exceptions in the United States are the highly successful 80 Plus program for voluntarily labeling power supply unit energy efficiency and the ENERGY STAR® voluntary labeling program for computer displays. Neither of these are particularly targeted at gaming or address the most energy intensive components within video-gaming systems or the systems as a whole, or the enormous vacuum in useful consumer information. Meanwhile, energy planners have largely overlooked this particular plug load in energy forecasting.

The Most Complicated Plug Load

Given that proper characterization of an energy end use requires a coordinated characterization of technology, market shares, and user behavior, computer gaming could prove to be the most complicated plug load. A supreme challenge is that the gaming marketplace is changing faster than data can readily be gathered and policy developed.

This report answers a wide array of critical questions not addressed in the existing public-domain literature. These include quantifying the characteristics and relative energy use of different families of gaming devices (desktops, laptops, consoles, and media-streaming devices), the role of duty cycle, energy use of emerging technologies such as virtual reality headsets, the effect of game choice and in-game settings on energy use, and energy-savings opportunities for modifiable desktop systems through hardware as well as BIOS and software settings. The research team isolated the influences of behavior and technology, shedding light on the roles of each independently and in combination.

A Highly Energy-intensive Plug Load

Per-unit energy use in desktop and laptop gaming equipment has been generally rising, while the installed base has expanded both in absolute terms and towards more energy-intensive, higher-end platforms. While one example of gaming computer performance) has improved in many cases—suggesting improved efficiencies—this can occur even as power requirements rise. Consoles have exhibited fundamentally different behavior, with energy use declining even as user experience is improved. Media streaming devices are among the newer gaming technologies and have comparatively low energy use at the device level, but high energy intensity in their connected networks and data centers. More recently, even ordinary PCs as well as consoles can be used for cloud-based gaming. As described below, gaming systems are among the most energy-intensive miscellaneous plug loads in California homes.

CHAPTER 2:
Energy Dimensions of the Gaming Marketplace

Computer gaming traces its roots to an exhibit created for the World's Fair in 1940.[5] Today, three-quarters of a century later, a third of humanity engages in the pastime (NewZoo 2016), through a myriad of types of electronic devices, including even smart watches.[6] In the United States, 66 percent of people over the age of 13 engaged in gaming in 2018, up from 58 percent just five years earlier (Nielsen 2018). The average gamer is 35 years old, and 41 percent of gamers are women (ESA 2016).

Surveys indicate steadily increasing numbers of gamers, amounts of time spent in gameplay, and consumer demand for progressively more vivid and immersive user experiences seems to have no bounds. Without offsetting efficiency gains, these driving forces stand to push energy demand for gaming far higher.

Researchers gathered and reviewed available energy-relevant information on the computer gaming market, including associated technology trends and gaps in the consumer information environment. The team developed a profile of the California marketplace for the purposes of performing energy analysis at the equipment level as well as the macro level.

The resulting analytical platform is based on best-available data and industry expert assessments. Constituent data include an array of specific gaming systems, operated by four user types across multi-step duty cycles, and running a representative assortment of popular game titles. This market segmentation spans the spectrum of gaming experience, system performance, and power requirements, leveraged to develop a characterization of the installed base of gaming equipment and its use in California.

Market Segmentation and Installed Base

Based on an extensive review of existing market research and on original analyses developed for this project by Jon Peddie Research (Mills *et al.,* 2017) together with subsequent survey data from Urban *et al.* (2017), the researchers developed a profile of the California marketplace for the purposes of performing energy analysis and specified a range of 26 pre-built and custom-built gaming systems that encompasses the range of price, functionality, and user requirements sought in marketplace circa 2016, the base year for the projections to the future. These include PCs, consoles, and media streaming devices. The desktop and laptop computers include those with discrete graphical processor cards (GPUs) purpose-built for gaming as well as "mainstream" systems with integrated graphics used for gaming. The researchers further group gaming computers into Entry-level, Mid-range, and High-end categories, based on price and

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[5] See https://en.wikipedia.org/wiki/Video_game_industry.

[6] See http://time.com/4617407/pokemon-go-apple-watch-release-date-2016/.

computing power. The team did not address popular mobile gaming devices such as smartphones used little if at all when connected to AC power.

The researchers found that there are currently more than 15 million video-gaming devices in use in California (the geographic focus of this study). Each user type is associated with a segment of the installed base for each system type (Figure 2). "Android TV" represented by the Nvidia Shield. The Nintendo Switch not yet introduced as of 2016, but is considered in the forward-looking scenarios presented later in this report. To place the population of computers used for gaming into a broader California context, approximately 15.4 million desktop computers exist in homes in the state (downscaled from national estimates from Urban *et al.,* (2017)), of which 15 percent are used for gaming. Of the 10 million laptops, 8 percent are used for gaming. The decision rule for inclusion in the analysis excludes systems used fewer than one hour per week for gaming, thus eliminating incidental use and out-of-service equipment. While the number of desktop systems in use declined in recent years in response to the increasing popularity of mobile gaming, it is likely to increase by about 10 percent by the year 2021, with the mix of platforms and their applications shifting towards increasingly energy-intensive configurations while time spent gaming is gradually increasing.

Figure 2: Installed Base by User Type for All Platform Types (2016)
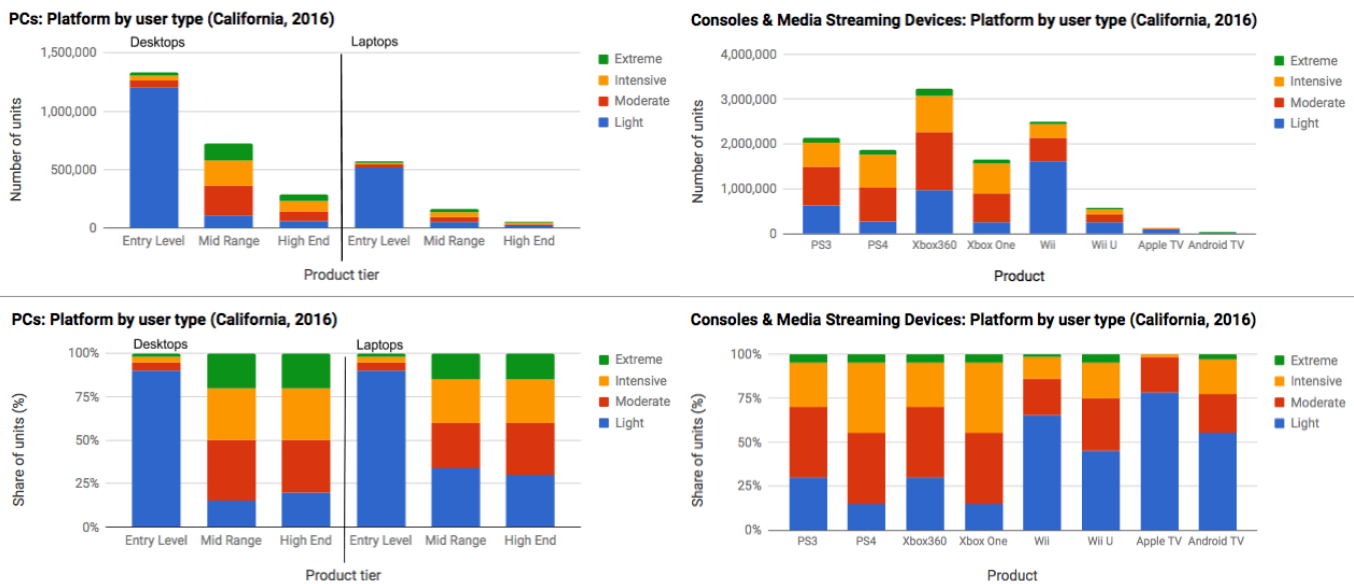
Source: Lawrence Berkeley National Lab

User Behavior and Duty Cycle

User behavior (software choices, settings, and gaming activity preferences) stands to strongly influence gaming energy use. Thus, to properly characterize energy demand, the researchers also developed profiles for the gaming duty cycle, disaggregated across each of the baseline systems and user types (Figure 3). The team divided utilization into a series of modes ranging from "off" to "gaming".

Figure 3: Duty Cycle by User Type: Personal Computers, Consoles, Media Streaming Devices, Displays: 2016
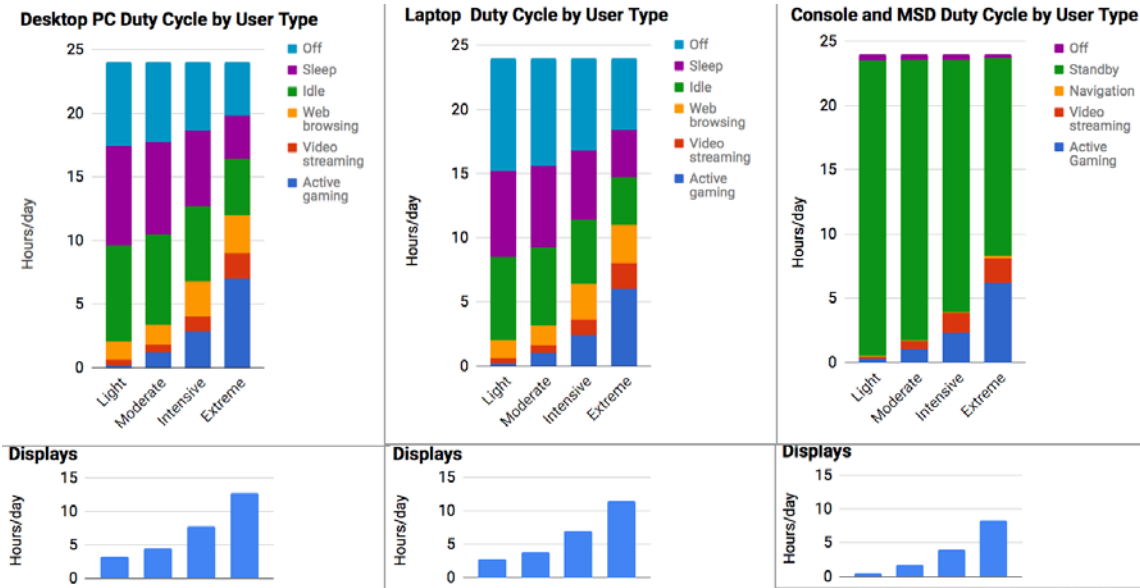
Source: Lawrence Berkeley National Lab

There are four types of users – Light, Moderate, Intensive, and Extreme (reflecting hours per day in gameplay mode) – each with its own duty cycles that include gaming and non-gaming activities performed on the equipment. As seen in Figure 3, Light users dominate among entry-level PCs, while Mid-range and High-end systems are used more heavily for gaming. Consoles and media-streaming devices have heavier gaming-use regimes than media streaming devices. As displays are integral to the gaming activity, the researchers incorporated them in the analysis as well.

The most impactful part of the duty cycle is time in gameplay. Across the literature, there were found estimates ranging from just a few minutes daily to more than seven hours, with most reports focusing on specific platforms and/or demographics, for example, children or other age groups (Mills *et al.,* 2018). In the characterization of PC user types, time in gameplay ranges from approximately 30 minutes per day for Light users to 7 hours per day for Extreme users of desktops and 6 hours for Extreme uses of laptops. For consoles and media streaming devices, the time in gameplay varies from 15 minutes to about 6 hours per day, respectively. For the intensive gamers, time in sleep/standby/off modes is proportionately lower.

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Online and Cloud-based Gaming

Gaming is rapidly expanding into the Internet, creating far-ranging implications for the extension of associated energy use into computer networks and data center infrastructure.

According to Entertainment Software Association surveys, 51 percent of the most frequent gamers play online games at least once weekly (ESA 2016), for an average of 0.9 hours per day for an average of 0.9 hours per day.[7] As far back as 2012, PC gamers reported spending 34 percent of their total gaming time in online mode (PWC 2012). Nielsen data suggest[8] that the popularity of online gaming is rising, with 21 percent of 7th-generation console hours spent in that mode in 2010, increasing to 28 percent for 8th-generation consoles in 2014. Console players now spend more time playing online games than offline games.

Online gaming is projected become the fastest-growing segment of residential Internet service globally, with the 1.1 billion users worldwide in 2015 growing to 1.4 billion by 2020 (Figure 4) (Cisco 2016a). These values do not include appreciable cloud-based gaming, which is still in a nascent stage of development. Source: Cisco (2014, and other years) VNI Forecast and Methodology reports. Notably, "online gaming" is one of only four segments of "consumer Internet traffic" data that Cisco disaggregates, the others being Internet video, web/email/data, and file sharing, and is the fastest-growing at 47 percent/year. Gaming devices are also used for other Internet-based activities such as web-browsing and video streaming, which of course also create Internet traffic.

Figure 4: Rapidly Escalating Global Online Gaming Throughput
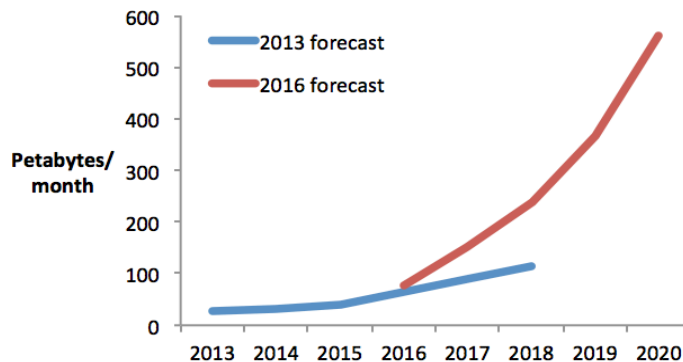
Source: Lawrence Berkeley National Lab

The original form of online gameplay retains heavy workloads on the local client, but exchanges meta-data among one or more gamers. Another use of the Internet in conjunction with gaming is where games are downloaded prior to play. An emerging trend with more significant energy

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[7] Gameplay time via personal communication, Michael Warnecke, ESA, February 24, 2017.

[8] See http://www.nielsen.com/us/en/insights/news/2016/gaming-gone-global-keeping-tabs-on-worldwide-trends.html.

ramifications is the actual hosting of gaming servers (including graphics processing) in data centers, referred to here as "cloud-based gaming". No analysis has previously been published on the relative allocation of energy use between the local gaming client and the network of supporting core and edge data centers (referred to here as cloud-based gaming). Cisco notes that "if cloud gaming becomes popular, gaming could quickly become one of the largest Internet traffic categories" (Cisco 2016b).

Consumers' Information Environment

While many gamers are highly literate regarding their technology options—some building their systems from scratch—the energy information available to them is incomplete and highly non-standardized.

Most relevant information for PCs is based on rough proxies (Thermal Design Point, or TDP, in thermal watts) of power requirements for individual components within the gaming system, with virtually nothing available to them (other than for displays) on actual power or ultimate energy use (combination of power and duty cycle assumptions). There are no actual power ratings for CPUs, GPUs, or motherboards, which also makes it impossible to right-size the associated power supplies. Of particular importance, the consumer is ill-equipped to assess the systems integration of disparate components and their aggregate power requirements. These systems can be "bottlenecked" in a number of ways and thus in effect oversized such that excessively power-intensive components cannot be fully used.

There are at present no game-specific standardized energy test procedures or ratings. Thus, consumers cannot know with confidence how their choices among different titles or genres will affect their energy use and costs. Official test procedures for computers tend to ignore active mode, which is problematic in the case of gaming since much of gaming system energy use occurs in during gameplay.

Technically oriented gamers can find many product reviews in the trade literature, some of which compare power measurements together with crude measures of performance. Unfortunately, scores of disparate games or simulated frame-rate benchmarks are used and there are no standardized measurement protocols. The net effect is that gamers cannot readily compare among these various information sources, and it remains difficult or impossible to find energy data on particular systems they may be interested in purchasing.

CHAPTER 3:
The Challenges of Measuring and Benchmarking Gaming Energy Use

Dozens of factors must be considered when seeking to measure gaming system energy use and normalize it in a fashion that reflects the widely varying possible user experiences. Among these are the system, its connected display (2D or virtual reality), the game or benchmark run during the test, and the metric(s) of perception deemed representative of ultimate user experience and enjoyment of their gaming session.

Measurement

The researchers established a Gaming Systems Test Lab at LBNL for the purposes of analyzing specific gaming devices and software variables (Figure 5). The lab allowed researchers to log power use and frame-rate/quality for each gaming system in both gaming and non-gaming modes (2D displays as well as virtual reality). A data acquisition platform was also developed to aggregate and analyze the large volumes of information collected.

Figure 5: Green Gaming Laboratory and Test Equipment
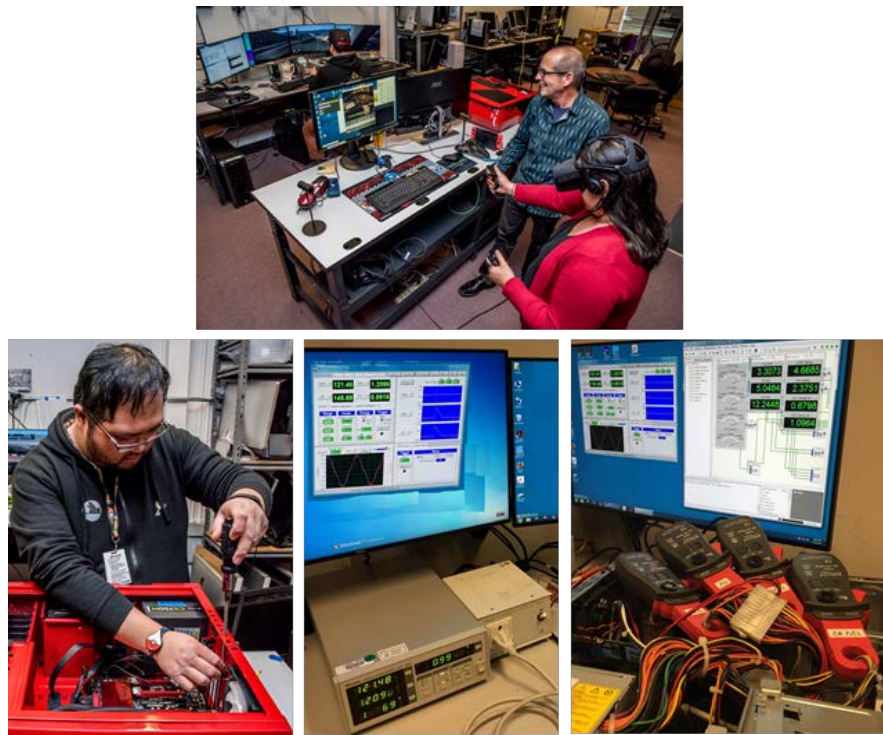
Source: Lawrence Berkeley National Lab

Key measurements made possible in the lab were including system-level high-accuracy power readings at one-second time intervals, power readings for individual components, large-volume video image output storage for later analysis, component temperatures, and the durations of individual frames produced during the gaming session

The research team evaluated 26 gaming systems (10 desktop PCs, 5 laptop PCs, 9 consoles, and 2 media streaming devices) representing the range of performance found on the market (Figure 6, Appendix A).[9] Desktop systems E1, E2, M1, and H2 were pre-built commercially available systems. The researchers custom-built the remaining six PC systems to fill in performance gaps along the spectrum and to represent the not insignificant do-it-yourself portion of the PC consumer market. CPU and GPU components used in the computer systems represent multiple generations of technology in accordance with an installed base that has developed over time.

As noted above, assessing the energy use of a gaming system requires that it be run in an automated fashion using a simulated game (commonly referred to as a frame-rate "benchmark") or by a person using a real game. The team experimented with 11 frame-rate benchmarks and 37 actual games drawn from 8 broad genres, together representing 209 game-system combinations (Bourassa *et al.,* 2018a-b).

All gaming-mode tests were conducted with external high-definition (HD) 1080p Dell 23in 1080p display (desktops, laptops, and consoles). In the case of C7 (Wii) the team used a Samsung 60 1080 TV monitor because the device only has a composite out. Desktop PCs were subsequently modified to achieve energy savings and retested, with complete packages of measures applied representative systems in the Entry, Mid-range, and High-end market segments.

The energy use measurements were made primarily at the system level (PC, console, and so on) because system integration determines ultimate energy use and the focus is on the effect of packages of measures rather than piece-wise analysis. Moreover, a given component's energy use will vary depending on which other components it is associated with. For example, the energy use of a given CPU will be influenced by the motherboard on which it is mounted and which GPU it is driving, and, in turn, the energy use of that GPU will vary depending on which display it is running. The overall system's energy use is further tempered by the choice of power supply. That said, selected component-level measurements were made to inform specific research questions.

After accounting for tests redone to resolve bad or missing data and system configuration changes, the final total of 876 unique parametric tests spanned a variety of variables and sensitivity studies covering a multi-step duty cycle (ranging from "off" to "gaming"). Detailed results are presented by Bourassa *et al.,* (2018b). PC energy use in non-gaming mode is reasonably well defined by ENERGY STAR® and other test methodologies. PC energy use and efficiency in gaming mode, however, is poorly defined, and not considered in ENERGY STAR® or other existing rating systems. Power requirements can vary considerably during gameplay, as a

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[9] For specifications, see http://greengaming.lbl.gov/technology-assessment/representative-gaming-systems.

function of underlying workload created by the application and the gamer's choices as they move through a game's storyline.

In developing the aggregate energy demand estimates for California, the researchers considered the entire technology and behavioral "ecosystem" influencing energy use for gaming, treating gaming as an activity rather than a discrete device or piece of software. These ensembles of factors comprise the core gaming platform together with a variety of peripherals including external audio, local networking equipment, external graphics card docks, displays, televisions, local networking equipment, virtual reality headsets and sensors, together with a wide range of user-driven behavioral choices that also influence energy use. Gaming systems are multi-function devices that perform gaming as well as other tasks for their owners.

Assessing Energy Use in Light of User Experience

Ideally, the energy performance of all gaming systems could be readily compared. However, comparisons based simply on absolute energy use for a standardized game do not suffice for most purposes, as the ability to play different games varies among devices, as does the quality of the gaming experience. In addition, users implement a variety of unique in-game settings, or game modifications ("mods"), each of which will simultaneously influence the system power draw and user experience. The CPUs and GPUs of some systems can be under- or over-clocked to change frame rates. The choice of display can also influence system energy use—and of course user experience as well—particularly in the case of virtual reality. Defining a "typical" or "standard" gaming setup, reference gamer behavior and game or frame-rate benchmark is thus an elusive goal at best.

Moreover, as found in this study, the choice of game (or simulated frame-rate benchmark) strongly influences energy use. While identifying and applying performance metrics as proxies for the energy services being delivered is essential to gauging technical energy efficiency, absolute energy use must also be kept in focus as the factor ultimately driving energy cost, pollution, and other consequences of energy use.

Two kinds of "energy services" are in play: computing services and entertainment services. The distinction is somewhat arbitrary, but they can be delineated as component-level metrics inside the system versus visual characteristics of the delivery of the gaming experience to the user.

Core computing services at the component level include abstract diagnostic factors such as clock-speed or numbers of threads in a CPU or teraflops of graphics power in the GPU. Rated metrics of this sort can be readily found for virtually any component, yet there is no explicit translation to user experience or the degree of fit to any particular game the user may seek to play. Moreover, there are system-integration factors that may or may not make full use of component-level functionality, or may manifest in some but not all modes of the duty cycle. An example of the latter is the power management capabilities of processors and the motherboard, translating into varying levels of power reduction in non-gaming modes.

The most elementary and common example of entertainment services in gaming is the frame rate (frames delivered per second, or fps) which can also be reported as its reciprocal, the frame time (the duration of each frame, in milliseconds). The first of many caveats regarding these

metrics is that the quality and delivery of frames can vary, resulting in undesirable attributes such as stutter (changes in the frame rate), partially-rendered or "runt" frames, and frames that are entirely dropped (rendered by the GPU but never delivered to the display). In an important distinction, consoles modify the quality of the frames to maintain a prescribed frame rate of 60 fps, while PCs attempt to fix quality while allowing frame rate to vary. Moreover, high frame rates are often immaterial (for example, during game segments with relatively little visual activity). Indeed, algorithms are now being introduced by the industry to vary frame rates during gameplay depending on the need. The research team used specialized monitoring systems to evaluate each and every frame in each PC test session (the technology is not available for consoles), yielding extensive information on frame quality.

However, frame rate is just one of at least eleven gameplay entertainment services defined by the industry (Figure 6), few if any of which can be readily measured or otherwise quantified in a consistent manner, although users can vary some of them with in-game settings.[10] There are human limits to perception, and infinitely increasing frame rates do not necessarily translate to a better user experience. Moreover, the relative values that end users place on these diverse metrics are entirely subjective and vary widely across the user population. Lastly, there is interplay and potential tradeoffs *among* these services and they manifest uniquely for each game title that might be played on a given gaming device, an example being the significant reduction in frame rate when high-definition (1080p) displays are replaced with 4k (2160p) displays. There is no methodology for measuring the value of these tradeoffs to users. The "integrated" service level is the user experience, which varies in a highly subjective way from user to user, and is not rigorously measurable. As Koomey *et al.,* (2017) point out, it is commonly known as unquantifiable "fun".

There is interest in comparing the performance of PCs to consoles, but there are no frame-rate or other benchmarks that run on both technology families or accepted methodologies for objectively, repeatably, and fairly comparing user experience. Moreover, games and gaming technology are constantly changing, further confounding efforts to establish energy-per-performance metrics that can be used over time. The researchers found that even the (automated) updates pushed to the local gaming system for a given game result in significant changes to test results. The complications and limitations of analyzing gaming energy use are discussed further Mills *et al.,* (2018).

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[10] For example, dynamic reflections vary with weather conditions in the game, as well as the amount of glass in the scene or level of detail in the reflection. Similarly, scene complexity is dependent on the number and complexity of artistic objects/elements in the game. This is further complicated as these elements can be adjusted dynamically and interact with one another in complex ways.

Figure 6: Factors Affecting Gaming Performance and User Experience

Term	Definition
Frame rate	• Frame rate, also known as frame frequency, is the frequency (rate) at which an imaging device displays consecutive images called frames. The term applies equally to film and video cameras, computer graphics, and motion capture systems. Frame rate is usually expressed in frames per second (FPS).
Resolution	• The display resolution or display modes of a digital television, computer monitor or display device is the number of distinct pixels in each 2D-screen dimension that can be displayed. It is usually quoted as width × height, with the units in pixels: for example, "1024 × 768" means width is 1024 pixels and height is 768 pixels.
Anti-aliasing	• In digital signal processing, spatial anti-aliasing is the technique of minimizing the distortion artifacts known as aliasing when representing a high-resolution image at a lower resolution. Anti-aliasing is used in digital photography, computer graphics, digital audio, and many other applications.
Tone mapping	• Tone mapping is a technique used in image processing and computer graphics to map one set of colors to another to approximate the appearance of high-dynamic-range images in a medium that has a more limited dynamic range
Rendering	• Rendering is the process of generating an image from a 2D or 3D model (or models in what collectively could be called a scene file) by means of computer programs. Also, the results of such a model can be called a rendering.
Special effects	• Special effects created for games by visual effects artists with the aid of a visual editor.
Procedural texturing	• A procedural texture is a computer-generated image created using an algorithm intended to create a realistic surface or volumetric representation of natural elements such as wood, marble, granite, metal, stone, and others, for use in texture mapping. In-game setting names are highly diverse, employing terms such as "texture", "surface", and "map" to identify the feature.
Scene complexity	• Scene Complexity controls the in-game representation of how detailed objects are. A higher setting here results in more complex geometry in things like particle movement, foliage, rocks, as well as making objects remain highly detailed at farther distances from the player. This is due to level of detail, which is used to swap lower-resolution objects in as the player moves farther away from them and higher resolution objects in as the player moves closer to them. Lower settings result in a less detailed world and objects lose their detail at closer distances to the player. Depth of field is also a component of scene complexity.
Graphical fidelity	• Graphical fidelity can be defined as the combination of any amount of the three things that make up beautiful games (or virtual beauty in general): detail, resolution, and frame rate
Dynamic reflections	• Realistic reflections and shadowing that move in relation to the position of objects in the game. Also referred to as ray tracing.
Visual density	• The perceived "visual density" of a screen—and thus the amount of anti-aliasing possibly needed to make computer graphics look convincing and smooth—depends on screen pixel density ("ppi") and distance from the user's eyes.

Source: Reproduced from Koomey *et al.*, (2017) with enhancements.

CHAPTER 4:
Energy Use Across the California Installed Base of Gaming Devices

The research team made extensive power measurements across the duty cycle (Bourassa *et al.,* 2018b), and combined them to estimate annual energy consumption per system (Mills *et al.,* 2018). The focus is on client-side energy (no network or data center consumption unless otherwise noted), and exclude peripheral uses such as displays, local networking equipment, and external audio.

Power Requirements at the Individual System Level

Defining the power requirements of a gaming device is no easy task, particularly under gameplay for which there is no readily established test procedure.

The research team sought to determine the variation in test results that might be encountered for gaming mode depending on testing approach. The team ran 11 frame-rate benchmarks on desktop computers selected from each of the three product tiers and one mid-range laptop and compared the results to those for 10 actual game titles. Running games under simulated frame-rate benchmarks is appealing because they are automated and highly replicable. However, the exercise made it evident that power requirements vary depending which frame-rate benchmark or game title is chosen.

Human gameplay is ostensibly more realistic than simulated frame-rate benchmarks, but potentially less repeatable. Researchers evaluated both approaches. To minimize "noise" caused by variations in human gameplay, the team developed a detailed test script for each game (Bourassa et al., 2018a). The metrics reported here are the average power measured over a standardized test period. For example, in the case of Skyrim, this period involved an approximate 6-minute test of a highly scripted and repeatable section of the game.

Contrary to a popular perception that simulated frame-rate benchmarks don't approximate real-world gameplay, exploratory testing found that all but two of the common benchmarks bracketed a range of power requirements very similar to those of the range of real-world games that were tested.

Given that actual games are as or more intrinsically representative of real-world utilization and energy use, the focus was on those results. As discussed below, the research team found that disciplined human testing of actual games to be highly reproducible. The researchers selected Fire Strike as the representative simulated benchmark (for PCs only) for all subsequent tests for cases where simulated benchmarks were preferred over human gameplay.

The team subsequently tested the full range of desktop and laptop computers as well as consoles and media-streaming devices (Figure 7). Across the systems and game titles, average power during gameplay varied 12-fold (34 to 410 watts) for the desktops, 10-fold (21 to 212

watts for the laptops, and 15-fold (11 to 158 watts) for the consoles. Two media streaming devices used similar amounts of power at approximately 4 and 8 watts.

Figure 7: Average System Power During Gaming and Non-gaming Modes: 2016
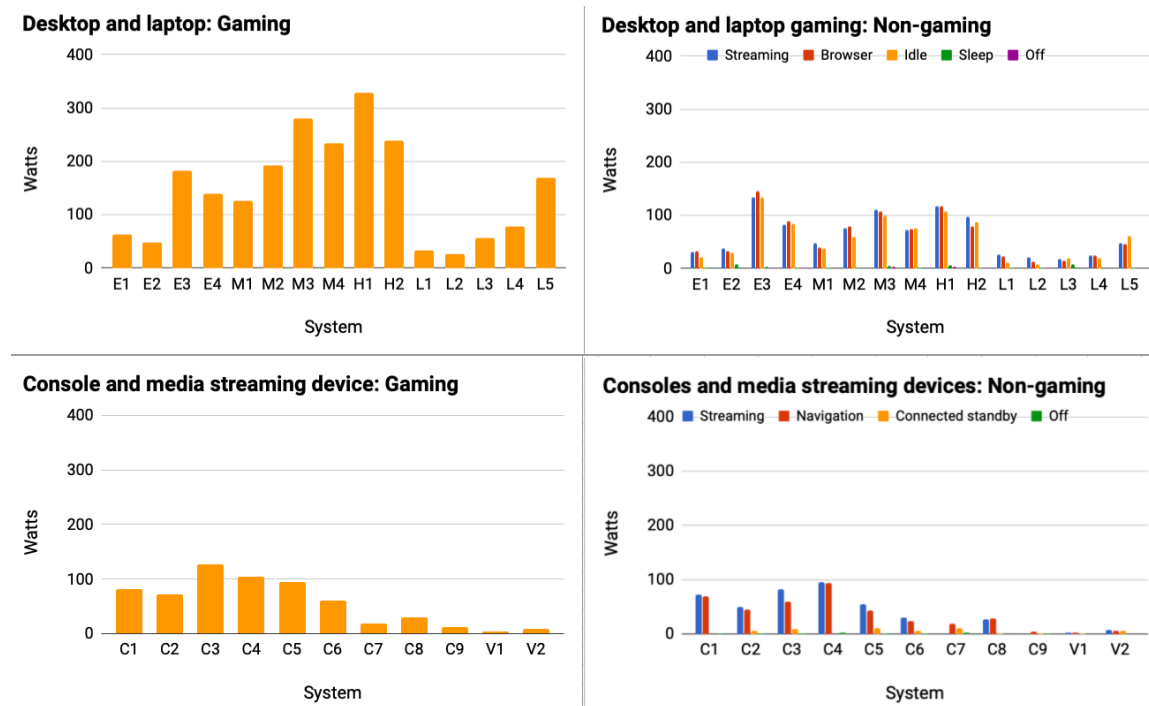
Source: Lawrence Berkeley National Lab

Conversely, for individual systems, gameplay power varied depending on the game chosen by 18-fold (15 to 270 watts) for the desktops, 41-fold (3 to 127 watts) for the laptops, 9-fold (7 to 61) watts for the consoles, and 2-fold (2 to 4 watts) for the media streaming devices. The non-gaming power use of these systems can be significant as well, and, interestingly, follows a different relative pattern across systems than during gameplay.

Manufacturers have brought to market external graphics-card docks for boosting laptop gaming power. Tests of such products resulted in a three-fold increase (by 60 watts) in gaming power in one case and two-fold (by 90 watts) in another.

The GPU plays an important role even in idle mode, and is dominant in Mid-range and High-end systems during gameplay. That said, the CPU-motherboard assembly is responsible for half or more of the total power in idle mode across all system tiers, and even in the entry-level system during gameplay. The role of GPU ranges from 45 percent (System E3) to 77 percent (System H1) in gaming mode, and is surprisingly significant in idle mode as well (12 to 33 percent) (Figure 8). Average power over gameplay. Entry-level system is E3, Mid-range is M4, and High-end is H1. Other is calculated as the residual of total system power minus GPU and Motherboard power.

Figure 8: Measured Taming Desktop Component Loads: The Role of Components Varies Significantly Depending on Duty Cycle and Product Tier
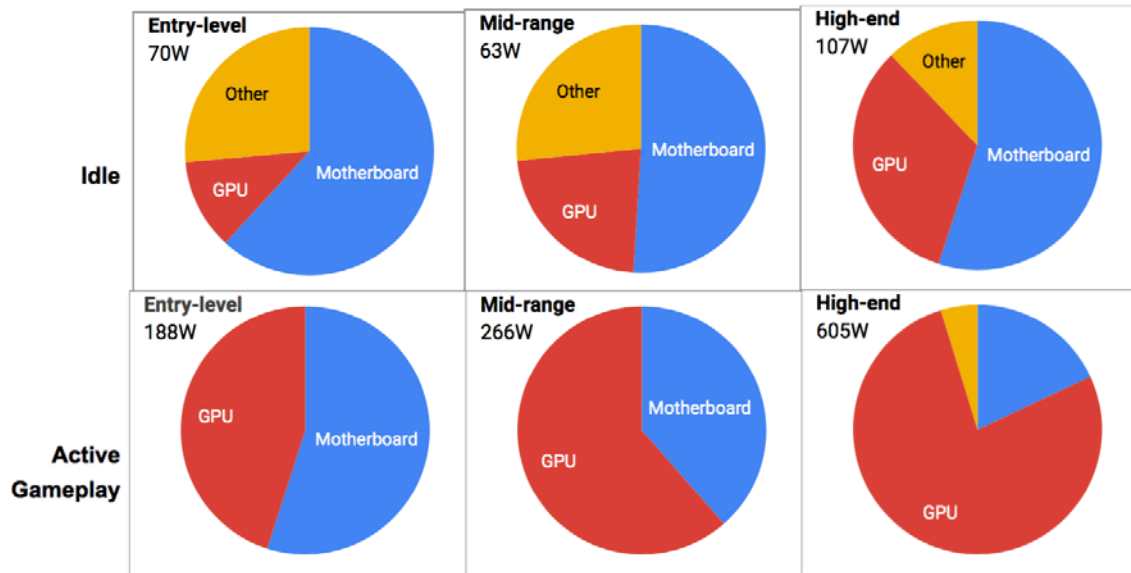
Source: Lawrence Berkeley National Lab

Component nameplate ratings are important insofar as DIY gamers use them to size power supply units, and energy analysts may use them to estimate energy use in lieu of measured values. The research team performed direct measurements of GPU and CPU/motherboard component power for a cross-section of the base systems. Measured maximum values did not agree well with nameplate, varying from 63 to 113 percent of actual for GPUs and 45 to 76 percent of actual values for CPUs for the units measured.

Power management

Gaming systems handle widely varying workloads, ranging from no gaming or other workloads in idle mode to full-on gaming. Ideally, power management is implemented in system design and system integration to scale power up and down in keeping with these varying workloads.

The concept of "energy proportionality" has been used to signify the degree to which energy use scales with the workload in computing equipment. The degree to which this factor has been considered in the design of the test systems clearly varies. Some of the systems performed barely better than a 1:1 ratio (no difference between gaming and idle power for PCs and navigation power for consoles and media streaming devices), with the best desktop PCs operating in the range of 4:1, laptops 4:1, consoles 2.5:1, and media streaming devices 1.5:1. An important caveat to this metric is that inefficiency in gaming mode can contribute to a greater differential and thus the appearance of "better" energy-proportionality.

Displays: 2D and virtual reality

Display choice strongly affects gaming power within the gaming system. While frame rate decline when switching from high-definition (1080p) to ultra-high definition (4k) resolution, PC system power requirements typically rise (in systems that can handle the added processing load). These power increases are sometimes very significant (up to 60 percent in the testing), while frame rates decline, resulting in a significant reduction in the fps/watt metric. The research team did not evaluate the effect of display choice on console power, but others have observed results analogous to ours for PCs (Microsoft, Nintendo, and Sony Interactive Entertainment 2017).

Console gaming is most commonly conducted using a television for the display, and increasingly so as these devices become the broader "entertainment hub" for streaming video and other services in the home. TV energy use varies widely. On-mode power requirements of 4k displays (2160p) range as high as 400 watts, and according to one report none meet the ENERGY STAR® 7.0 qualifying levels (NRDC 2015). The leading recommended television for console gaming from one consumer site was a 65" 4k unit, rated at 212 Watts of power when in use.[11] This is substantially more than the device-specific gaming-mode power use of most of the consoles tested. Among 55" 4k displays, measured on-mode power use varies from 60 to almost 170 watts, and, among the simpler measures, automatic brightness control can reduce on-mode power requirements from 10 to 50 percent (NRDC 2015).

The average computer display power used in the assessments was 25 watts in 2016, while that for average television was 82 watts. Treatment of displays is described more fully in Mills *et al.,* (2018).

Virtual reality (VR) is gaining considerable interest among gamers, with several manufacturers bringing products to the market for gaming computers and consoles. Initial consideration suggests an intrinsic potential energy savings, due to the smaller active display area which is rendered to the full display emitter resolution. However, VR requires much higher frame rates than two-dimensional displays, thus placing greater computing demands on the gaming system and in some cases independently powered sensors and headsets. Moreover, 2D displays are routinely used in conjunction with VR for orientation and to enable others in the room to follow the gaming session.

The researchers produced the first publicly available measured data on gaming computer and console energy use under VR. The variations in PC energy use between viewing gameplay on 2D displays versus VR headsets are notable. The direction of change varies, ranging from an increase of 38 percent (93 watts) to a reduction of about 15 percent (52 watts run in a more energy-efficient rendering mode).

These results include energy used by the VR headset and sensors. The Oculus Rift headset is powered by a USB connection to the system, while the HTC Vive has a constant 16.2-watt

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[11] See https://www.sony.com/electronics/televisions/xbr-x900e-series/specifications.

accessory load provided by an external power supply that was added to the system power. Left on continuously, the HTC sensors would consume more than 140 kWh/year.

Virtual reality is also available for PlayStation consoles. Energy use for the Batman Arkham title under VR for the PlayStation 4 Slim and PlayStation 4 Pro resulted in power in gaming mode of 74 watts and 127 watts, respectively (excluding external display). Unfortunately, the other Batman Arkham series games available for conventional console displays bears little resemblance to the VR version, and so it was not possible to make the absolute comparison to 2D gameplay. System power for this game under VR was 22 to 32 percent higher than that of a variety of 6 other popular 2D games on the PlayStation. Foveated rendering appears to be embedded in the Playstation VR system, but with no user control or settings.

The Role of Game Choice

Variations in image quality and complexity among games suggest a wide range of rendering workload, yet the actual correlation and corresponding variations in energy use have been largely unquantified. The team measured gaming power requirements while running 37 games on selected systems (none can be run on all platforms) and 11 frame-rate benchmarks.

The researchers conducted tests of 19 popular game titles across the 16 base PC systems. Even within many of the individual systems, the range in gameplay energy was on the order of a factor of three or ~150 watts, depending on which game title was played. For the game most widely playable. Somewhat surprisingly, among the PC game titles tested, energy use did not correlate with game genre (Figure 9). For example, power requirements for Candy Crush and Sims4 did not trend lower than that of more intricate and high-fidelity games, and indeed drew even more power in some cases (for example, compared to Skyrim TES and League of Legends).

Figure 9: Personal Computer Power in Gameplay Does Not Vary by Genre: 19 Popular Personal Computer Games

Not all systems are able to play all games. The Fire Strike frame-rate benchmark is included for reference.

Source:
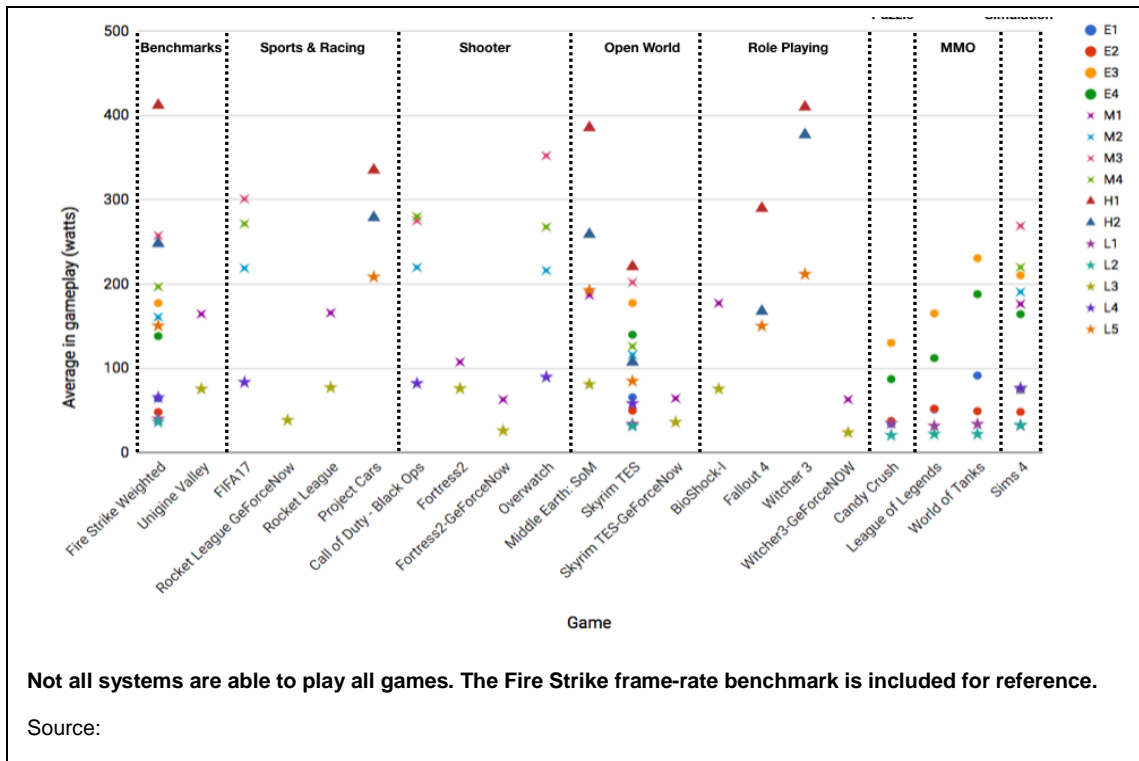
The team evaluated 9 consoles and 2 media streaming devices across 21 popular games and found qualitatively similar results (Figure 10), although with only one exception, variation within a given platform was much less than for PCs. Measured energy use for the Nvidia Shield was relatively low, but this is because most of the workload is shifted to upstream networks and data centers, an issue treated later in the report. Apple TV only supports local client gaming.

To provide a more in-depth view of how much power for given game varies across PCs and consoles, the team evaluated power use for Skyrim across the 22 of the 26 systems with which it is compatible (Figure 11). Skyrim is one of the least energy-intensive games evaluated in the testing, but is available over the broadest variety of systems and hence appropriate for the analysis depicted here. Skyrim is generally capped at 60 fps, but laptops L1 and L2 and desktop E2 experienced bottlenecks that resulted in lower frame rates. Gameplay power levels are the average power measured across all games. Average power during gameplay ranged from 32 to 85 watts across 5 laptops, 50 to 221 watts on 10 desktops, and 11 to 143 watts across 9 consoles. In all, gaming power while gaming varied by 21-fold across the systems. Interestingly, frame rates are fixed at 60 fps in this game, so there are no performance differences by that metric (except for three systems that were not capable of running at 60 fps). Researchers ran the other widely applicable game, Sims 4, on 12 PC systems. Sims is much more computationally-intensive than Skyrim. Average power during gameplay ranged 8.3-fold, from 32 to 269 watts.

Figure 10: Console and Media Streaming Device Power in Gameplay Does not Vary by Game Genre: 21 Popular Console Games
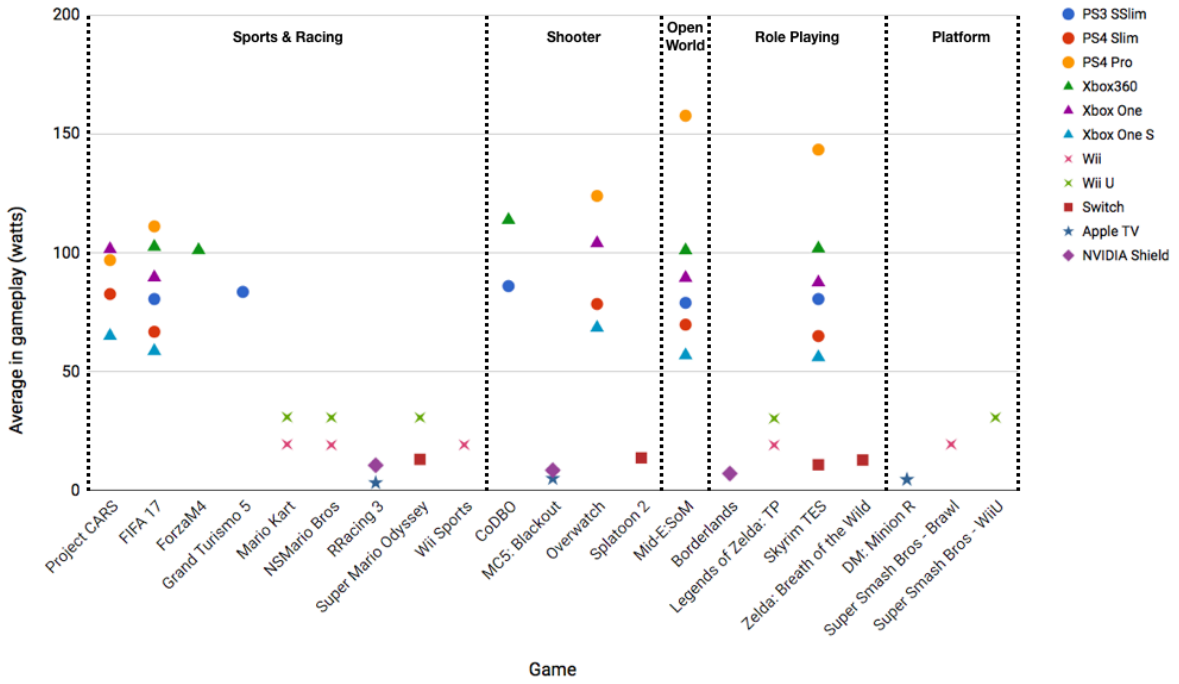
Source: Lawrence Berkeley National Lab

Figure 11: Gaming power for Skyrim TES Varies 21-fold (from 11-221 watts)
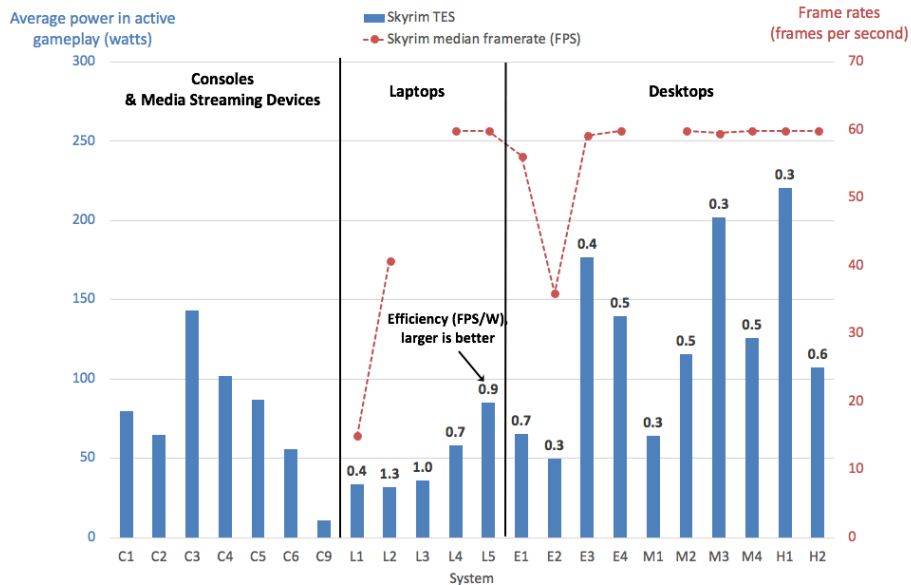
Source: Lawrence Berkeley National Lab

Notably, in comparing across PC and console product categories, there is clear overlap in gaming power for the more energy-intensive consoles and, all levels of gaming laptops, and the entry-level gaming desktops (as well as one of the mid-level desktops). Also, of interest, system H2 (the Digital Storm - Velox) is the highest-performing system, yet under Skyrim TES uses less energy than many of the lesser desktop systems and less than the PlayStation PS4 Pro.

Hardware and software settings and in-game "mods"

In-game settings are user-adjustable attributes of a game's look and feel, influencing the level of detail and realism of the scene. These effects are highly subjective and not all are necessarily detectable by gamers. The effects measured for ten different adjustments varied between 1 percent and 6 percent. Another adjustment, VSync, achieved a far larger impact, discussed later in this report. The ranges of effects applied individually; energy impacts would likely be greater when applied in combination.

Games often support unique "mods" that can be installed by the user to enhance the gaming experience. The energy effects of these settings have not previously been described. The research team examined a series of mods for Minecraft and discovered significant impacts on gaming power requirements.[12] In particular, the Optifine mod (which increases framerate but has no other visual impact) increased base power from 187 to 218 watts (a 16 percent increase). Adding shaders to this setting (which dramatically enhance illumination quality, shadows, and other details) increased power to 252 watts (a 35 percent increase from the base settings).

The team conducted exploratory tests to determine the effect of the popular behavior of "over-clocking" the GPU and underclocking the CPU. GPU underclocking had a greater effect on system power than overclocking (range -25 percent to +6 percent), while CPUs responded strongly in both directions (-26 percent to +37 percent). Power use typically changed more rapidly than performance, resulting in declining efficiency metrics (fps/W). Underclocking can serve as a legitimate energy-savings measure, particularly in cases where changes in framerate are not particularly noticeable to the gamer.

Variations in gameplay power requirements among actual gamers

During structured testing, the researchers captured the gaming power requirements of gaming systems during highly scripted gameplay sessions conducted by two research staff members and, for PCs, from simulated frame-rate benchmarks with near-perfect reproducibility.

The team also recruited 22 experienced gamers to play 87 individual game sessions in their own way on the some of the gaming systems. The testers played a variety of game titles: fifteen games on desktop gaming systems, eight games on consoles and two virtual reality titles also used in the standardized bench tests.

Average power during gameplay was highly similar to the Fire Strike frame-rate benchmark and human-gameplay measurements during the scripted lab-bench trials. Average results for given

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[12] These were implemented on the energy-efficient high-end PC described in Mills and Mills (2015).

system-game combinations for PCs were on a par at 2.5 percent lower (4 watts) with the average bench tests and 1.7 percent lower (1 watt on average) for consoles. These discrepancies are within the measurement error of the testing process. These testers also scored their user experience based on five criteria. No particular pattern emerged suggesting that the "higher-end" systems yielded a superior user experience.

These results provide high confidence in the realism and representativeness of the energy measurements taken using lab-bench test methods, while reinforcing the aforementioned concern that there are many elements of user experience that simplified framerate measurements do not capture.

The Energy-versus-Frame-Rate Nexus

Popular mythology holds that boosting performance requires more energy input. While it is true that frame may increase with rated power, the correlation is overwhelmed by many other factors. As discussed at length above, most aspects of performance are highly subjective and difficult or impossible to measure. The research team has been able to measure the most accessible user-experience metric, frames per second (fps), in great detail and compare it with measured power during gameplay. While frame rates are the predominant metric used in the marketing of games and in product reviews, they fail to capture many aspects of user experience.

As seen in Figure 12, high frame rates can be achieved at almost any power level. Measured average fps and power over the frame-rate benchmark test cycle: all games and configurations. Not all games are played or playable on all systems. Only windows systems are shown, as it was not possible to measure frame rate for Mac OS or consoles. Conversely, at a given power level, the frame rate achieved varies widely. Variations are similarly large when outcomes are viewed in terms of efficiencies (frames per second per watt). A high level of efficiency does not correlate to lower absolute power requirements.

Figure 12: Frame rate Does Not Correlate with PC Power: Laptop and Desktops
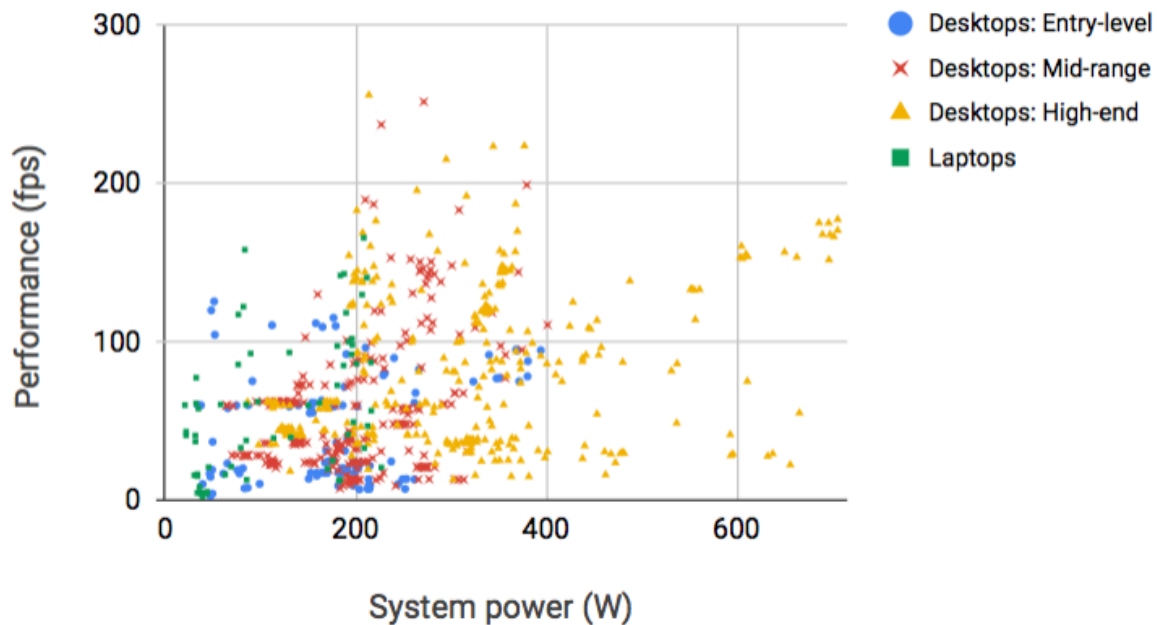
Source: Lawrence Berkeley National Lab

The caveats about framerate notwithstanding, these results underscore the notion that improved efficiency needn't require a performance compromise in the range of frame rates generally deemed respectable.

Unit Energy Consumption

The researchers integrated the preceding assessments of power requirements by mode with the duty cycles and other behavioral factors to estimate annual energy use for gaming. The results represent an enormous envelope of unit energy consumption, driven by many technological as well as behavioral variables. As with the power consumption data shown in preceding sections, here the focus continues to be on client-side electricity consumption (no network or data center consumption), and exclude peripheral uses such as displays, networking equipment, and external audio.

In many cases, energy use during gameplay is on the order of one-quarter to one half the total annual energy use across all parts of the duty cycle for the weighted-average case of all user types. For "Extreme" users the value can rise to nearly 75 percent. An additional overarching observation is that user type (intensity of gameplay) has as much or more impact on total annual energy use as does the selection of gaming platform.

Client-side gaming

For desktops, absolute and relative energy use across the duty cycle varied substantially (Figure 13a), with particularly low relative gaming energy among the Entry-level systems. Upper panel (a) is absolute energy; lower panel (b) apportionment by system. Total annual energy use varied by 3-fold (248 to 648 kWh/year) across the three broad tiers of systems and their stock-weighted average duty cycle (and much more across individual systems comprising these tiers). Behavioral factors also strongly influence outcomes (which vary approximately five-fold), as indicated in Figure 13b. Variations are even high within a product tier. For example, the High-end systems' energy use varies from 337 kWh/year for "Light" users to 1,124 kWh/year for "Extreme" users (excluding displays and network energy), depending on user type. Viewed differently, an Extreme user on an Entry-level system uses significantly more energy than a Light user on a High-end system.

Figure 13: Baseline Unit Energy Consumption for Desktops by User Type and Duty Cycle
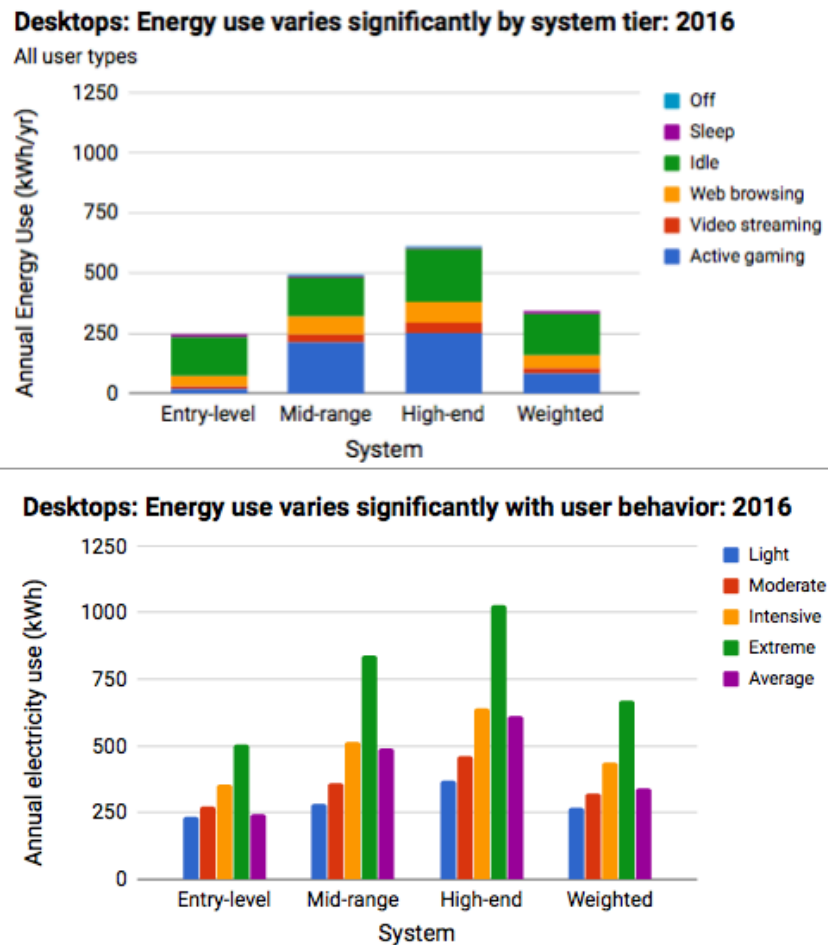
Source: Lawrence Berkeley National Lab

For laptops, absolute and relative energy across the duty cycle also varied substantially (Figure 14a), with particularly low relative gaming energy among the Entry-level systems. Upper panel

(a) is absolute energy; lower panel (b) shows apportionment by system. All laptop testing conducted with batteries removed or fully charged; thus energy losses associated with charging are not included. Total annual energy use varied by 6-fold (45 to 249) kWh/year) across the three broad categories of systems (and much more across individual systems comprising these tiers). Behavioral factors also strongly influence outcomes (which vary approximately 12-fold), as indicated in Figure 14b. For example, the High-end systems' energy use varies from 139 kWh/year for "Light" users to 515 kWh/year for "Extreme" users. Viewed differently, an Extreme user on an Entry-level system uses only slightly less energy than a Light user on a High-end system.

Figure 14: Baseline Unit Energy Consumption for Laptops by User Type and Duty Cycle
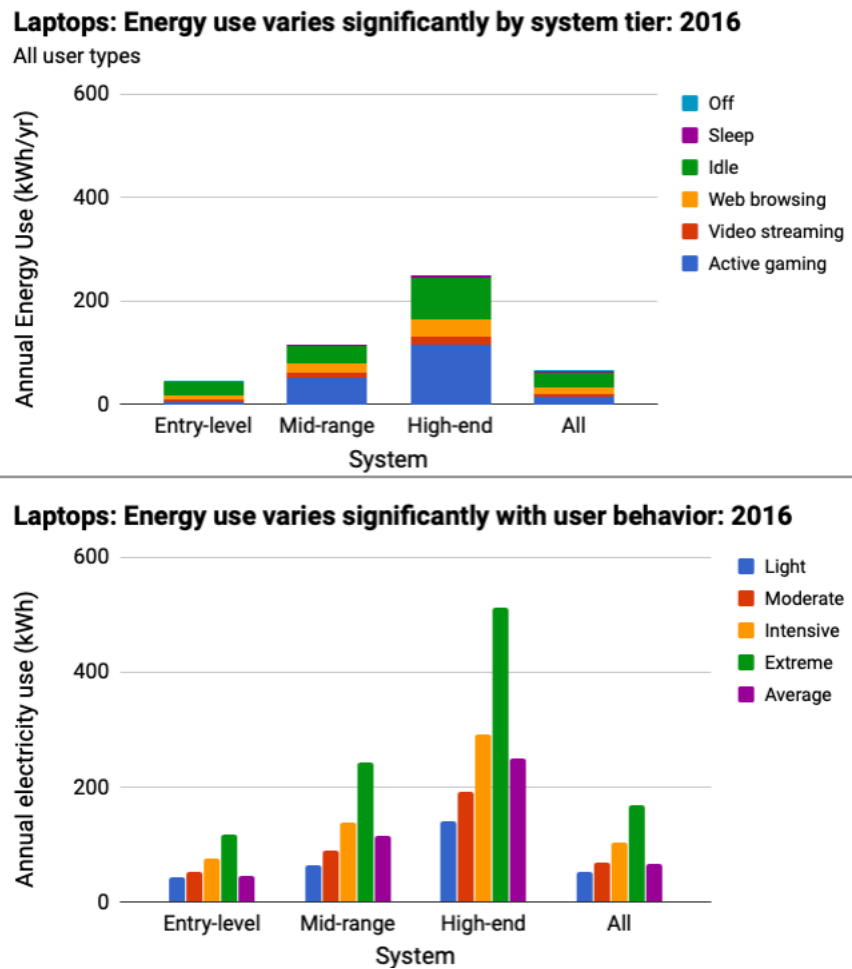
For consoles, absolute and relative energy use across the duty cycle varied substantially (Figure 15a). Upper panel (a) is absolute energy; lower panel (b) shows apportionment by system. Annual energy consumption varies 18-fold (10 kWh/year for the Switch to 182 kWh/year for the PS4 Pro) and 7-fold (8 to 51 kWh/year) for the media streaming devices. As discussed below, additional unavoidable energy use not shown here is required in the upstream network and

data centers by the Nvidia Shield. Behavioral factors also strongly influence outcomes (which vary approximately 75-fold), as indicated in Figure 15b. For example, the Xbox 360 varies from 34 kWh/year for "Light" users to 319 kWh/year for "Extreme" users. Viewed differently, an Extreme user on the relatively low-energy Switch uses as much energy as a Light user on the Xbox 360 or the PlayStation 3 Super Slim. Unlike the preceding analyses for PCs, here the research team evaluated two generations of consoles since both are heavily represented in the installed base. The "learning-curve" effect of improving efficiency over time is reflected the comparison of the Nintendo Wii to the Wii U to the Switch. Current-generation systems (for example PS4 Pro and Xbox One) will likely exhibit further improvements as their market lifecycle progresses.

Figure 15: Baseline Unit Energy Consumption for Consoles by User Type and Duty Cycle

Consoles and media streaming devices: Energy use varies significantly by system tier: 2016
All user types

Consoles and media streaming devices: Energy use varies significantly with user behavior: 2016
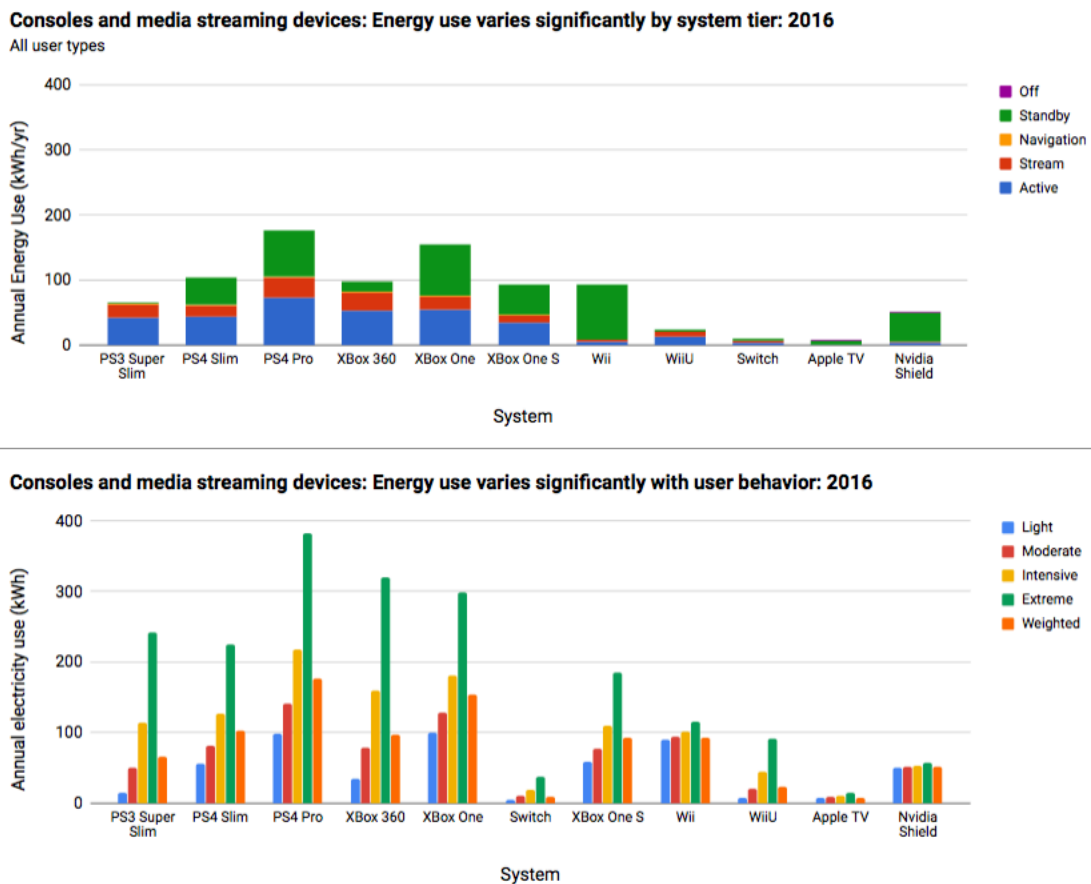
Source: Lawrence Berkeley National Lab

The research team assessed a hypothetical "worst-case" setup, involving the average of the two High-end PC systems, overclocking, three displays at 4k resolution, cloud-based gaming (see below), and the "Extreme" user profile. This configuration would result in annual electricity use of 2,560 kWh/year (at 2016 Internet network electricity intensity), which is more than double the Baseline unit energy consumption for that equipment tier.

This information can be put into context by comparisons with other residential plug loads (Figure 16). Envelopes shown for the various platforms reflect the range of equipment selection and time in active use (gaming, streaming, browsing) across the four user types defined in this study. The upper bound reflects the Extreme user on the High-end equipment product tier. Worst-case examples shown for cloud-based gaming on each device, including associated network and data center energy. Some users will game an even greater number of hours than indicated here. Non-gaming device values per Urban et al., (2017) and the Home Energy Saver database. See http://hes-documentation.lbl.gov/calculation-methodology/calculation-of-energy-consumption/major-appliances/miscellaneous-equipment-energy-consumption/default-energy-consumption-of-mels. Gaming desktop computers are among the very most energy-intensive plug load activities in homes. Consoles also rank quite high, especially for more intensive use cases. Media streaming devices rank much lower, although their gameplay energy is deferred to networks and data centers. When counting this "upstream" energy use, the media streaming device is as or more intensive as the desktop PC. Also, of note, gaming energy use is more sensitive to behavior than most other plug loads.

Figure 16: Gaming is One of the Highest Energy-using Plug Loads
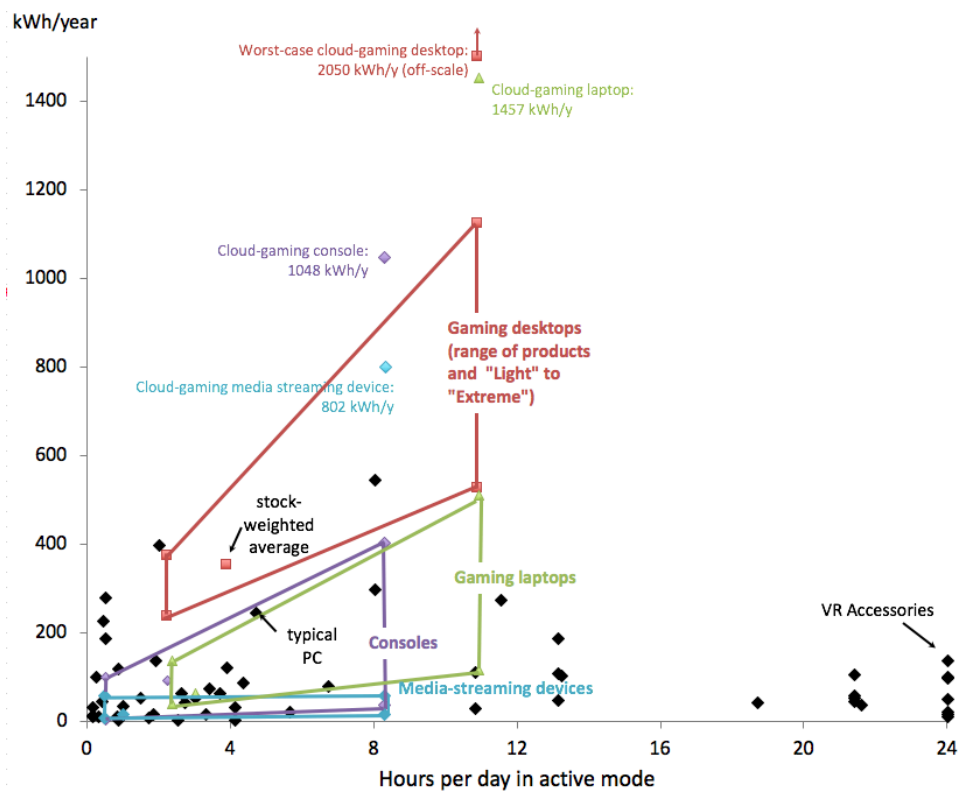
Source: Lawrence Berkeley National Lab

Cloud-based gaming

The emergence of cloud-based gaming shifts an increasing amount of gaming activity, along with its associated energy use, into the Internet. This type of gaming requires energy-intensive

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server equipment located in off-site data centers to execute the game logic and render game images, as well as the use of data networks to receive and send data from these servers to the client-side user devices. The assessment described here is documented in substantially greater detail in Mills *et al.,* (2018).

The estimates of cloud-based gaming energy requirements are based on the beta version of Nvidia GeForce NOW for the Mac, the Nvidia Shield TV system[13] and analogous systems for consoles and related published literature on data center and data network energy use in the United States

The client-side in cloud-based gaming mode typically requires minimal power (typically 10 to 15 watts) since the majority of computer processing is occurring remotely, however the amount of data streaming to and from the client device is significant. The Shield, for example, streams at average rate of 15 Mbps, or 6.75 GB transmitted hourly, which translates to approximately 180 watts at the Internet electricity intensity levels prevailing in 2016.

GeForce NOW currently uses rack servers enhanced with eight Tesla P40 Nvidia GPUs. Average server electricity use, excluding GPUs, is estimated to be 257 watts per user,[14] based on typical hardware and operation characteristics found in large data centers. When accounting for data center server and auxiliary power, as well as the data center power when gaming services are not being used, 340 watts is required per user at the data center while in cloud-based game. Together with Internet requirements, total power is about 520 watts while in gameplay. This excludes the gaming device in the home that receives the information.

The team conducted a similar analysis for consoles, which are also beginning to have access to cloud-based gaming services such as Playstation NOW. In the absence of publicly available data, the team developed a generic configuration. Network energy is identical to that in the Shield example, at 180 watts on the network, plus 120 watts in the data center during gameplay. Total cloud-based gaming power is thus about 300 watts.

Where systems elect cloud-based GPUs, the base energy on the client-side declines, although the net effect will tend to be an increase in overall energy use unless the associated network losses are offset by extremely significant efficiency gains within the servers in relation to the client-side systems. Figure 17 shows that for these systems 23 to 82 percent of total system energy use falls in networks and data centers. Values are shown for video streaming as well as gaming. Cloud gaming values include network energy and energy used in the data center. Lower values for Entry-level systems reflect the relatively high proportion of "Light gaming" user types. There is currently no cloud-based gaming option for PS3, Xbox 360, Nintendo devices, or Apple TV. Display energy not included. Accounting for network and cloud-computing energy requirements reduces the relative energy-use differential between desktops, laptops, consoles, and media streaming devices. For conditions prevailing in 2016, cloud gaming adds approximately 40 to 60 percent to the otherwise total local annual electricity use for desktops,

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[13] See https://www.nvidia.com/en-us/shield/shield-tv/.

[14] Assumes a dual-processor volume server with an average processor utilization of 50 percent.

120 to 300 percent for laptops, 30 to 200 percent for consoles, and 130 to 260 percent for media streaming devices. Cloud-based gaming is by far the most energy-intensive form of gaming via the Internet (compared to traditional online gaming or downloading games), and while the electricity intensity of networks is declining quickly, that of data centers is not.

Figure 17: Network and Cloud-gaming Energy is Often More Than Half of Total Electricity Use: 2016 Conditions
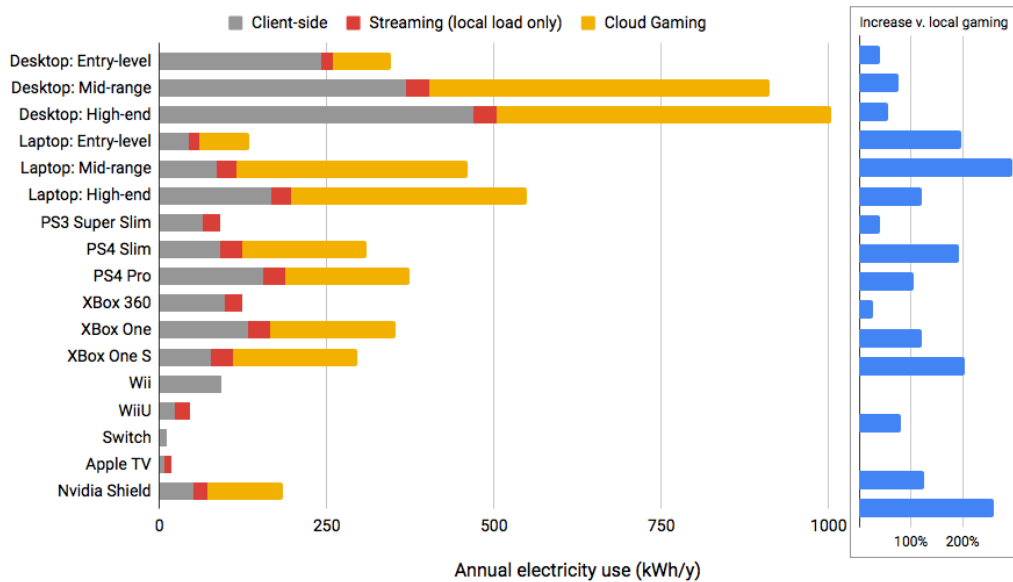
Source: Lawrence Berkeley National Lab

These estimates are based on representative equipment and published data, but cloud-based gaming is an increasingly diverse and rapidly evolving gaming medium. The centralization of servers handling the graphics workload provides unique opportunities for efficiency improvement (technological and operational) as well as introducing carbon-free power sources. The energy efficiency of data networks has drastically improved while the amount of data being transferred is constantly increasing. That said, the energy use attributed to cloud-based gaming is reliant on the amount of time the equipment remains unused and idle while still consuming electricity. Providing more cloud-based gaming capacity than needed will ultimately increase the energy intensity of these services. Much uncertainty remains in the specific energy use values of current and future cloud-based gaming, but the estimates provide a framework for future analysis and outline the energy-consuming components associated with cloud-based gaming that require attention to better understand the energy impact of this emerging form of popular entertainment.

It is important to note that other use modes available for client-side gaming devices also consume network energy. During video streaming, the client-side user device is used to view video content stored in the cloud through services such as Netflix, Hulu, or YouTube. While the data center energy use during video streaming has been shown to be negligible on a per-viewer basis (Shehabi *et al.,* 2014), the data streaming to and from the client device can be significant depending on the quality and resolution of the video, corresponding to about 100 watts during streaming.

CHAPTER 5:
Opportunities for Gaming Energy Savings

The gaming industry (and makers of components used in gaming systems) has made material efforts at improved energy efficiencies, in some cases in tandem with policy efforts and in other cases on their own.

Component efficiencies have improved steadily, along with efforts to achieve power management through software and BIOS avenues. Console manufacturers have made the greatest strides. What can be observed is that each in-generation release of consoles has historically achieved energy savings compared to the prior version, and that the cross-generation trend is generally downwards. The researchers estimate that the historical rate of improvement in console power per unit has been 11 percent per year, representing a blend of potential current-generation and next-generation improvements. The leading manufacturers have publicly identified thirteen specific strategies that have been applied to various usage modes of the 8th-generation Microsoft and Sony consoles, and project these to reduce energy use in compared to the baseline by 65 percent by the year 2020 although claim "little further opportunity for reduction" beyond that, although recognizes that greater reductions are "conceivable" (Microsoft, Nintendo, and Sony Interactive Entertainment 2017).

As an indication of further potential, there remain large variations in energy use during gameplay across the representative systems evaluated while providing similar measurable user experiences, as well as variations in the ability of systems to use less power in non-gaming modes. Moreover, for PCs, a steady stream of software innovations is entering the market that depends on users to implement.

The researchers tested a wide range of commercially available hardware and operational changes and measured their savings, individually and in packages (Mills *et al.,* 2018), but did not estimate the potential of future technologies yet to be commercialized.

Hardware Efficiency Measures for Desktop Personal Computers

Historical progress notwithstanding, virtually every component in gaming systems can be more efficient. This includes central processing units, graphical processing units, motherboards, power supplies, cooling, as well as displays and other peripherals devices. For networked gaming, the opportunities extend into networks and upstream data centers.

GPUs offer by far the greatest fractional savings opportunities. As an illustration of these improved GPU opportunities, the upgrade of a High-end DIY system (H1) achieved substantial energy savings by changing from two AMD R9 Fury X GPUs (the base system) to one RX Vega 64 liquid-cooled GPU. Notably, savings varied considerably depending on which game and display was in use (Figure 18). That said, power consumption for each game increased when the high-

definition (1080p) display was replaced with the ultra-high-definition (4k) display. The metric fps/W improved for all cases.

Figure 18: Dual-Graphics Processing Unit System Draws Substantially More Gaming Power and with Lower Frame Rates than Single-Graphics Processing Unit System, and More Still in 4k
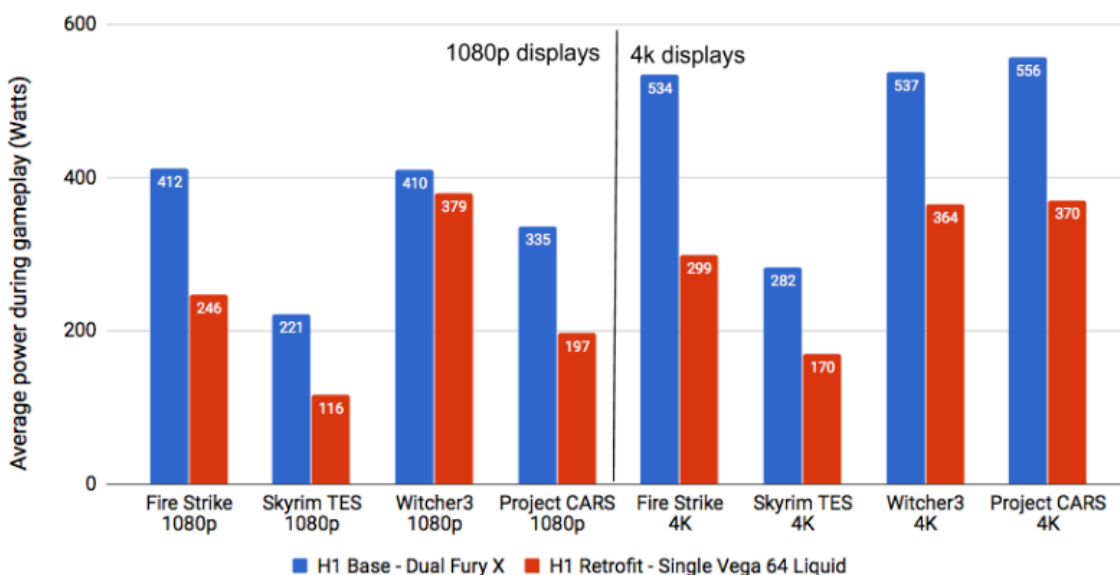
Source: Lawrence Berkeley National Lab

Of note, the researchers observed significantly improved power management within the efficient GPUs evaluated. In these cases, the ratio of gaming-to-idle power increased considerably.

Power supply units also offer material savings opportunities. Potential improvements over the units shipped with the tested commercial systems averaged 13 percent. Moreover the systems were virtually all significantly oversized by a factor of three on average for the desktops and by 25 percent for the laptops--suggesting further savings opportunities.

Software, Operational Choices, and Other User Behaviors

User choices regarding system BIOS and software settings, duty cycle, and in-game settings can have as much influence on energy use as their hardware choices. Parametric analyses were used to isolate the effect of these variables, and to understand their influence in combination.

Gamers have historically been irked by visual anomalies in 2D displays such as image "tearing" and "stuttering". Tearing occurs when a frame is outputted by the GPU while the monitor is in the middle of a refresh. One solution to this issue involves enabling VSync (Vertical Sync), forcing the GPU to wait to release frames until the monitor is ready to refresh itself. Energy savings can result if the system would otherwise operate at higher frame rate, essentially reflecting a system that is undersized for the game it is trying to run. However, this can cause

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unacceptable delays in screen refreshes which users must trade off against lower-quality frames. In the testing, VSync achieved 14 percent and 39 percent power reductions for the M2 and H2 systems, respectively. The researchers did not observe material savings for other 2D-display strategies such as G-Sync and FreeSync.

Among the particularly impactful operational measures is dynamic voltage frequency scaling (DVFS), which automatically slows frame rates when the rendering requirements are not critical. Other studies have found large savings from this strategy,[15] although savings were far lower on game types where activity levels are particularly constant.

Another dramatic savings opportunity observed was foveated rendering for virtual reality, in which image quality is gradually attenuated towards the periphery of the field of vision. Researchers measured 30 to 36 percent savings for this strategy, depending on which VR headset was in use (Figure 19). Results are for system H2. Excludes power of secondary 2D display commonly used in conjunction with VR. An important caveat for the future is that gaming equipment manufacturers or software developers could "take back" these savings in the form of increased performance and associated computing power.

Figure 19: Virtual Reality Foveated Rendering Gradient Lowers Gaming Power >30 percent
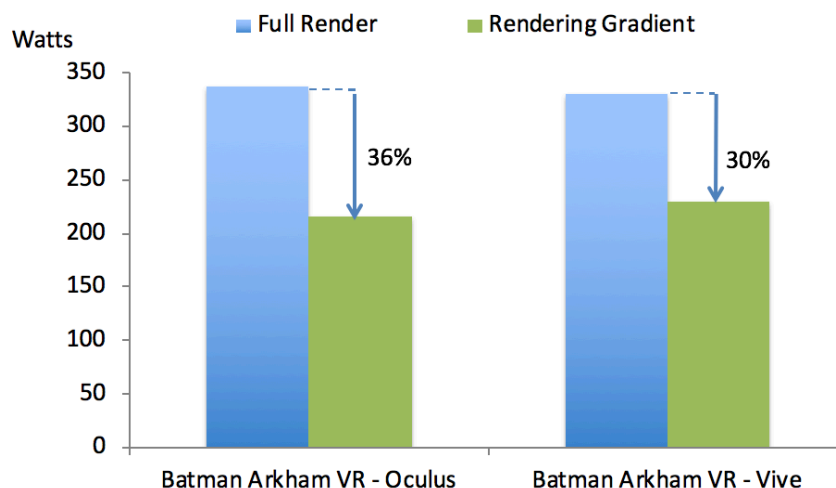
Source: Lawrence Berkeley National Lab

When properly implemented, neither of these strategies compromise user experience, and can in fact enhance it by reducing congestion in the graphics pipeline.

The preceding discussion provides a sense of the array of efficiency measures available to gaming system designers and owners. A cross-section of results from the testing is provided in Figure 20. These results are on diverse systems (noted in the axis labels) are measured independently of other measures applied to the given system. Thus, these values cannot be combined in an additive or multiplicative fashion. The Antialiasing and Qualities cases reflect

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[15] See https://www.tomshardware.com/reviews/amd-radeon-chill-ocat-relive,4846.html.

the change in power use over the full range of settings. VSync tests did not give reliable FPS results, which are omitted here. The PSU impact is calculated across a range of system types. Chill is likely to have significantly greater savings on games with less constant activity levels. Frame rate could not be measured while in VR.

Figure 20: Test Results for Specific Energy Efficiency Measures
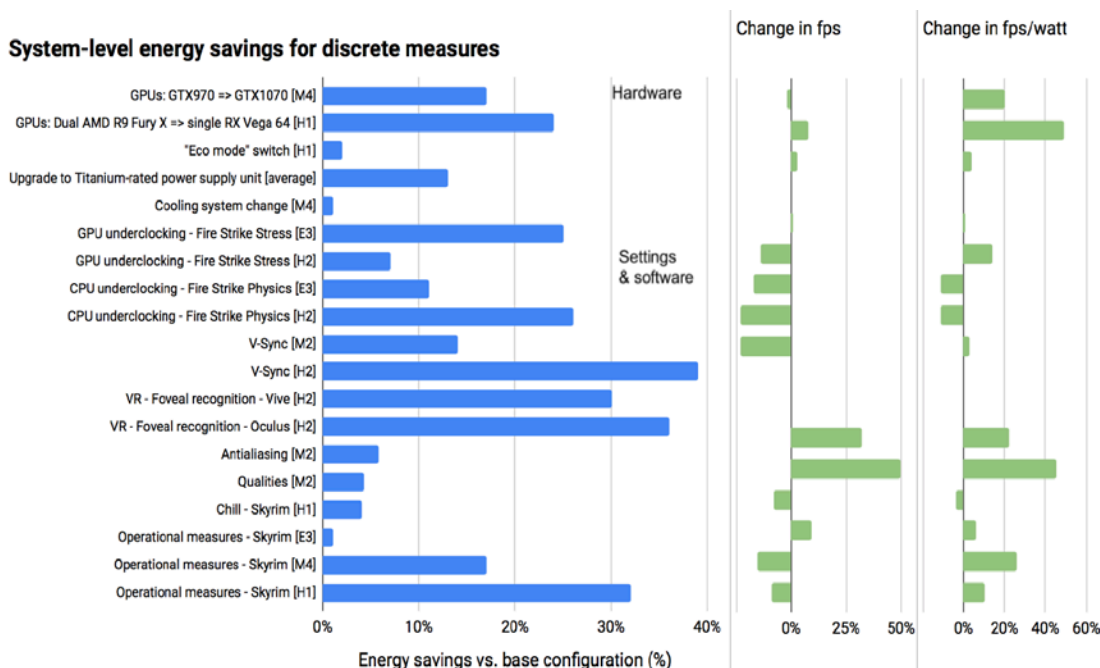
Source: Lawrence Berkeley National Lab

Systems Integration

Gaming involves complex assemblies of components. The primary device (PC, laptop, console, or media-streaming device with associated data centers) contains many interacting components and subsystems, and are in turn connected to peripheral devices (displays, VR headsets, audio equipment, and so on) that create further interactions. And, of course, the gamer is part of the system as well, making key operational choices and decisions and ultimately perceiving the output, which is the ultimate service produced by the system. As with virtually every energy-using system, proper systems integration offers pathways to reduced energy use and improved performance beyond what can be achieved by piecemeal measures.

Even with today's much-improved componentry, gains can be made with right-sizing. The most familiar sub-optimization in this regard is the oversizing of power supplies, which operate less efficiently on either side of 50 percent load. Other subtler interactions occur when systems are

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"over-spec'd", meaning components are more powerful than needed to run the games desired by the user, and/or one component's capacity causes bottlenecks with another. The typical case of the latter is a CPU more powerful than necessary to run the selected GPU, creating "bottlenecking" that results in higher than necessary energy use with no performance benefit.

The measurements determined that display choice has a strong effect on energy use within the PC, particularly the graphics card. As shown above, the choice of virtual reality can have an even more profound influence on energy use and when the gamer is recognized as part of the "system" advantage can be taken of diminished perception in the periphery of the field of vision to throttle back rendering (and thus computing workload and associated energy use) in that region.

Finally, the energy use patterns of gaming equipment cannot be defined without understanding key user preferences: game choice, in-game settings, and the duty cycle.

Savings packages

The research team assembled packages of hardware, BIOS, and system-settings measures for each of the three PC systems (one from each market tier), which were tested under efficiency measure retrofit scenarios. Detailed breakdowns of the measure packages are provided by Mills et al., (2018). Given the large number of potential component combinations, and limitations on the number of tests conducted suggest that deeper energy savings could well be identified. This applies particularly in the case of CPUs and motherboards, as well as to software and in-game settings. The team also did not include VSync, which can clearly achieve large savings in higher-performance systems. Based on lab-bench testing of the PCs, researchers identified sets ("packages") of applicable measures and evaluated their impact on the desktop systems from each of the performance tiers. Among the hardware measures, the primary focus was on the GPUs, as they are the key driver of energy use. The efficiency packages for PCs varied by system.

For the desktop systems, the team found overall average measured savings of 52 percent in gaming mode and 48 percent in non-gaming mode. The resulting savings in gaming mode ranged from 29 to 54 percent and those in the non-gaming mode ranged from 35 to 62 percent. A further breakdown for hardware and operational measures is outlined in Figure 21. Additional energy saving factors and strategies have not been included in this analysis. Among these are:

- Deep savings are possible through VSync, but the measure is only applicable to systems that are sufficiently powerful to not experience unacceptable reductions in frame rate.

- Benefits of "right-sizing" componentry, particularly GPUs to match actual gaming need and displays set at a resolution matching the need.

- Certain minor component-level measures. These include more efficient fans or fan-less cooling of PCs.

- Innovations in game design and code management to reduce energy use without compromising performance or user experience.

- Behavioral choices that could be made by gamers involving duty cycle changes.

- Consumer product choices (beyond those captured in the scenarios) made with the intent of reducing energy use. Among these would be a shift towards less energy-intensive laptop computers for gaming or a shift to less energy-intensive consoles or media streaming devices.

- In many climates, waste heat from gaming contributes to household air-conditioning costs, which will decline as gaming systems become more efficient.

Figure 21: Efficiency Improvements for Three Tiers of Desktop Systems
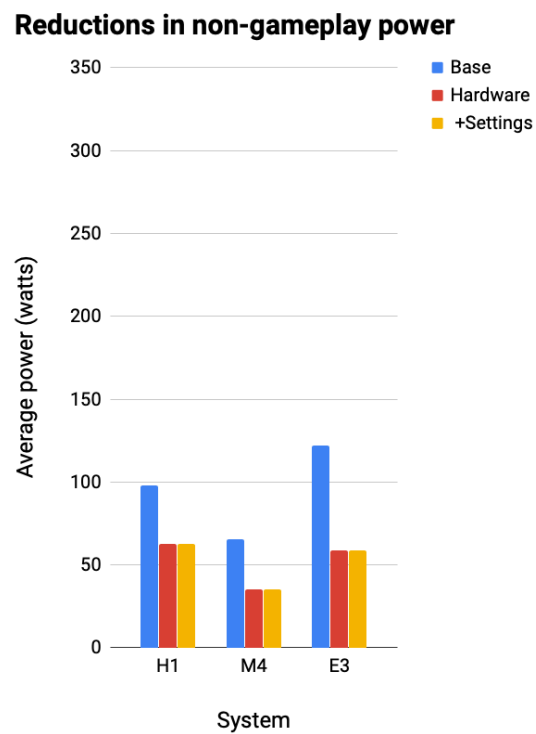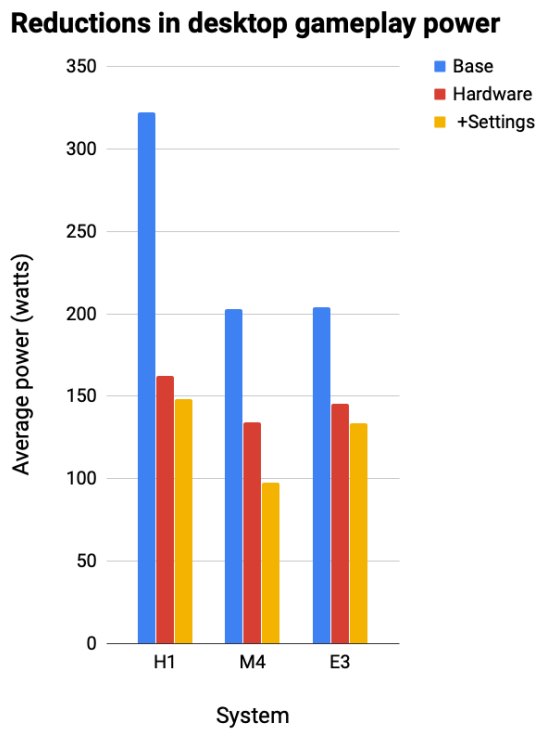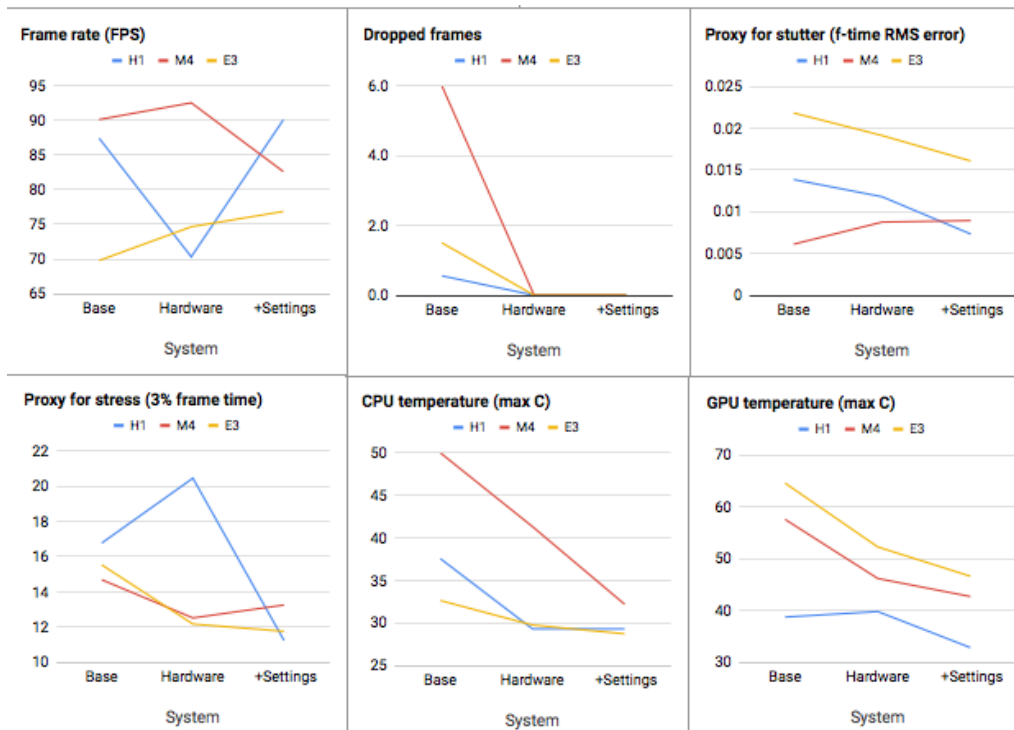
Source: Lawrence Berkeley National Lab

A key observation from Figure 21 is that the energy use of the improved high-end system was in range of that of the entry-level system. Performance and temperature metrics are averages measured during gameplay. Non-energy factors occurring in parallel with the energy efficiency improvements include cases of improved frame rates, improved frame quality, reduced system stress, and significantly reduced CPU and GPU temperatures.

Laptops and media streaming devices are sealed systems, and represent a very small segment of gaming energy use. The researchers did not attempt to estimate efficiency opportunities for these devices.

Efficiency Opportunities for Consoles

As video game consoles are also sealed proprietary systems, the research team did not attempt any direct efficiency improvements to these devices. Rather, the team estimated the historical year-on-year reductions power levels for 7th-generation consoles (Xbox 360, PS3) and fitted these to obtain an average improvement rate of 41 percent by the year 2021. The researchers applied this improvement rate to the latest-generation Xbox One and PS4 systems' power levels, as these are the models that replace older consoles in the stock projections and which will likely be undergoing further improvements, or succeeded by more efficient models. The consoles industry does not readily discuss or publish energy efficiency opportunities going forward.

Real-time Energy Feedback to Gamers

The vast majority of gaming consumers do not particularly understand or prioritize addressing the energy consumption of their gaming systems. Moreover, the wider computer game developer industry does not have a significant built-in market incentive to produce game titles that consider and visualize the game system energy consumption among its primary concerns. Looking at this from the game developer and user's point-of-view, Task 6 of this project began with the hypothesis that easily-assimilated real-time energy reporting readouts, integrated within the gaming user interface, could alter the gamer's consideration of their game system energy consumption.

To test this assumption, the project team documented the current state of the hardware, software and game developer industry ability to deploy real-time energy reporting software implementations that can be implemented in server-client gaming systems (Vaino *et al.,* 2018). The primary research vehicle for this exploration was a proof-of-concept energy reporting software system on high performance computer (HPC) workstations currently in use by the LBNL Engineering Division,[16] running applications such as Computer Assisted Design (CAD), modeling software or scientific data analysis tools.

The software that was developed collected real-time power draw data using APIs provided by the GPU manufacturer. The power draw data was stored on a central database, with metadata about the hardware, operating system, CPU and GPU loads, and running applications.

In addition, within the multiple gaming industry outreach activities and recruitment of Technical Advisory Council members for the project, the team met with three established game developers for ideas that can help integrate game system energy efficiency into the active incentive structures of multiplayer games.

The exploration of technical and gaming industry development factors found that the real-time reporting concept is plausible despite some soluble technology barriers. However, more favorable market conditions are needed before the concept can attract the right gaming industry champions to take on the challenge.

Non-energy Factors

Non-energy factors are often key drivers of consumer interest in improved energy efficiency (Mills and Rosenfeld 1996)—or, conversely, can become reasons that consumers reject the efficiency recommendations. For most gamers, these benefits (or perceived downsides) are decidedly more important than energy use *per-se.*

A current example is the strong desire to achieve wireless VR headsets. First-generation headsets are physically tethered to the PC, creating discomfort and restricted range of motion for the gamer, as well as safety hazards. Energy efficiency may offer a pathway for solving this problem.

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[16] http://engineering.lbl.gov.

In a more generalized example, waste heat production is a side effect of high energy intensity that irks most gamers. All electricity entering the system ultimately becomes heat, and thus a 500-watt gaming system is like a 500-watt space heater. The problem is significant enough that it is some gamers place a portable fan or AC unit next to their gaming area. Conversely, energy savings translate directly into less heat production.

Cooling systems in desktop systems, usually involving multiple fans, are also a source of unwanted noise that many gamers find distracting. More efficient devices can enable the elimination of fans, or algorithms that run the fans only when needed.

Gaming laptops offer an interesting "existence proof" of how non-energy factors drive efficiency improvements. Key design constraints are heat removal and duration of gameplay on a given battery charge, both of which are served by maximizing efficiency so as to reduce waste heat and obtain the greatest number of hours of operation on a given battery charge. Systematically lower energy use is attained by gaming laptops. The advent of the Nintendo Switch is another example of this process, that is, miniaturization and efficiency pursued to achieve portability and long battery life.

There are indications that certain energy efficiency strategies may improve game performance. Following are examples encountered in the testing and market research:

- AMD states that its "Chill" software, which varies frame rate depending on the required rendering loads, can achieve up to 30 percent energy savings (battery life improvements) and reduced GPU temperature, while decongesting the graphics pipeline with unneeded frames thereby improving user experience (37 percent decrease in frame time).[17] This benefit is highly game-specific and negligible for games where activity levels are consistently high.

- Systems are often "over-spec'd", meaning that they are overpowered for the games desired. This results in energy use that does not contribute to performance or user experience. Better system integration will save energy and reduce system cost. In some of the test trials (perhaps due to bottlenecks arising from poor systems integration), under-clocking the GPU reduces power requirements while increasing graphics performance.

- Mismatches in component sizes can create bottlenecks. For example, a CPU more powerful (and energy-using) than needed to drive the GPU will not add value. Again, system integration is the solution to first-cost savings.

- By varying refresh rates to meet the need, G-sync and FreeSync displays can provide imagery that many gamers believe matches the smoothness and quality of that otherwise generated by higher-power GPUs, although the team did not test this hypothesis in the research.

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[17] See https://gaming.radeon.com/en/radeonsoftware/adrenalin/chill/.

- The application of foveated rendering in VR headsets saves energy while enabling better user experience and opening up new opportunities for in-game functionality. According to Nvidia,[18] resolution can be boosted well above normal in the central area of vision even while saving energy overall by relaxing resolution in the periphery, where it won't be noticed. Meanwhile, knowing where the eye is focused will allow game developers to key storylines to where the user is looking.

In defining the efficiency packages, the researchers looked closely at a set of non-energy indicators. The metrics included frame rate, dropped frames, proxies for stutter and system stress, and maximum temperatures in the GPU and CPU. In virtually every case the indicators moved in the direction of improved user experience as efficiency was improved (Figure 21).

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[18] See interview of Nvidia's Anjul Patney in Issue #5 of *Green Gaming News* – see http://greengaming.lbl.gov/newsletter/issue-5.

CHAPTER 6: Statewide Energy Demand and Projections

By applying the baseline unit energy consumption values for each system (weighted by the associated mix of user types and duty cycles) to the current installed base of equipment represented by that system, the researchers have estimated statewide gaming energy use and projections for the future (Figure 22). Solid lines are baseline projections, while dotted lines of the same color represent near-term efficiency improvements for the indicated scenario (same proportionate savings assumptions as Baseline scenario described in the text). The "Frozen efficiency and market shares" case (dotted black line) reflects constant unit energy consumption and unchanging proportionate mix of the various gaming products, while the overall installed base increases. Includes energy associated with displays, local network equipment, and external speakers, as well as networks and data centers involved in cloud-based gaming and video streaming. In the short timeframe of this scenario, savings do not fully reflect stock turnover of core systems and displays. None of these trajectories are intended or presented as predictive forecasts, but, rather, exercises to help outline the bounds of how energy demand could develop under different market and technological circumstances.

Figure 22: Enormous Potential Variations in California Computer Gaming Energy Demand Driven by Market Structure, User Behavior, and Energy Efficiency: 2011-2021
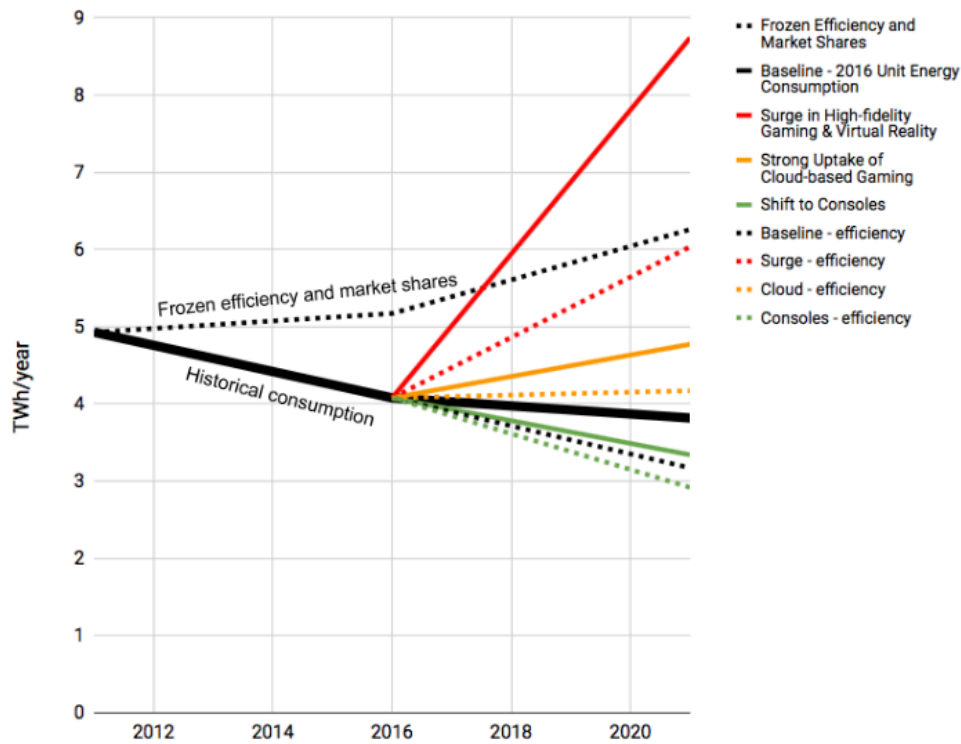
Source: Lawrence Berkeley National Lab

An initial Baseline scenario looks at the effect of structural change at present efficiencies. Providing context for alternate broader structural market developments, the team created three alternative Baseline scenarios reflecting structural and market trends that could drive energy use either upward or downward. The research team cast each scenario in the context of existing and improved efficiencies. The resulting combinatory array of 8 scenarios illustrates an envelope of possible energy futures. The savings estimates thus defined are to be regarded as reflecting full-saturation technical opportunities considered for the particular set of measures considered, as distinct from what might actually be achieved in practice. These improvements could be achieved by any combination of advances emanating unilaterally from industry, choices made independently by consumers, and/or as the result of policy initiatives interjected by third parties. Not all potential savings measures have been assessed. Furthermore, it is equally possible that improved efficiencies will be offset by increased workloads (for example, for streamed VR gaming).

In this stage of the analysis, additional second-order energy use is also estimated. This includes that of displays, household networking equipment and audio peripherals as well as upstream network energy associated with streaming video and games. For cloud-based gaming, the researchers also included energy used in data centers hosting gaming servers, per the method described above.

Cloud-based gaming takes on varying importance in the scenarios. While on the one hand power requirements of GPUs and other componentry in cloud-gaming servers may decline over time, the base systems represent best-available current technology and this project has not scoped possible "technology roadmaps" that could lead to new technology introduction in that segment of the market. Nor has the team modeled the prospective rate of absorption of new technology into widespread use. Furthermore it is equally possible that improved efficiencies will be offset by increased workloads (for example, for streamed VR gaming). Meanwhile, the broader Power Utilization Efficiencies assumed for the base-year data center facilities overall are lower (more efficient) than typical practice and even projected improvements in the tier of facilities currently hosting cloud-servers (Shehabi *et al.,* 2016). They are also not much higher than projected stock-averaged "Best Practices" for the short timeframes of the scenarios. Thus, the researchers did not alter server characteristics or the PUE-1.5 assumption across scenarios. This is an area that merits future investigation.

Games can also be downloaded from the Internet, which results in incremental energy use associated with Internet data transmission. Insufficient data are available on the prevalence of this activity, particularly by system type and model, to make rigorous estimates. Other secondary sources of energy use associated with gaming include that in manufacturing and distributing games and gaming equipment, but insufficient data were available to incorporate that in the analysis.

A key assumption for both cloud-based gaming and game downloads is the rapidly evolving network electricity intensity (kWh/GB of data transmitted).[19] This strongly attenuates the

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[19] Per Aslan *et al.,* (2018) the researchers assume a rate of 0.1449 kWh/GB in 2011, 0.0266 kWh/GB in 2016, and 0.0049 in 2021.

energy that would otherwise be used in association with streaming and cloud-based gaming. The researchers assume that the streaming rate stays the same, although it could well go up given trends and the need to transmit increasingly large amounts of data.

Past and Present Structure of Demand

Innovations in gaming technology (hardware as well as software) are progressing at a rapid pace, consumer preferences are evolving, and the Internet is becoming increasingly amenable to high-performance streaming gaming. Near-term changes in market factors driving energy demand for gaming are far more dynamic and difficult to predict than those of more commonplace energy-using equipment such as water heaters and air conditioners.

Historically (2011 to 2016), the rapidly changing nature of the installed base is evident (Mills *et al.,* 2018). Between 2011 and 2016, a shift to a less energy-intensive mix of gaming products in the marketplace and improvements in display efficiency roughly offset the growth in electricity demand that otherwise would have occurred due to increasing numbers of systems in the installed base. However, actual gaming electricity demand fell considerably as a result of significant reductions in the electricity intensity of internet infrastructure which lowered energy use for video streaming. The researchers estimate California gaming electricity demand at 4.9 TWh for the year 2011.

Entry-level PC systems (with their relatively low energy intensity) dominated in the past, but lost significant market share to Mid-range and High-end systems and consoles, and continue to do so going forward. Gaming laptops saw a decline in each tier, while consoles saw an approximately 20 percent increase in the installed base, as well as the introduction of media streaming devices that shift the gaming workload to data centers. The decline in the installed base of PCs used for gaming between 2011 and 2016 is attributed primarily to the rising popularity of mobile gaming together with a migration from casual to higher-end PCs for those who stay with that type of platform. Additional sources of attrition are broken or dormant systems and those that are used less frequently than the one-hour-per-week cutoff that defines the use model.

The researchers estimate total gaming equipment energy use (across the duty cycle) in California was 4.1 TWh as of 2016. When allocating network energy, displays, and other peripheral loads to the respective system types, consoles are responsible for 66 percent of the total system-level energy use for computer gaming across the duty cycle, followed by 31 percent for desktops, 3 percent for laptops and less than 1 percent for media-streaming devices (Figure 23), with the shares shifting toward PCs by 2021 in the Baseline scenario. In the upper panel, the energy use of each system includes associated displays and peripherals (audio, local networking equipment) as well as upstream network and cloud-based computing workloads. Media streaming devices were just emerging in 2016 and their energy use was nominal at that time. When considering only energy use at the core system level, PCs and consoles consume similar amounts of energy by 2021 (0.9 and 1.2 TWh/year, respectively).

Computer gaming—including the primary systems together with associated connected devices such as displays and upstream network energy and data centers—is responsible for nearly a

fifth (19 percent) of all energy consumed within the residential miscellaneous end-use in California. Computer gaming emerges as the second largest category of consumer-electronics plug loads in the state, second only to television and other media viewing, consuming about 25 percent of the total.

Figure 23: Structure of California Gaming Energy Use: 2016
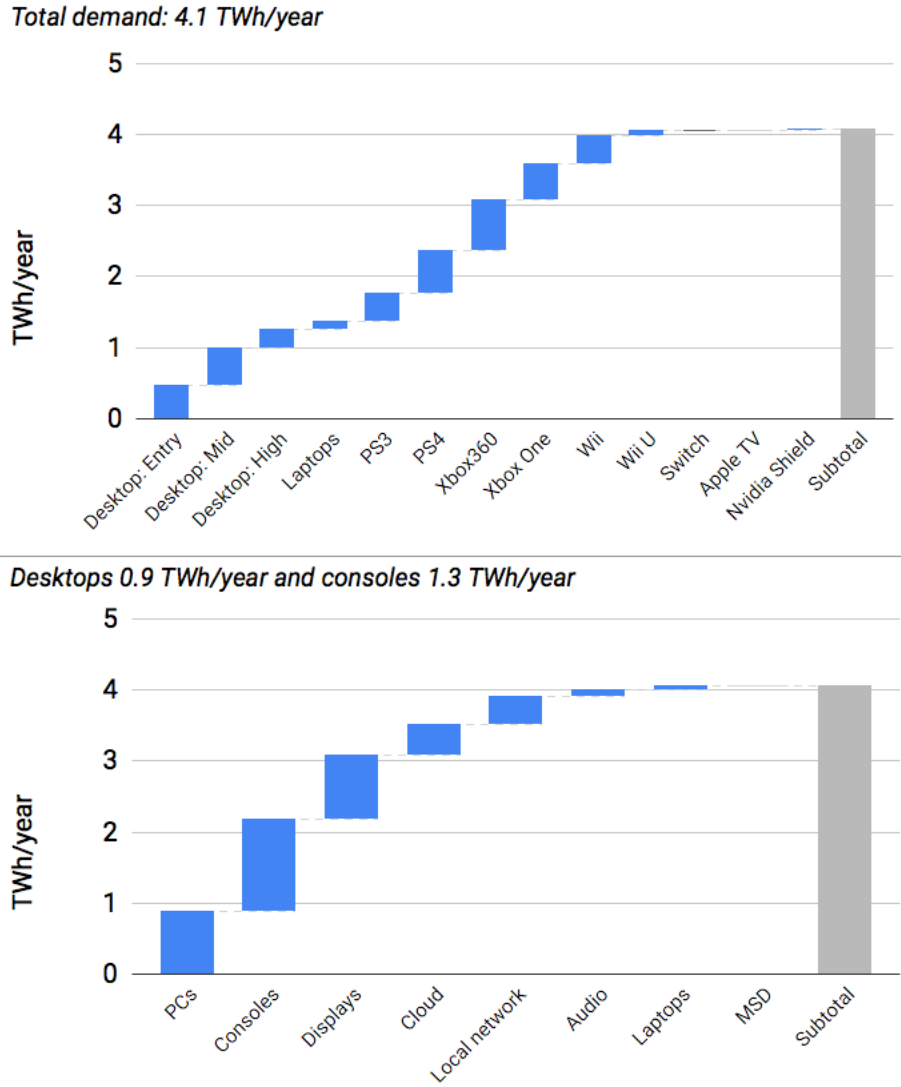
Source: Lawrence Berkeley National Lab

Baseline Scenario: 2021

The research team defined a primary Baseline scenario for how the installed base might evolve to the year 2021. Market shares of Entry Level, Mid-Range, and High-End systems shift towards the more energy-intensive end of the spectrum by 2021. The year-2016 unit energy consumption for each system is held constant in this reference case, although the long-standing trend towards improved efficiency in Internet infrastructure is assumed to continue. The resulting California electricity demand is 3.8 TWh in 2021.

Energy Efficiency Opportunities: 2021

Applying the penetration of efficiency options defined in the preceding sections to the Baseline scenario results in a reduction in aggregate electricity demand in 2021 from 4.1 to 3.5 TWh/year (15 percent). This reduction represents the diverse bundled impacts of systems, displays, peripherals, and so on For the Baseline scenario, two-thirds of the 650 GWh/year savings in 2021 are attributable to PCs with the balance from consoles. The underlying per-unit package savings for are blended with other components, some of which are not addressed, such as networks and data centers hosting cloud-based gaming servers. Savings are also attenuated due to the short timeframe in which not all equipment changes over.

Alternate Baseline Scenario 1 – Surge in High-fidelity Desktop Gaming and VR: 2021

In this scenario, falling prices, higher-performance processors, sharper displays and virtual reality headsets, combined with a swing of consumer preferences away from mobile and console gaming contribute to an even greater intensification in growth in PC gaming and high-fidelity displays than projected in the primary Baseline scenario. This trend is magnified by increased focus on operating systems tuned for gaming and a trend towards availability of console titles for PC gaming,[20] as suggested by recent indications that Microsoft may essentially convert its Xbox line into compact television-linked PCs. Thus, of most importance in terms of energy, the 2021 projections reflect an underlying shift towards higher-performance, and more energy-intensive desktop PCs as well as larger and higher-resolution displays and televisions used for gaming. Under this scenario, the proportion of high-end PCs increases while many console users convert to PCs (mid-range and high-end systems). In parallel with these developments, virtual reality technology becomes more comfortable and convenient thanks to wireless support, with expanding libraries of applicable titles, and lower purchase costs, resulting in steeply increased penetration of VR headsets into the console and mid- and high-end PC installed base. The trend towards increased time spent gaming continues, with 25 percent more time spent in gameplay and 20 percent of gamers implementing CPU overclocking.

Alternate Baseline Scenario 2 – Strong Shift Towards Cloud-

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[20] For an illustration of this trend, see http://www.xbox.com/en-US/windows-10.

based Gaming: 2021

In this scenario, faster networks and purpose-built thin clients lead to more reliance on cloud computing, which triggers some restructuring of the installed base towards far less energy-intensive system choices on the customer side, and resultant load growth occurring instead in data centers and downstream networks. The popularity of streaming gaming technology explodes due to new compression techniques and an intensive infrastructure push that lays fiber to many more California households, coupled with attractiveness of subscription pricing compared to purchasing gaming titles. Industry also foresees growth in the overall number of gamers due to the increased convenience and lower investment cost for consumers (Eisler 2017). Under this scenario, three-quarters of gaming hours shift to cloud-gaming with media streaming devices on the user side. In addition, the total number of gamers increases due to the lower cost and appeal of this new gaming format. As current on-line gamers tend to game more, time spent in gameplay increases by 25 percent across the various platform types. In the near term, local gaming devices (PCs and consoles) continue to be used on the client side, with their associated "non-gaming" energy use and loads during gameplay equivalent to those while streaming. The research team assumed a Power Utilization Efficiency (PUE) in the data centers of 1.5, as described above. Meanwhile, centralized computing allows for more coordinated improvement of component efficiencies and "right-sizing" of computing infrastructure to meet the gaming load suggested by the user. Energy management of non-processor loads (HVAC) in data centers must be considered and managed separately by data center builders and operators.

Alternate Baseline Scenario 3 – Some Personal Computer Gamers Switch to Consoles: 2021

In this scenario, improved console performance and competitive pricing, coupled with growing market concern about energy costs and other consequences of energy use, results in conversion of half of laptop and desktop users to consoles. A corresponding proportion of displays change to those typical of consoles.

Gaming Energy Futures for California

The heavy dotted black curve in Figure 22 labeled "Frozen efficiency and market shares" represents a thought experiment (rather than a full-fledged scenario) in which the mix of product types does not change (as compared to the Baseline scenario) as the stock of gaming platforms grows. Unit energy consumption is also held constant. Year-2016 Baseline consumption is 21 percent lower than this "Frozen efficiency and market shares" level, and the 2021 consumption is 39 percent lower. In contrast, the solid black curve indicates the effect of projected structural changes, in which energy demand declines somewhat due to relatively large numbers of lower-energy-using consoles being added to the installed base, offsetting energy demand increases in other segments. The Baseline energy efficiency scenario yields a 17 percent energy demand reduction from this Baseline scenario.

The other curves indicate outcomes for the three alternate market scenarios, at current (solid lines) and with corresponding cases (dashed lines) representing improved efficiencies. Savings at the individual systems level are substantially higher than the aggregate values shown because loads 2016 stock of systems and displays that hasn't turned over, loads in data centers are not affected, and so on. Figure 24 disaggregates demand by gaming system type. This Includes energy associated with displays and peripherals, as well as network and cloud-based workloads.

Figure 24: Consoles or PCs Dominate Energy Demand, Depending on Scenario
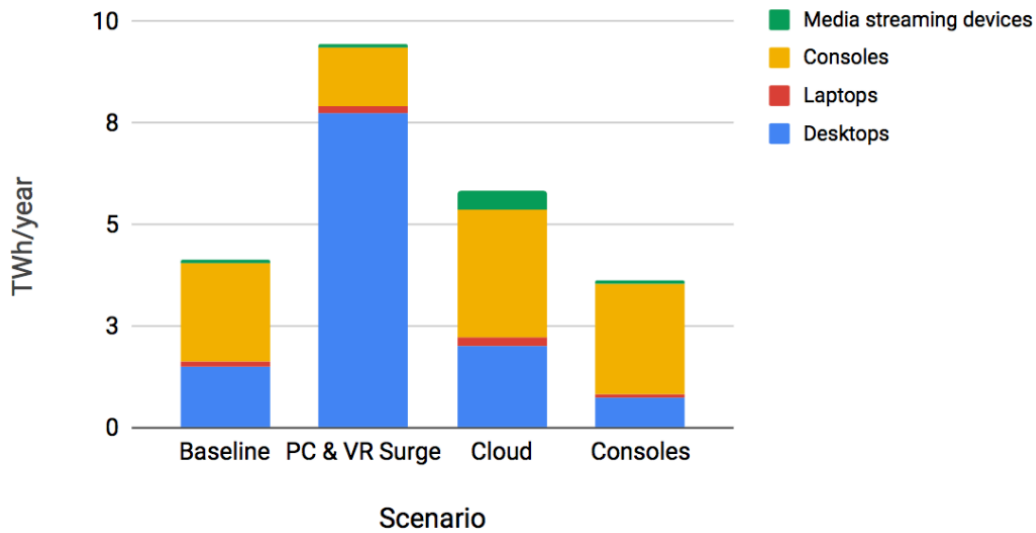
Source: Lawrence Berkeley National Lab

Figure 25 further segregates the results by user type. Intensive gamers tend to be the user group associated with the largest segment of energy use across all platforms. This includes energy associated with displays and other peripherals, as well as network and cloud-based workloads. Consoles and PCs alternate in dominating energy demand, depending on scenario.

Figure 25: The "Intensive" User Type is the Dominant in Most Cases and Scenarios
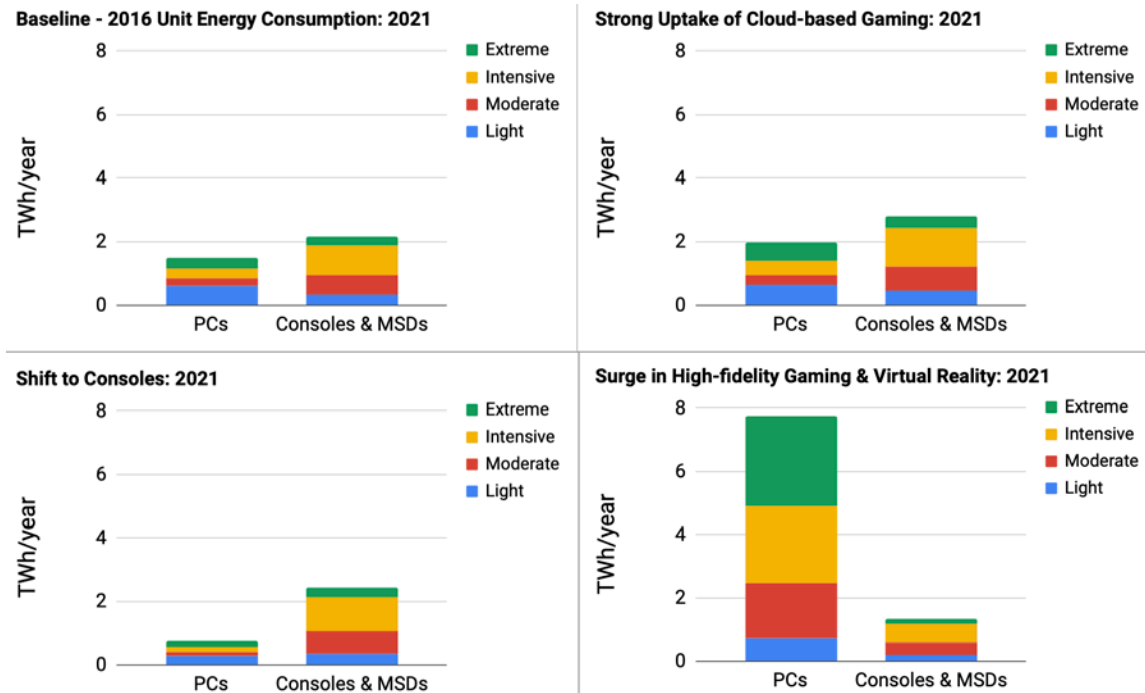
Source: Lawrence Berkeley National Lab

Figure 26 breaks down the total electricity use of the primary Baseline and alternate scenarios by system type (left column) and by locus of electricity use, for example, systems, networks, peripherals, on the right column. It is readily visible that alternative market trajectories could be very disruptive in terms of the magnitude as well as the structure of computer gaming electricity demand. The key findings, by scenario, are as follows:

- Baseline Scenario: Of note, given that energy efficiency is not considered in this case and despite an increase in total installed base, total electricity consumption decreases by 6 percent from 2016 levels. This is due to structural shifts in the installed base towards less energy-intensive gaming systems, that is, increased market share of consoles and declining electricity use among the newer consoles, as well as projected improvements in internet electricity. As in the 2016 baseline conditions, consoles remain the highest electricity-using component (in aggregate), followed closely by electricity use in associated networks and data centers. Efficiency options result in a 22 percent reduction in aggregate demand.

- Surge in High-fidelity PC Gaming and Virtual Reality: The greatest demand growth from 2016 levels (114 percent) occurs through the "Surge" scenario, in which high-fidelity PC gaming becomes more popular and PC electricity use consequently comes to dominate the landscape. Meanwhile, network and cloud-based gaming electricity eclipses that of consoles. Efficiency options restrain the growth to 48 percent

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- Strong Uptake of Cloud-based Gaming: In the scenario where cloud-based gaming becomes wildly popular, overall computer gaming electricity demand grows by 17 percent. Aggregate network and data electricity is larger than that used locally by consoles or PCs. Efficiency options constrain the growth to 2 percent.

- Shift to Consoles: Electricity demand declines by 18 percent in the scenario where consoles replace half of the more energy-intensive PCs. Consoles become the largest segment of electricity use, but in the context of lower combined demand across all gaming activity. Efficiency options reduce the demand by 28 percent.

- Other possible outcomes: A combination of increased cloud-based gaming and the transition to more PC gaming, could yield a far higher electricity demand trajectory – around 11 TWh/year.

Examples of factors that could give rise to higher energy consumption than captured in these scenarios include introduction of new energy-consumptive peripherals (for example, 8k displays, now entering the market), more energy-intensive user experiences requiring more computationally intensive software (for example, cloud-based gaming for portable devices or streaming virtual reality for the systems evaluated here), VR systems that function on Entry-level and lower-performance Mid-range PCs, or equipment price reductions inducing greater growth in the installed base. The energy embodied in manufacturing or distributing games (disks or by networks) or gaming equipment has not been included in this analysis. The research team has not estimated the energy-conversion losses from charging laptops. Given the dominance of consoles in the gaming equipment installed base, introduction of consoles that use more power than existing systems and do not improve as their generations mature would drive overall gaming energy use higher.

Figure 26: California 2021 Scenarios: Systems (left) and Categories (right)
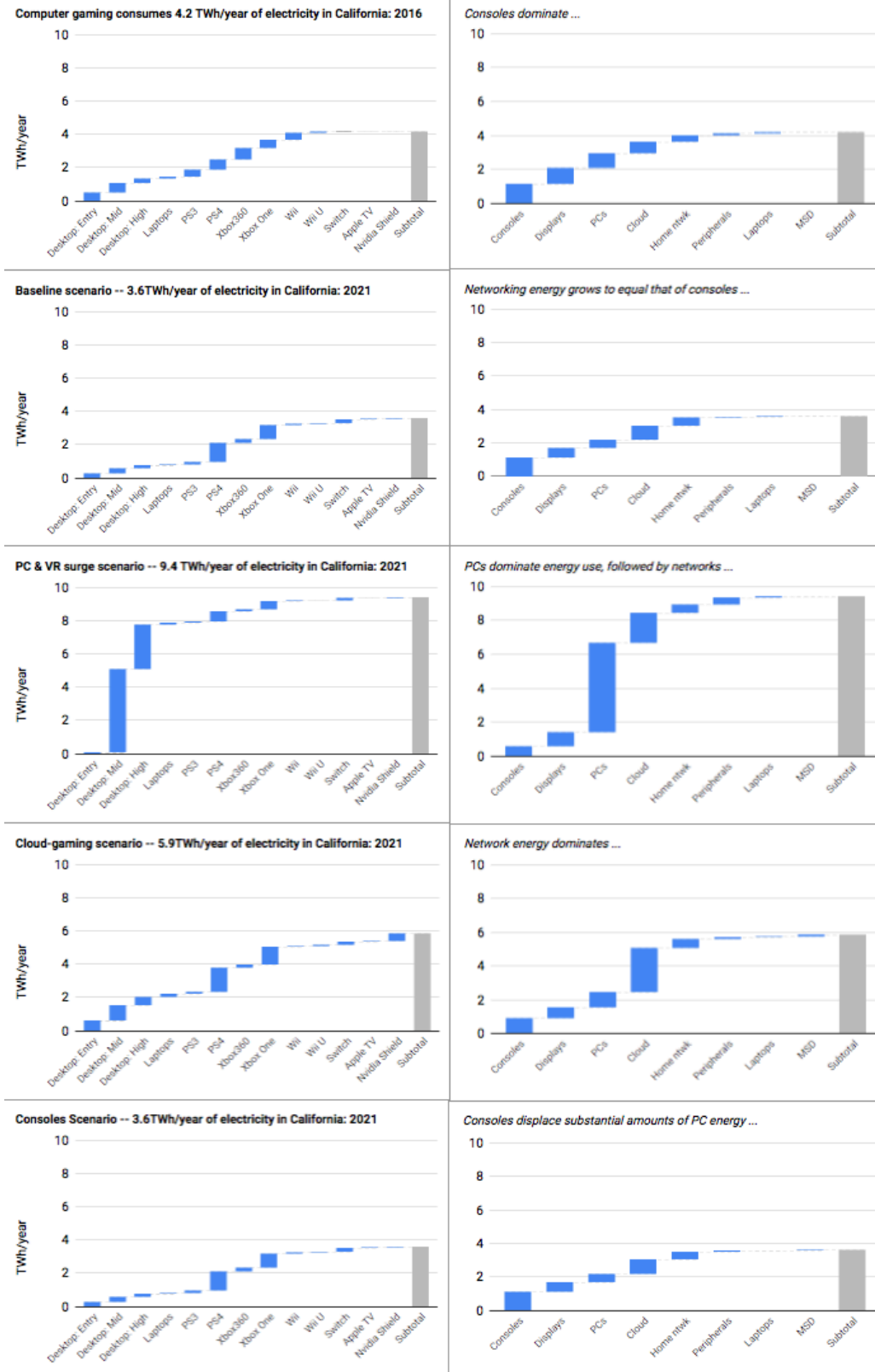
Conversely, examples of factors that could give rise to lower energy demand include reduced popularity of gaming, energy management in data centers, breakthroughs in energy efficiency beyond those described here, and the powerful non-energy drivers that are the primary shapers of gamer decision-making. Game choice and design can influence energy use upwards or downwards. Again, given the dominance of consoles, breakthroughs or shifts among currently available brands and models to less energy-intensive choices (such as the Nintendo Switch and PlayStation Classic) would drive aggregate energy demand downwards.

Of importance for energy planning, different system types assume varying levels of importance in the scenarios. PCs become the dominant energy users in the "Surge" scenario, representing about 84 percent of total gaming energy demand. Conversely, in the Consoles scenario, consoles' demand declines in absolute terms (offset by the introduction of lower-intensity devices such as the Nintendo Switch), but represents about 76 percent of total baseline gaming energy demand in 2021. Media streaming devices are responsible for 7 percent of total demand in the Cloud scenario. A breakdown of projected aggregate energy use and unit consumption by system type and scenario is found in Mills et al., (2018). Laptop and media streaming devices represent a very small fraction of total demand in all cases.

Cost of Ownership, Statewide Energy Expenditures, and Greenhouse-gas Emissions

Gaming involves considerable investment on the part of individual consumers, more than most other plug loads. The desktop systems evaluated ranged from several hundred to several thousand dollars, while consoles are in the $250 to $500 range.

Operating costs are an often-hidden element of the total cost of ownership. These are driven by the combination of energy use and energy prices. Across a spectrum of system types, user types, and energy prices, a gamer can spend anywhere from $5 to $1,700 on energy over a 5-year product life. In some cases, these values approach or even exceed the purchase price.

From an aggregate perspective, the 4.1 TWh/year that computer gaming systems use today in California translates to approximately $700 million/year[21] million in energy expenditures, rising to $1.1 billion/year as the stock grows but without efficiency improvements or structural changes that can influence energy demand. Under the most energy-intensive ("Surge") scenario, costs rise to $1.5 billion per year, while they fall to $500 million/year in the least energy-intensive ("Consoles" plus efficiency) scenario.

Electricity is a particularly carbon-intensive energy source in most markets. California's grid is relatively "clean", with an emissions factor of 0.730 lbs. CO_2-equivalent/kWh. Coupled with the aggregate energy demand estimates from this study, statewide greenhouse-gas emissions

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[21] Assuming the Energy Commission default state-average residential electricity price of $0.1698/kWh. At the marginal prices where this actually occurs, the value would be approximately 50 percent higher.

associated with computer gaming are approximately 1.5 million tons today, ranging from 1.2 to 3.2 million tons in the future depending on how market structure and efficiencies evolve.

Energy consumption, expenditures, and emissions are summarized in Table 1. Costs computed at average residential electricity prices. At the marginal prices where this actually occurs, the value would be approximately 50 percent higher.

Table 1: Annual California Energy Consumption, Expenditures, and Emissions for Computer Gaming

	Annual electricity use (TWh)	Annual electricity expenditures ($billion/year)	Annual greenhouse-gas emissions (Tons CO2-eq)	Change from 2016
2016	**4.078**	**$0.7**	**1.5**	
2021				
Frozen efficiency and market shares	6.258	$1.1	2.3	53%
Baseline	3.818	$0.6	1.4	-6%
with efficiency packages	3.171	$0.5	1.2	-22%
PC & VR Surge	8.739	$1.5	3.2	114%
with efficiency packages	6.034	$1.0	2.2	48%
Cloud gaming	4.772	$0.8	1.7	17%
with efficiency packages	4.170	$0.7	1.5	2%
Consoles	3.440	$0.6	1.3	-16%
with efficiency packages	2.918	$0.5	1.1	-28%

Source: Lawrence Berkeley National Lab

CHAPTER 7:
Policy and Planning Pathways for Achieving Greener Gaming

Virtually all demand-side energy management policies are based on a philosophy of reducing energy demand while maintaining or improving service levels. For most energy-using technologies, the service levels are reasonably well characterized and unchanging over time. Examples include desirable water temperatures, adequate light levels, sufficiently clean clothes, and so on In other cases, where the service may be changing gradually over time or across product categories (for example, with larger and larger refrigerators), normalizations of efficiency metrics (for example, energy use per cubic foot of refrigerated space) are readily conceived and deployed through standards.

Gaming technology has certain fundamental differences from most other technologies familiar to energy policymakers. Perhaps most challenging in this regard is the highly varied and subjective nature of the services provided (Table 1), as well as users' varying perceptual abilities and the values they place on these services.

The gaming duty cycle is also more varied than that of most other products, and includes, in addition to gameplay, activities such as web browsing, video streaming, and music playing. In the case of PCs used for gaming, conventional computer tasks are also often performed on these systems. The duty cycle characterizes the time-weighted mix of these uses, but in practice behavior varies quite widely. While some avid users may game many hours per day, others may game far less and rely on the device primarily for other functions. And energy use by game or simulated game benchmark also varies widely. These factors confound efforts to define a "typical" gaming system, forecast energy use, or construct robust energy-per-performance metrics that have significance and meaning for a wide variety of consumers. Although the gaming-PC industry and gamers themselves focus heavily on it, frame rate is an inadequate metric for describing the widely varying contributors to user experience.

Conventional PCs are only in true active mode (processor working) a small proportion of the time, and thus active power requirements are much lower than for PCs intended for gaming. This is why existing policies for PCs focus only on non-active modes of operation. For gaming devices, however, the majority of energy use can easily fall into (active) gaming mode, which thus cannot be ignored.

Some sort of energy-per-performance assessment process is essential to certain policy strategies applicable to computer gaming. Specialized metrics can be highly useful for certain inter-product comparisons and can contribute to consumer awareness of energy issues. The use of such metrics for regulatory purposes is not, however, particularly promising as it is highly subjective and cannot capture the full user experience. Fuel-economy ratings serve an example of how problematic policymaking based on "benchmarking" can become when it doesn't reflect how consumers actually use products. As driving conditions and habits changed over time (and

roadways became more congested), the United States fuel-economy ratings eventually under-predicted actual energy use by more than 30 percent in some cases (USEPA 1980), thereby reducing ratings' credibility in the eyes of consumers and their ability to predict energy use and savings for policymakers. These types of influences, however (thermostat settings, patterns of water consumption, and so on), exist for most other products for which successful energy standards have been developed. While energy-per-frame-rate cannot capture all the nuances, if it reflects *relative* efficiency rankings, it may be workable in contexts such as relative tracking system performance in energy efficiency testing.

Certain peripherally connected technologies are produced by vendors other than the PC or console manufacturer. These include primarily external displays (including televisions as well as VR headsets), but a wide variety of products such as powered racing simulators are in the market. Moreover, as described above, each game imposes a different energy load on a given gaming platform, with energy use further varying throughout the course of the game. Given these factors, gaming hardware manufacturers cannot unilaterally determine the ultimate energy use and efficiency of their products. The combined implication of these factors is that gaming is arguably among the very most difficult energy-using activities to quantify in the context of performance and user experience.

In terms of attaining overarching policy goals of reduced aggregate energy demand compared to 2016-efficiency scenarios, there are considerable downside risks of basing performance targets on a single metric. Unfortunately, frame rates are one of the few readily quantifiable metrics. Responding to technology changes and/or shifting user needs, technology manufacturers and game developers may focus on user-experience factors not reflected in the metric. This would be exemplified by efforts that improve frame-delivery while holding frame rates constant, for example, FreeSync or G-Sync displays would not be properly evaluated. Conversely, measures that reduce frame rate while holding power use constant but maintaining or improving user experience would be misinterpreted as a *reduction* in efficiency where metrics like fps/W are used. Moreover, selecting a single metric could thus stifle innovation while failing to recognize true efficiency improvements and their relation to user experience.

As previously noted, while energy efficiency (for example, watts per unit of performance) may be increased, this does not in and of itself ensure that absolute energy use is being managed downwards. In fact, the recent history of improved efficiency of desktop computer graphics cards has been paralleled by a level or increasing absolute energy use in many cases. Console manufacturers have demonstrated a more decisive reduction in gaming power requirements in recent years. For a broader perspective, viewed over the much longer history of gaming, Pong and other rudimentary games of the 1960s ran on machines drawing perhaps 10 watts, while those (far better-performing devices) of today draw many hundreds of watts. When considered in terms of the efficiency metric fps/W, Pong would be deemed 10-times more "efficient" (at 3 fps/W) than the best High-end system (H2, at 0.3 fps/W), but this is if little significance in an energy policy context given the vast differences in actual service levels provided and user expectations.

These challenges notwithstanding, there remain many productive avenues for policy and program design and improved collection of data essential for policymaking. As the scenarios

go, the dominant energy-using system in the future could be either PCs or consoles, depending on how the market evolves. That said, absolute energy demand is far lower in the scenarios dominated by consoles, whereas scenarios in which substantial demand growth manifests are driven by PCs. Moreover, the majority of energy efficiency gains in the Baseline scenario accrue from PCs. Hence, policy attention to PCs is of particular importance, particularly given the paucity of such attention to-date.

Market Tracking and Demand Forecasting

To pinpoint the relevance and potentially effective targeting of policies and programs, it is essential to more precisely characterize the market. Rapidly changing conditions (platform preferences, technologies, and user demographics) create a need for *ongoing* in-depth energy-relevant market research. This information is also necessary for forecasting and updating savings potential projections. Of particular importance is better data on the time users spend in gameplay and other parts of the duty cycle as well as their energy-relevant settings (for example, number and type of displays in use, in-game settings, overclocking, power management practices, choices of peripherals). Consideration should be given to incorporating such information in existing energy end-use surveys, and/or fielding specialized surveys for this purpose. The Consumer Technology Association's periodic surveys currently provide the best-available information at the national scale (Urban *et al.,* 2017), but they do not delve deeply into gaming. California-specific surveys have yet to be conducted.

Consumer Information and Tools

Consumer information on gaming energy is scant and unstandardized. Campaigns and information could be carefully tailored for diverse user audiences ranging from young children to amateur adult gamers to technically focused gamers. Promulgation of consensus energy-per-performance metric protocols and associated test procedures would make information much more consistent across sources, but development of such protocols has thus far proven elusive. This would entail stipulated duty cycles beyond the gameplay mode. The mismatch between measured power and nameplate ratings suggests need for improvement in that area. This mismatch is present in many other consumer products.

Web sites supporting the common practice of do-it-yourself (DIY) assembly of PCs for gaming could aid consumer decision-making by adding more energy information to their reports and product reviews. Respected industry sources such as PCPartpicker and Tom's Hardware have enormous platforms for such information. Both organizations expressed interest in promoting energy efficiency, but more persistent drivers are needed to keep their long-term attention on the subject due to fast-moving, consumer-driven gaming market pressures that dominate their businesses.

Consumers are also generally unaware of the effect of no-cost user-side changes to the hardware, software, or firmware, as well as game choice and in-game settings. Product reviewers tend to focus less on these variables than on hardware options.

A promising means of supporting consumers is to create a flexible web-based energy cost calculator in partnership with existing portals such as PCPartpicker and Tom's Hardware, allowing for user-entered assumptions about duty cycle and gameplay preferences. Various entities have offered rudimentary calculators for gaming, but they rely heavily on default data, furnish information only on power (not energy)[22], or address only one component in the system (for example power supplies[23]). A more comprehensive tool could support consumer evaluations of the value of energy saved through no-cost behavioral changes or the cost-benefit tradeoffs of purchasing more efficient equipment, and be useful to energy analysts as well.

Engagement with the Game-development Industry

As found in this study, energy use varies widely by game even on a particular gaming device. Many of the design decisions made by game developers have energy implications. Examples include complexity of scene, textures, presence of fine particle effects such as smoke, and so on Moreover, in some cases (for example, in implementing DVFS techniques such as "Chill") game developers need to code their applications to accept associated external instructions. Game developers have not historically incorporated energy considerations in their design process. It could prove fruitful to enable game developers to obtain real-time feedback on the energy consequences of their design decisions and perhaps establish a set of best practices in this regard. The results of Task 6 in this project may be of use in that regard. Perhaps even more importantly, opportunities may exist to work with the creators of game-development engines – there are 17 such engines, in addition to proprietary in-house engines used by some developers. Competitions could be created to encourage exploration and recognize innovators. To engage gamers, energy performance feedback could be incorporated into the gaming experience, with gamers receiving merit (for example, "buffs" or "power ups") for optimizing energy use during their session. Games could offer an optional "eco-mode", which would load settings appropriate for minimizing power requirements.

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[22] See http://energyusecalculator.com/electricity_gameconsole.htm.

[23] See https://outervision.com/power-supply-calculator.

Voluntary Game Ratings

As demonstrated above, game choice has enormous influence on energy use. Energy labeling of games may not be practical, as energy use for a given game varies widely across platforms. However, establishing a relative rating, or coarse "A-F" scale may be possible. As user experience is so subjective, it would be left to consumers to weigh these ratings in the context of other amenities of the game. The International Game Developers Association's existing self-regulatory practices, which address issues such as violence, sexism, Internet privacy, and positive impacts of video games, and the Entertainment Software Rating Board's content ratings for parents[24] may provide models that an interested third-party could offer to the marketplace. Creating new energy-based game genres would be a complementary way to categorize games, as it is clear from the assessment that, perhaps counter-intuitively, energy use does not track genre among PCs or consoles.

Voluntary System Ratings

Energy ratings can conceivably be applied to integrated systems (as distinct from individual components), although there are serious complications, discussed at length above. ENERGY STAR®'s v6.0 voluntary rating for mainstream PCs is largely ineffective for gaming devices given that it does not address active modes of operation, such as gaming. The United States EPA once considered labeling for consoles, but they struggled with finding an appropriate energy-per-performance metric and there was not enough product diversity to have meaningful thresholds even had they developed an acceptable methodology.

Arising from a policy recommendation in a 2009 study, the three major gaming console manufacturers (Sony, Microsoft, and Nintendo) became engaged with the European Commission in developing a voluntary agreement on improving the energy efficiency of game consoles.[25] The parties adopted a "self-regulatory approach", which they describe as more effective and adaptable than formal regulation. Per the official website:

> "The Voluntary Agreement commitments industry must make regarding maximum power limits and auto-power down for different types of mains-powered game consoles 'placed on the market' within EU countries (except those consuming under 20 W). Commitments made under the Voluntary Agreement will improve game console energy efficiency without compromising console performance and the gaming experience. Gamers will also benefit by receiving additional information on the energy consumption of their consoles and instructions on how to minimise energy consumption."

The EU agreement focuses on non-gaming modes (and calls for automatic power-down), but does require that manufacturers measure and publicly report gaming-mode power requirements. Identifying a methodology for implementing this requirement has proven to be an elusive goal (Koomey *et al.,* 2017).

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[24] See https://www.igda.org/page/advocacy and https://www.esrb.org/ratings/ratings_guide.aspx.

[25] See http://www.efficientgaming.eu.

Lack of attention to PCs and laptops reflects a lack of perspective on the importance of PC energy (in gaming mode, as well as other parts of the duty cycle). There is risk of a perceived double standard if policymakers impose requirements on consoles while turning a blind eye to PCs used for gaming. These PCs should be a key concern for energy policymakers, particularly given their rising popularity and energy intensity. Reinforcing this point, the long-standing trend for consoles is towards decreasing power requirements while that for PCs does not yet seem to be consistently following that pattern.

Voluntary Component Ratings

Component-level ratings for gaming hardware may be more viable than system-level ratings. Voluntary rating systems have thus far been successfully applied to only two of the components found in gaming systems: power supply units (80 Plus) and displays/televisions (ENERGY STAR®). Building upon these initiatives, ratings for other components could be considered, for example based on the efficacy of power management. For CPUs, GPUs, and motherboards this might include the ratio of peak to idle performance under standardized conditions (as a proxy of power management). As console and media-streaming-device power supplies are not included in 80 Plus, their efficiencies could be more carefully studied to determine the need for efficiency improvements. Any strategy would require careful policy design, as amenities vary and the definition of "similar" product classes would be more difficult than for more common products.

Aside from the two examples given above, PC components are rarely energy labeled on the packaging. In some cases, the Thermal Design Point (TDP) of CPUs and GPUs is available online or inside the packaging. However, this metric may be confusing to consumers, as it is expressed in (thermal) watts yet has been shown to often deviate significantly (Mills *et al.,* 2017) from actual power requirements. Electric power requirements information is generally not included on internal gaming component packaging or spec sheets. While 80 Plus ratings are often shown as bands on packaging, the specific efficiency levels are not necessarily stated. Displays falling under the ENERGY STAR® program receive a "yes/no" rating for compliance, but power is not listed. Official nameplate ratings (even TDP) for motherboards are not available to consumers.

As demonstrated in this report, power requirements vary considerably depending on the test procedure, which game is being played, and so on Thus, to have any sort of product labeling an agreed representative testing protocol must be identified. One alternative is the derivation of a relative performance score based on component efficiencies given to a system, as is done with the Enervee rating.[26] However, such a score would not necessarily be predictive of actual energy use, which will vary based on contextual factors. Issues such as the frequent spikes in power use during idle mode suggest the need for real-world idle test cycles rather than idealized ones.

Mandatory Standards and Ratings

The latest California standard for personal computers effectively excludes those purposely

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[26] See https://enervee.com/video-game-consoles.

built for gaming. This occurs by virtue of exclusions for "high-expandability" computers, which means a computer with any of the following:

(1) An expandability score of more than 690;

(2) If the computer is manufactured before January 1, 2020, a power supply of 600 watts or greater and either:

(a) a first discrete GPU with a frame buffer bandwidth of 400 gigabytes per second (GB/s) or greater; or

(b) a total of 8 gigabytes or more of system memory with a bandwidth of 432 GB/s or more and an integrated GPU.

(3) If the computer is manufactured on or after January 1, 2020, a power supply of 600 watts or greater and either:

(a) a first discrete GPU with a frame buffer bandwidth of 600 gigabytes per second (GB/s) or greater; or

(b) a total of 8 gigabytes or more of system memory with a bandwidth of 632 GB/s or more and an integrated GPU.

Moreover, by virtue of omitting energy use during gaming mode, the standard does not effectively address high-end PCs used for gaming or the perhaps some conventional PCs that are used for gaming.

The three major console manufacturers under a European Self-regulation Initiative have proposed establishing automatic power-down modes and "power caps" for certain non-gaming modes for consoles (Microsoft, Nintendo, Sony Interactive Entertainment 2017).

There are many vagaries of energy-per-performance metrics, a process upon which many regulatory measures depend. Even were gaming-mode system-level standards to be workable, a higher-level challenge is that the pace of technology change is an order of magnitude faster that the rate at which regulatory processes can be carried out. Scope may exist for component-level standards, for example, regarding power management in CPUs, GPUs, or motherboards. The benefits of component-level standards would spill over into mainstream PCs as well.

Cloud-based Gaming

Cloud-based gaming is emerging as an increasingly significant source of energy use. Fortunately, many energy efficiency programs and policies already address data centers, but their focus is primarily on the infrastructure (HVAC and power conditioning) rather than the servers themselves. As these installations are highly centralized and implemented by sophisticated parties, there is opportunity to engage at a high level and with economies of scale. However, the majority of gaming data servers are co-located in data centers managed for other primary uses, which creates inertia in the process of implementing energy efficiency. Partnerships would be useful once the industry begins to build dedicated data centers for cloud gaming. Much more analysis is necessary to clearly characterize this source of gaming energy

use and to identify efficiency opportunities within these specialized servers, and how to minimize part-load losses.

Broader Applications of Gaming-grade Computers and Componentry

While the locations of gameplay are classically in the home, it is likely that some amount occurs in workplaces (and thus manifests as "non-residential" use). Some casinos are discussing introducing computer gaming systems alongside traditional gaming equipment, which could result in an increase of energy use in those facilities (Marcelo 2016). Lastly, policymakers should keep in mind that the technologies embedded in gaming equipment are finding wider and wider application in other sectors. For example, virtual reality (and the computers that run it) is being used in fields ranging from science to medicine to architecture. High-performance GPUs are increasingly used in data centers and supercomputers (Mishra and Khare 2015) and for non-gaming activities such as mining crypto-currencies (Mooney and Mufson 2017).

CHAPTER 8: Technology Transfer: From the Lab to the Marketplace

Technology transfer was integral to the project approach. Key audiences included utilities, researchers, policymakers, gaming industry representatives, and consumers. Approaches included publications, websites, convening stakeholders, and engagement in industry activities (Mills 2018). All project activities have been described on one public-facing website for technical audiences (http://greengaming.lbl.gov) (Figure 27) and another for consumers (http://greeningthebeast.org) (Figure 28).

Figure 27: Green Gaming Website for Technical Audiences
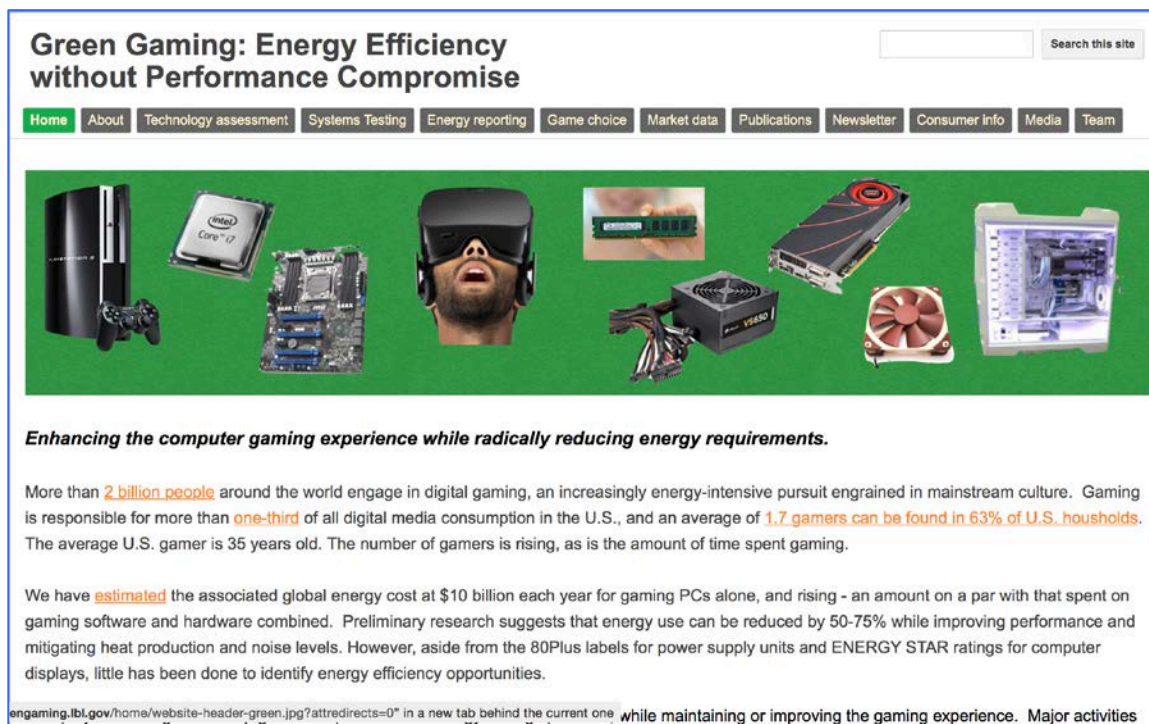
Source: Lawrence Berkeley National Lab

LBNL's work in this area has received considerable mainstream and trade media coverage prior to and during the EPIC project period.[27]Coverage included *Forbes, Grist, Newsweek, R&D Magazine, Science Daily, Slate,* and *Wired.* LBNL produced a news release at the project outset and a 15-minute interview was broadcast on BBC near project completion.

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[27] See http://greengaming.lbl.gov/media.

Figure 28: Greening the Beast Website for Consumers
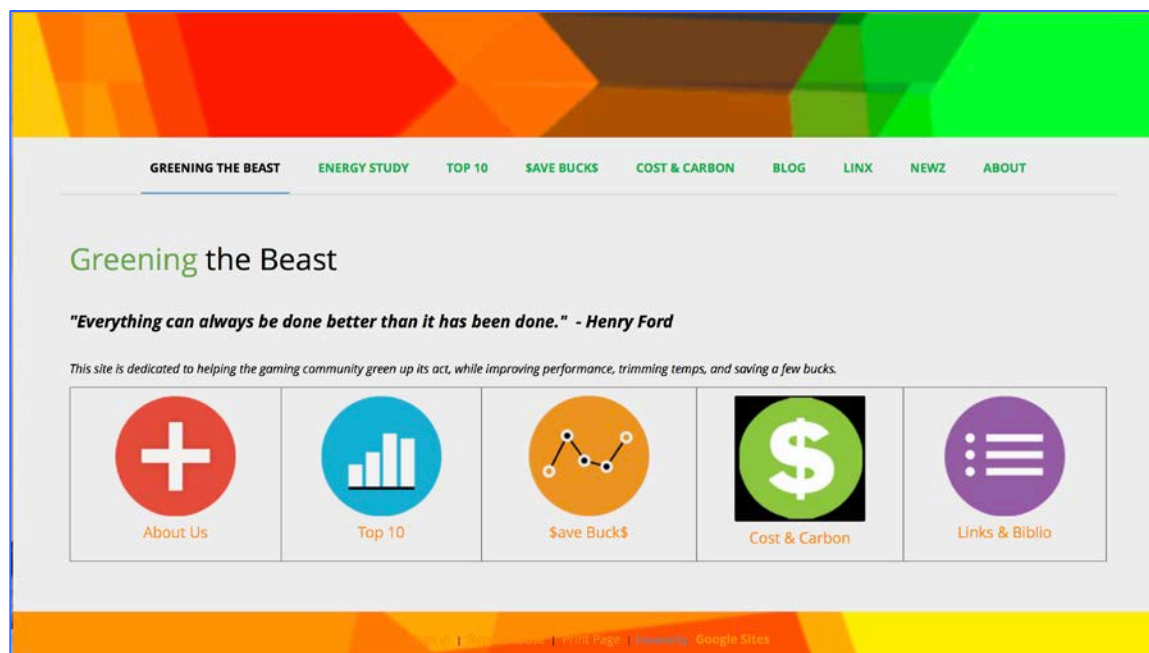
Source: Lawrence Berkeley National Lab

The researchers launched an electronic newsletter (*Green Gaming News*) early in the project as a vehicle for sharing information and insights with the stakeholder group, and to disseminate research results more compactly and more quickly than could be done in formal reports.[28] Departments included interviews with industry leaders, descriptions of the testing capabilities and research results, news on emerging technologies and otherwise relevant activities within the gaming industry, notes on the gaming marketplace, and tips for gamers.

Technical Advisory Committees are intrinsic elements of all EPIC projects. In constituting this project's TAC, individuals were recruited from across the industry, and from relevant stakeholder groups. The committee provided a built-in "focus group" used during the course of the project to vet ideas, seek review of strategies and work product, and so on. TAC members will also likely become early users of the project results.

Over the course of the project, representatives of several gaming product manufacturers visited the testing lab, or otherwise engaged in discussion of product performance. This included multiple in-depth meetings and teleconferences with high-level technical staff at the two leading graphics processor manufacturers, AMD and NVIDIA.

The project team also engaged with the console manufacturers, as well as their United States-based trade organization called the Entertainment Software Association (ESA). The team held an in-depth workshop at LBNL, attended by senior representatives of Sony, Microsoft, and Nintendo as well as ESA. The event involved a two-way exchange of information on gaming

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[28] See http://greengaming.lbl.gov/newsletter.

markets and technology, and the status of energy-efficiency and energy-per-performance metrics research within the consoles industry.

The project team had a presence at certain key industry meetings such as the Game Developers Conference (GDC), the GPU Technology Conference, and the Electronic Entertainment Expo (E3), all held in California. The team also has presented at a DOE seminar on miscellaneous electric loads. The LBNL team subsequently had substantive input to the EU's Voluntary Agreement regarding energy use and efficiency goals for consoles.

Developers of a consumer-focused platform for power supply information requested support from the team in developing a web-based calculator to help easily quantify the benefits of improved efficiency. The research team provided extensive input and recommendations that were subsequently incorporated in the company's offering.[29]

The team also took multiple opportunities to interact directly with gamers. These included visits to LBNL by students of Kennedy High School as well as several dozen LBNL employees who participated in structured gameplay trials held in the Green Gaming Lab.

Technology transfer is essential to the success of the project's testing protocol and development. As part of this strategy, the research team engaged with energy policy agents such as ENERGY STAR® for whom the availability standardized energy-efficiency measurement techniques are critical. Many other stakeholders (NGOs, industry, product reviewers, and so on) were also involved.

Given that gaming software plays as important a role in gaming energy use as hardware, the project made efforts to engage the game developer community. Aside from traditional communication approaches (newsletter, posts on key blogs, and trade press outlets such as *GamesBeat*, and so on), the team explored whether the providers of the software used to author games[30] would be receptive to various forms of collaboration, such as integrating consideration of energy-oriented metrics into the game-design process. Bob King, a seasoned game developer with 25 years in the industry provided extensive discussions and an in-depth interview for *Green Gaming News.*[31]

California utilities are natural users of the project's results. They may, for example, develop consumer information and/or incentive programs to promote more energy-efficient choices. The market assessment conducted in Chapter 2 (Mills *et al.,* 2017) and energy scenarios developed in Chapter 5 (Mills *et al.,* 2018) will assist utilities in segmenting the market and identifying savings potential and market sub-segments worth particular focus. Results of the market characterization performed in Chapter 2 will also help improve end-use characterizations at the individual house level as well as energy demand forecasts at broader geographic scales.

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[29] See (http://outervision.com/power-supply-calculator).

[30] Examples include Unity, Lumberyard, and Steam, as well as tools developed in-house by major game publishers such as Entertainment Arts.

[31] See https://sites.google.com/a/lbl.gov/greengaming/newsletter/issue-3.

In preparation for their definitive 2017 report on consumer electronics, Fraunhofer USA sought LBNL's advice on how to differentiate gaming computers from ordinary computers. An outgrowth of this interaction was that the Consumer Electronics Association included new questions in their statistically representative survey of 1,000 United States households regarding the presence of independent graphics cards as well as hours per day spent in gameplay (for laptops and desktops and systems with and without discrete graphics cards). The findings were important: average daily game time was higher than indicated in earlier and less-well-documented market research used in the researchers' study (Urban *et al.,* 2017). This enabled researchers to improve the estimates of energy use.

Broad-based uptake of "energy thinking" in the gaming marketplace, and among gamers themselves, is a long-term challenge that cannot be addressed by a single project or report. The researchers made concerted attempts to hold a session at the Game Developers Conference without success. Attempts to collaborate with information services that help gamers specify and build do-it-yourself systems were also unsuccessful. The early experiences with disseminating energy information directly to gamers were met with some skepticism and disinterest. As gaming energy issues become more widely known and appreciated, the marketplace is likely to become more receptive to the information.

In the absence of ongoing R&D sponsorship, there is at present no follow-on work in this area at LBNL, and thus the Green Gaming Laboratory will be disassembled and technology transfer activities will be negligible following completion and distribution of the final project reports. The *Green Gaming Newsletter* will cease to be published.

CHAPTER 9:
Emerging Research Questions

Many avenues remain to be explored, with broad opportunities spanning technology, user behavior, and energy policy. User choices manifested in the duty cycle and in-game behavior ultimately influence energy use as much as technology choices.

Market Issues

The computer gaming marketplace is among the most dynamic and rapidly changing segments of the consumer electronics industry, and thus of plug loads more generally. Trends such as consumer choice of broad gaming product categories (for example, consoles *vs* desktops), equipment selection within those very broad categories (entry-level *vs* high-end), gaming modality (local *vs* streaming) have a profound influence on energy use. The duty cycle—also in flux—shapes energy use in an equally strong fashion. Choices of games played are also key drivers. Energy-relevant market data is scarce, and becomes out of date quickly. Thus, improved and continuous market tracking is a critical need.

The definition of energy services in the context of computer gaming remains an elusive one. Frame rates are very narrow measures of performance and user experience, yet are one of the only readily quantifiable metrics. Moreover, the fact that progressively higher frame rates aren't necessarily perceived by humans, while other metrics of performance are independent of framerate, constitute important research frontiers that can only be addressed through extensive human testing trials and survey work with actual gamers.

The lack of energy-focused tools and information for gamers is a critical problem. While gamers make intensive use of in-game diagnostics, energy use is not one of them. As feedback becomes available it should be effectively delivered to the gamer in real-time through energy reporting techniques. Where enabled, developers may consider "gamifying" this information. Gamers seek out goal-driving systems for scoring and garnering merit for doing so. Energy/carbon could be introduced as another variable.[32]

For energy planners, computer gaming should be rigorously and explicitly integrated into end-use-based demand forecasts, routinely updated to reflect the rapidly changing demographics and technology choices among the diverse gaming community. Given the very short product cycle (measured in months, not years) of gaming componentry, along with shifting structure of the installed base and user preferences, routine market assessment and system testing must be performed to maintain awareness of changing marketplace and associated drivers of energy demand. While this report provides a major step forward in characterizing the gaming market and quantifying energy use at the state level, it will rapidly become out of date.

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[32] See interview in *Green Gaming News* with game developer Bob King at http://greengaming.lbl.gov/newsletter/issue-3.

Technology Issues

The evolution of gaming technology has shown that, on the one hand, improved efficiencies can readily be captured, but also that the energy penalty for increased performance and more immersive user experiences can overshadow reductions in absolute energy use that would otherwise occur. There is a qualitative difference in PC and console gaming trends insofar as absolute power for consoles is falling despite improved performance, while that of computer-gaming systems is generally being traded off against improved performance. More work is needed on development of gamer-experience benchmarks.

Among the many issues and technologies meriting better understanding are display-system interactions, fan-less cooling, CPU-motherboard savings opportunities, and a host of software-side issues including the role of in-game settings and more energy efficient image rendering.

Virtual reality may become a dominant upward influence on energy use for all gaming platforms. With rising popularity of VR and very rapid technical development underway, this technology should be closely monitored for both hardware and software energy implications and efficiency opportunities. An illustration of one such technology is "Foveated Displays", in which the display participates process of de-emphasizing regions of view not requiring high fidelity to not only reduce the rendering workload, but also transmit and display fewer overall pixels. Important when considering energy use outside of gaming, VR technology is rapidly finding professional applications in science, medicine, and other fields.

Among the important research questions for cloud-based gaming is the efficiencies of data centers hosting the GPUs, part-load conditions experienced by the GPU servers, and bitrates that occur during all forms of networked gaming. Network energy use downstream of the data centers is also a significant locus of gaming energy use and applies to gameplay as well as video-streaming activities conducted on the gaming device.

Increased attention to power management appears to be one promising avenue for capturing energy savings across the entire spectrum of gaming devices. As suggested by the analysis, current efficacies of power management are uneven across gaming products. Best practices could be more widely promulgated, and emerging technologies and control software more usefully deployed.

CHAPTER 10:
Conclusions

Computer gaming is best approached as a broad system of interconnected technical and behavioral elements rather than focusing on isolated devices. The system in question includes not only technologies—from the home to the data center--but also sophisticated software, and a host of human perceptual and behavioral factors that shape energy demand equally strongly.

The researchers find that 4.1 TWh/year in electricity is consumed for gaming in California today, corresponding to a $0.7 billion/year expenditure by consumers, and 1.5 million tons CO_2-equivalent/year of greenhouse-gas emissions. The current trends involving faster growth of consoles than PCs and reductions in Internet electricity intensity are offsetting the otherwise increase in aggregate energy demand growth that would be caused by an expanding installed base of gaming systems.

User choices and in-game behavior ultimately influence energy even more than technology choices. The lack of relevant energy-focused tools and information for gamers is a critical problem.

The research team achieved *per-system* electricity savings of about 50 percent for the desktop PCs and estimated a scope for about 40 percent savings in consoles by the year 2021. The team was not able to modify or otherwise estimate savings for laptops or media streaming devices used for gaming, which, in any case, represent, a very small portion of aggregate gaming energy demand. When these per-unit savings are combined with other drivers (continued shift towards higher-end PCs, the trend towards cloud gaming, larger displays, and so on) the aggregate energy demand declines by 22 percent from 2016 levels. The alternate baseline scenarios defined an envelope in which near-term energy use, cost, and emissions rise by 114 percent or by 28 percent, depending on how the product choice and user behaviors evolve. The relative shares of different gaming product families (PCs, consoles, media-streaming devices) vary substantially among these scenarios, with consoles dominant in some and PCs in others.

High-performance gaming computers are among the very most energy-intensive plug loads in use, and are arguably the most difficult to characterize. Taken in aggregate, gaming energy use is greater than that of many more well-understood plug loads.

Many avenues remain to be explored, with broad opportunities spanning technology, user behavior, and energy policy. Much more must be done to define and promulgate methodologies for testing and understanding the relationship between energy use and user experience, for example, how to cope with highly varying energy use across games, establishment of standardized test procedures for gaming mode, and development of non-gameplay test procedures that reflect the way gamers use their systems and displays in practice.

There are two key reasons that addressing gaming energy use is challenge for energy planners. First, the rate with which energy policy and programs can be developed is much slower than the gaming technology product cycle. Second, because there are multiple, often unquantifiable,

determinants of energy services rendered by gaming, the concept of "energy efficiency" in gaming end-use defies simple definition. For both of these reasons, mandatory energy standards are unlikely to be practicable.

GLOSSARY

Term	Definition
CPU	Central Processing Unit. Conducts the primary computing tasks, and is one of the most important nodes of energy use in the gaming system.
Cloud-based gaming	Gaming conducted on a local client using a remote server to provide the graphics processing, thus shifting the associated workload to a data center.
Computer game	Any electronic game played on PCs, consoles, or media streaming devices. Also referred to as a "video game".
USDOE	United States Department of Energy.
DVFS	Dynamic Voltage Frequency Scaling. DVFS involves changing power states in real time to better match the resources actually required by the computing process (for example, graphics rendering in the case of gaming systems).
Firmware	A type of software that provides low-level control of a computer's hardware. Typically not modifiable other than through user-accessible settings. It is held in the non-volatile memory.
Foveated rendering	The process of gradually reducing the precision of rendering along a gradient from the fixed center of view to the periphery of view. The eye's fovea is most sensitive in the central area.
Foveated reconstruction	With the assistance of built-in eye-tracking, high-fidelity rendering is performed only in the part of the field of view at which the gamer's eye is looking, irrespective of head position.
fps	Frames per second. The rate at which images (frames) are displayed each second; a highly limited (although widely used) measure of user experience and system performance.
Frame-rate benchmarking	In the gaming industry, many benchmarks (for example, Fire Strike) are used to estimate frames per second under different system loads.
GPU	Graphics Processing Unit. Also referred to as a "graphics card" or "video card". Provides computing power for visual information, including 2D & 3D rendering and animation.
HD	High-definition 1080p display resolution.
Hz	Hertz, cycles per second.
In-game settings	User-adjustable attributes of a game's look and feel, influencing scene detail and realism.
kWh	Kilowatt-hour, unit of electricity use.

Term	Definition
MMORPG	Massively Multiplayer Online Role-playing Game. A game played with multiple players sharing the same gameplay environment.
Mod	A modification to a computer game. Examples include enhanced textures and shaders that dramatically enhance illumination quality, shadows, and other details in the gaming scene.
Motherboard	The main circuit board in a computer. The CPU and most other gaming system components are mounted on and orchestrated by the motherboard. The motherboard also holds the chipset that manages data flows among internal and external components.
On-demand gaming	See "cloud-based gaming".
Online gaming	Gaming for one or more players in which some content is provided via the network and/or gamers exchange information to play in simultaneously coordinated worlds.
PC	Personal computer (Mac OS or Windows).
PSU	Power Supply Unit. Converts mains AC current to low-voltage regulated DC power for the internal components of a computer.
PUE	Power Utilization Efficiency. A facility-level energy efficiency metric for data centers. PUE is the ratio of total facility power to the power used exclusively by the IT equipment. Lower is better. A facility with, for example, large air conditioning loads will have a higher PUE.
Streaming gaming	See "cloud gaming".
TDP	Thermal Design Power (sometimes called Thermal Design Point). The peak power generated by a computer processing chip (CPU or GPU) at its rating point.
TWh	Terawatt hour (one billion kilowatt-hours).
Video game	See "Computer game".
VR	Virtual Reality. An immersive and interactive three-dimensional simulation viewed through a specialized headset on a computer-gaming system.
1080p	1080p display resolution. Also referred to as high definition (HD).
4k	2160p display resolution. Also referred to as ultra-high definition (UHD).

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APPENDIX A:
Gaming Systems Evaluated in this Study

Product Category	System ID	Make and Model	Mother-board	CPU	GPU	GPU - Integrated / Discrete	Power Supply Rating
Entry-level desktop PC	E1	Dell/Alienware - Alpha (GTX850M)	Unknown	Intel Core i3-4170T	NVIDIA GeForce GTX850M GPU	Discrete	unknown
	E2	HP - Pavillion All in One	Unknown	Intel Core i5-6400T	Intel HD Graphics	Integrated	unknown
	E3	DIY	MSI 970 Gaming	AMD FX-6300	AMD R7 360	Discrete	80+ White
	E4	DIY	MSI Intel Z97 LGA 1150 DDR3	Intel Pentium G3258	AMD XFX R7 370 GAMING 2G Graphics Card	Discrete	80+ White
Mid-range desktop PC	M1	Apple - iMac 27"	Apple	Intel Core i7	Radeon R9 M390	Integrated	unknown
	M2	DIY	MSI Z97 Intel LGA 1150 DDR3	Intel Core i5-4690k	NVIDIA GIGABYTE GeForce GTX 960 4GB WINDFORCE 2X OC EDITION	Discrete	80+ Bronze
	M3	DIY	ASUS Crosshair V Formula Z	AMD FX-8350	AMD Sapphire Radeon R9 Nano	Discrete	80+ Gold
	M4	DIY	ASRock Fatal1ty Gaming Z97X Killer	Intel Core i7-4790K	NVIDIA ASUS GeForce GTX 970 STRIX-GTX970-DC2OC-4GD5	Discrete	80+ Gold
	H1	DIY	EVGA X99 Classified	Intel Core i7 5820K	AMD 2x R9 Fury X	Discrete	80+ Gold

Product Category	System ID	Make and Model	Mother-board	CPU	GPU	GPU - Integrated / Discrete	Power Supply Rating
High-end desktop PC	H2	Digital Storm - Velox	ASUS Z170-E	Intel Core i7 6700K	NVIDIA Titan XP	Discrete	80+ Platinum
Entry-level laptop PC	L1	HP ENVY x360	n/a	AMD FX Series	Radeon R7	Integrated	Category VI
	L2	Razer Blade Stealth New	n/a	Intel i7-7500U	Intel	Integrated	Category VI
Mid-range laptop PC	L3	Apple	n/a	Intel Core i7	Intel Iris Pro	Integrated	Category VI
	L4	Alienware 13	n/a	Intel i7-6500U	Nvidia GTX960m	Discrete	Category VI
High-end laptop PC	L5	Origin EON15-X 10 SERIES	n/a	Intel i7 6700K	Nvidia GTX1070	Discrete	Category VI
Consoles	C1	PS3 - Super Slim CECH-4000B					
	C2	PS4 Slim - CUH-2015A					
	C3	PS4 Pro - CUH-7015B					
	C4	Xbox360 Elite - Jasper chipset					
	C5	Xbox One - 1540					
	C6	Xbox One S - 1681					
	C7	Wii - RVL-001					
	C8	Wii U - WUP101(02)					
	C9	Nintendo Switch - HAC-001					
Media streaming devices	V1	Apple TV - A1625					
	V2	SHIELD (Android TV) - P2897					